Modeling of Sliding Shear Resistance of Reinforced Masonry Squat Walls

J. Centeno & C.E. Ventura
University of British Columbia, Canada

S. Brzev
British Columbia Institute of Technology, Burnaby, BC, Canada

SUMMARY:
This paper presents the results of an ongoing research study on the sliding shear mechanism in reinforced masonry (RM) shear walls. An overview is presented of the current design procedure and its limitations. Findings of previous studies have been used to develop an analytical model that will allow to simulate the sliding shear response of RM shear walls subjected to earthquake ground shaking in a realistic manner, comparable with the results of experimental studies. The proposed analytical model is described in this paper, and the preliminary results are compared with the results of relevant experimental studies.

Keywords: Reinforced Masonry, Sliding Shear Mechanism, Seismic Response

1. INTRODUCTION

Sliding shear is usually the governing failure mechanism for ductile reinforced masonry (RM) squat shear walls with a height/length (H/L) aspect ratio below 1.0 and with low axial load designed according to seismic design provisions of Canadian masonry standard CSA S304.1-04. These walls are built using hollow concrete blocks with vertical and horizontal reinforcement placed inside the blocks (in the hollow cells), which are subsequently filled with cementitous grout. . In addition to this, results of previous experimental research studies indicate that even for squat walls that yield in flexure, the displacements at the top of the walls are the result of both flexure and sliding shear mechanisms. Due to a limited experimental evidence and an absence of rational analytical model, the understanding of the sliding shear mechanism and the manner in which it affects the response of a building is limited at this time. This paper outlines the objectives and the status of a research study focused on modelling the sliding shear mechanism. The study investigates the effects of friction resistance, dowel action and flexural hinging. A constitutive analytical model has been developed to establish the criteria for the occurence of sliding shear mechanism and estimate displacement demands.

2. BACKGROUND

Squat RM shear walls are most common in low-rise masonry construction in Canada, including design applications such as school buildings and fire halls. Fire halls are designed as post-disaster facilities in the NBCC (2010) and require the seismic force-resisting system to have a ductility factor R_d of 2.0 or higher. This requirement forces the design of squat walls to follow provisions for "moderately ductile squat shear walls" according to CSA S304.1-04 and use the capacity design approach.

The capacity design approach sets out to achieve a ductile failure by ensuring that the shear strength is not less than the lateral force necessary to develop a flexural yielding mechanism in the wall. In following this design approach for masonry squat walls, after horizontal reinforcement has been provided for sufficient shear resistance, in certain conditions it has been found that the sliding shear strength is lower than the force required to develop the plastic hinge mechanism.

The current Canadian masonry design standard CSA S304.1-04 Cl. 10.10.4 (CSA 2004) provides the equation to estimate the sliding shear resistance, V_r, for a RM shear wall, as follows

$$V_r = \phi_m \mu P_2 \tag{2.1}$$

where:

ϕ_m = resistance factor for masonry
μ = coefficient of friction
P_d= axial compressive load on the section under consideration, based on 0.9 times dead load.
P_2= $P_d + T_y$, compressive force in the masonry acting normal to the sliding plane.
$T_y = \phi_s A_s f_y$, the factored tensile force at yield of the vertical reinforcement
ϕ_s = resistance factor for steel reinforcement
A_s = area of vertical reinforcement
f_y = yield stress of steel

However, for masonry squat walls with an (H/L) aspect ratio below 1.0 and with low axial load it is found that the sliding shear resistance calculated according to this equation would be insufficient to develop a flexural yielding mechanism. Moreover, if a new design iteration is made and more steel dowels are added to increase sliding shear resistance, the governing mechanism continues to be sliding shear due to an increase in flexural resistance (Anderson & Brzev, 2009). Current code provisions do not address this issue and there is no guidance on whether to consider sliding shear as a brittle or a ductile mechanism. As a result, the wall is designed either by ignoring the possibility of sliding shear, or by considering it a possible mechanism and making an assumption regarding its seismic performance.

3. MECHANICS OF THE SLIDING SHEAR MECHANISM

The current knowledge of sliding shear is that there are two possible loading conditions according to which the sliding can occur: i) when the initial sliding shear resistance of the sliding plane is lower than the force required to develop a flexural yielding mechanism, and ii) when the frictional resistance is reached after the wall sustains one or more cycles of inelastic flexural rotation. While CSA S304 recommendations are based on the former mechanism, the experimental evidence shows more cases of the latter sliding shear mechanism.

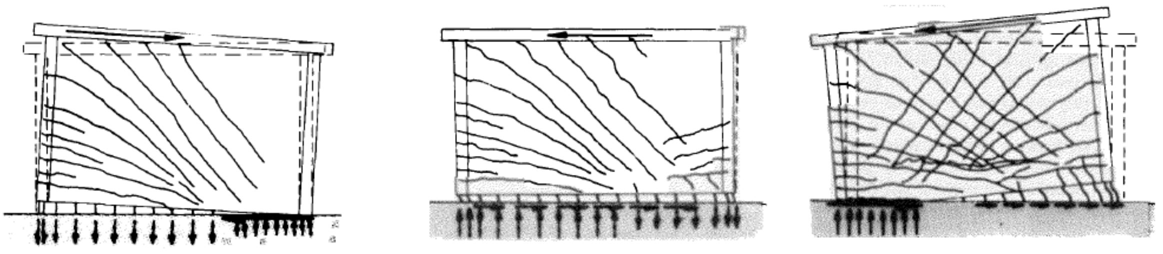
Based on the estimation of shear resistance in reinforced concrete beams, the shear resistance available along a horizontal sliding plane is a function of the following factors: friction due to gravity loads, aggregate interlock, shear friction, and dowel action. This section presents examples of sliding shear mechanism in RM squat shear walls reported by several researchers, which have formed the current state of knowledge of this mechanism.

3.1. Experimental Studies

Priestley (1977) stated that the sliding shear mechanism is a consequence of significant inelastic flexural deformation in one direction, resulting in a wide open crack at the wall; this is followed by a reversal of load direction, when the crack becomes open over the full length, thereby cancelling friction resistance and forcing the entire shear load to be resisted by vertical reinforcement through the dowel action. Once the flexural crack is closed, the resistance increases rapidly and sliding ceases. An illustration is presented in Figure 1.

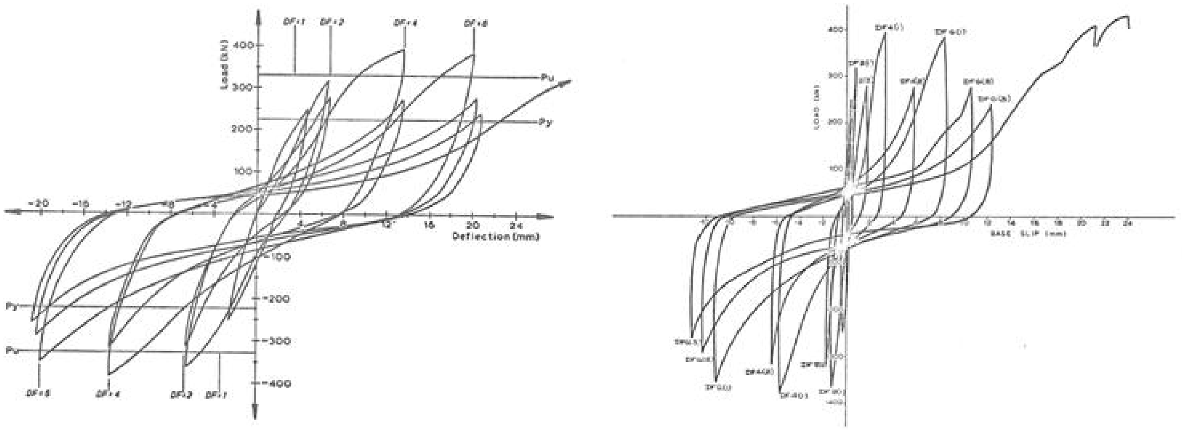
Figure 2 shows the experimental results on wall elements with the aspect ratio H/L =0.68 tested by

Priestley (1977). The results show that for the displacement ductility ratio(DF) of 4.0 and above, approximately half of the total displacements were due to sliding shear at the base. Another finding is related to the loss in stiffness, which increased with the increasing ductility level (and it did not depend on the applied load level). Figure 2 also shows a contribution of sliding shear displacements to the stiffness reduction in the wall; this has been observed as a lower load achieved when applying a new cycle of deformation using the same amplitude as for the previous cycle.



a) b) c)

Figure 1. Sliding shear mechanism in combination with the flexural yielding: a) flexural yielding occurs , b) loading direction is changed, and sliding has been initiated, and c) shear resisted through dowel action until the flexural crack is closed (Paulay, Priestley, Synge, 1979)



a) b)

Figure 2. Resulting load-displacement plots for cantilever wall specimen A3 with aspect ratio H/L=0.68: a) load-deflection, and b) load-base slip. (Priestley, 1977)

Shing et al. (1989) conducted a research program to study the effect of the applied axial stress and vertical and horizontal reinforcement on the lateral resistance, failure mechanism, ductility, and energy dissipation capability of a wall panel. Three out of more than 20 specimens demonstrated the sliding shear failure mechanism at the base of the wall, in combination with either a flexural or a shear mechanism. All three specimens (6, 8, and 11) were tested under zero axial stress conditions. As the specimens were loaded to reach the ultimate lateral load capacity, the contribution of base wall sliding to the total deformation was approximately 10%. At higher ductility levels, base sliding contributed to 25% of the total deformation for specimens 6 and 11, and more than 50% of the deformation for specimen 8. In addition, it was reported that base sliding influenced the observed degradation in lateral load capacity and, to a lesser extent, the ultimate strength achieved for these specimens.

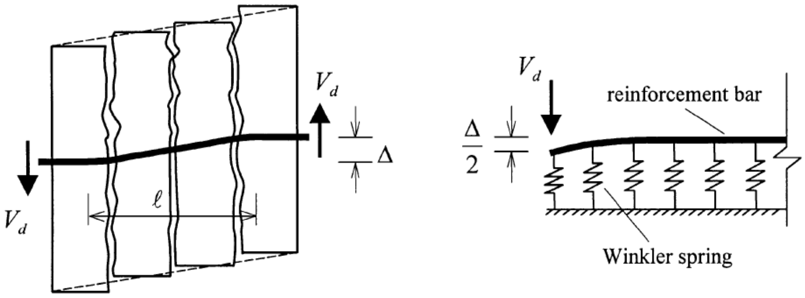
Voon (2007) performed a research study on the shear strength of concrete masonry walls by testing ten full-scale RM shear walls under reversed cyclic loading. The contribution of base wall sliding in test walls with shear-dominant response was mostly negligible once the tested walls were loaded beyond ±4.0 mm displacement. In the case of Wall A3, designed to fail in flexure, sliding contribution increased as the displacement demands were increased, reaching about 20% of the wall lateral displacement at the end of testing. It was concluded that the base wall sliding and the transfer of a portion of the shear force by dowel action may have resulted in the specimen not reaching the expected lateral strength estimated based on beam theory.

Other reported evidence where sliding shear slip contributed significantly to the maximum displacement measured at the top of the specimen for walls designed to yield in flexure included reversed cyclic tests (Abrams, 1988; Shing et al., 1989; Shedid, Drysdale, and El-Dakhakhni, 2008;), and shake table tests (Seongwoo, 2010 and Stavridis, et al. 2011.). These specimens had H/L ratio values in the range from 1.0 to 2.0, and were subjected to zero axial loads.

3.2. Analytical Model

One of the most significant challenges related to modelling the sliding shear mechanism has been related to taking into account the contribution of dowel action. Although the current CSA S304 sliding shear design provisions do not account for dowel action, experimental studies have shown that, after the loss of friction resistance that wall specimens present a remaining stiffness where dowel action is a contributing factor (Priestley, 1977).

The shear strength and stiffness contribution due to dowel action in RM walls is dependent on the interaction between the vertical reinforcement and the surrounding grout. In recent research studies on dowel action, this interaction has been modelled using a model similar to a beam on an elastic foundation, where the foundation modelled as a bed of Winkler springs (El-Ariss B. 2006, He & Kwan 2001), as shown in Figure 3.



(a) (b)

Figure 3. Modeling of dowel action using elastic springs: (a) dowel action in reinforced concrete beam after cracks are formed, and (b) Winkler spring representation of dowel action (He & Kwan, 2001).

Dowel strength may be derived from three possible mechanisms: i) the flexure of reinforcing bars, ii) the shear across the bars, and iii) the kinking of the reinforcement. Assuming that a dowel action is controlled by flexure and by simplifying the deformed shape to a linear expression, Priestley and Bridgeman (1977) determined the maximum dowel shear resistance of 0.30 A_sf_y for reinforced brick masonry (this corresponds to the development of flexural hinge). Paulay, Priestley & Synge (1979) reported experimental values of 0.40 A_sf_y for dowel action in reinforced concrete. Dulacska (1972) proposed a similar equation for estimating the dowel force at the ultimate, which is equal to $0.36A_sf_y$ for concrete compression strength, f'_c, of 20 MPa. These research studies presented values of yield slip for dowel action in the range of 1 mm to 5 mm. However, depending on the dowel cross-sectional area, its shear capacity may be limited by either the bearing strength of the surrounding concrete or the yield strength of the reinforcement.

Experimental testing has been conducted to study the structural properties of dowel action in cast in-place reinforced concrete (Soroushian, et al., 1988; Vintzeleou & Tassios, 1987) and precast concrete structures (Tsoukantas & Tassios, 1989). There are no reported research studies related to dowel action in reinforced concrete block masonry structures.

4. ANALYTICAL STUDY

Current engineering practice can benefit from design tools that can better predict the onset of sliding shear response and establish whether sliding shear can be considered as a ductile mechanism for seismic design. The goal of the proposed research is to develop a constitutive model that can adequately simulate the triggering of the sliding shear mechanism.

4.1. Proposed nonlinear model

A two-dimensional (2-D) model has been developed in OpenSees for simulating the development of the sliding shear mechanism at the base of a RM cantilever wall. The model has been developed to account for the coupling of the flexure and sliding shear mechanisms, simulating the variations in friction resistance, and triggering of dowel action. In addition, the model includes a nonlinear beam element to account for the contributions of shear and bending deformations along the wall height.

The plastic hinge region at the base of the wall is modeled by discretizing the wall base as a series of compression-only beam elements to simulate masonry in compression, and steel reinforcement bars as a series of nonlinear axial springs (see Figure 4). This discretization of the wall base allows the model to simulate both the flexural yielding mechanism and the sliding shear mechanism.

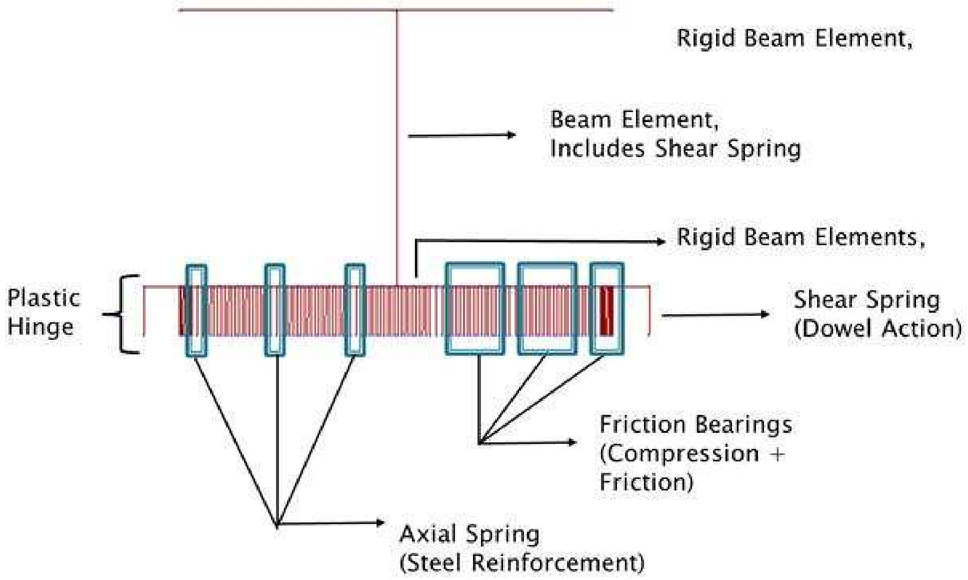


Figure 4. Key elements of the proposed 2-D Model

The series of compression-only beam elements allow to simulate the friction resistance at the base of the wall. These elements are modeled using the “Flat Slider Bearing” beam element which calculates internally its shear resistance following a Mohr-Coulomb friction model. When the residual strains in the tension elements prevent compression on this element, its friction resistance becomes zero. As a result, the model can develop a loss in friction resistance at the base if none of its compression-only elements are loaded in compression. To develop shear resistance in each compression element, the selected boundary conditions are fixed at its top node and pinned at the bottom. These boundary conditions were selected to ensure the wall's overturning moment corresponding to the onset of yielding was adequately modeled as a function of the axial force-deformation behavior of the compression and tension elements.

Two shear springs are added at the sides of the plastic hinge region to model the dowel action. The shear springs are linked to the plastic hinge region using beam elements. The rebar's yielding stress in dowel action was set equal to 30% of the axial yielding stress, f_y, and it does not depend on the acting axial stress on the reinforcing bar. The hysteretic behaviour was modelled as pinched and was made by adding three parallel springs: two elastic-perfectly plastic gap springs, and one elastic perfectly plastic spring. An example of the resulting hysteretic behavior is presented in Figure 5.

4.2. Preliminary Results

This section presents the results of the first application of the 2-D model. The wall analysed was the specimen A4 from the experimental program conducted by Priestley (1977).

The specimen A4 was a RM wall with height of 1820 mm, length of 2430 mm with concrete block units of 140 mm. The wall had vertical reinforcing of 6-16 mm diameter bars and horizontal reinforcing of 8-16 mm using high strength steel deformed bars. The specimen was not subjected to external axial loads and had a self weight of 13.2 kN. The masonry compression strength f'_m was of 21 MPa and the yield strength of the steel reinforcement was of 454 MPa.

The analytical model for this specimen was made using the same wall dimensions, setting 15% of the total height for the plastic hinge region at the wall base. The properties of the beam element used for bending were cracked section properties, with a 0.50 and 0.25 coefficients for the cross sectional area and inertia, respectively; and an elastic modulus, E_m, of 4.0 GPa.

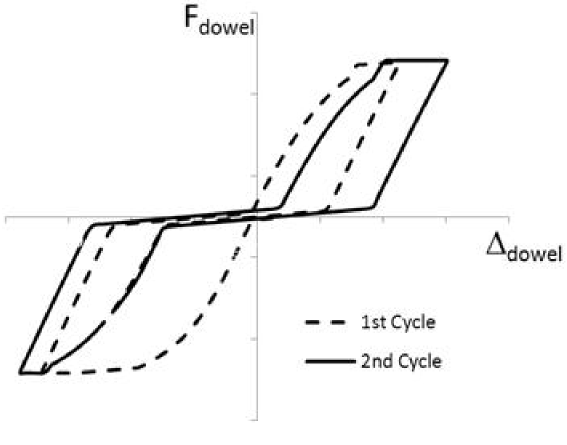


Figure 5. Force-deformation relationship for a shear spring model used to simulate dowel action

The plastic hinge was modelled using 130 "Flat Slider Bearing" beam elements for the compression elements and 6 uniaxial springs with nonlinear material properties for the vertical reinforcing steel. For the compression-only beam elements, a linear elastic behavior was used to model axial compression ,with an elastic modulus of, E_m, of 10.0 GPa; and for the friction resistance, a friction coefficient μ of 0.70 and yielding displacement of 1.0 mm were used. The vertical reinforcement was modelled using the steel 02 material element with yielding strength f_y of 454 MPa with a strain hardening ratio of 0.001. Dowel action was modelled to have a yielding displacement of 2 mm.

A comparison plot of the analytical and experimental results is shown in Fig 6. The analytical model is able to simulate many aspects of the force deformation behaviour of the tested squat wall. The model matched the wall's force-deformation slope and maximum force, for the ductility factor, DF, equal to 1. The model is able to capture the apparent loss of lateral strength after a cycle of deformation is repeated and often with satisfactory accuracy.

The model's force-deformation behaviour shows a pinched hysteretic behaviour. This behavior is found to be similar to that observed in the experimental test. The loss in stiffness in this behavior is a result of the opening of a flexural crack across the entire length of the wall base and the wall sliding resistance being controlled by dowel action alone. When in the force deformation plot the lateral stiffness is increased; it is due to the flexural crack closing and the friction resistance being regained.

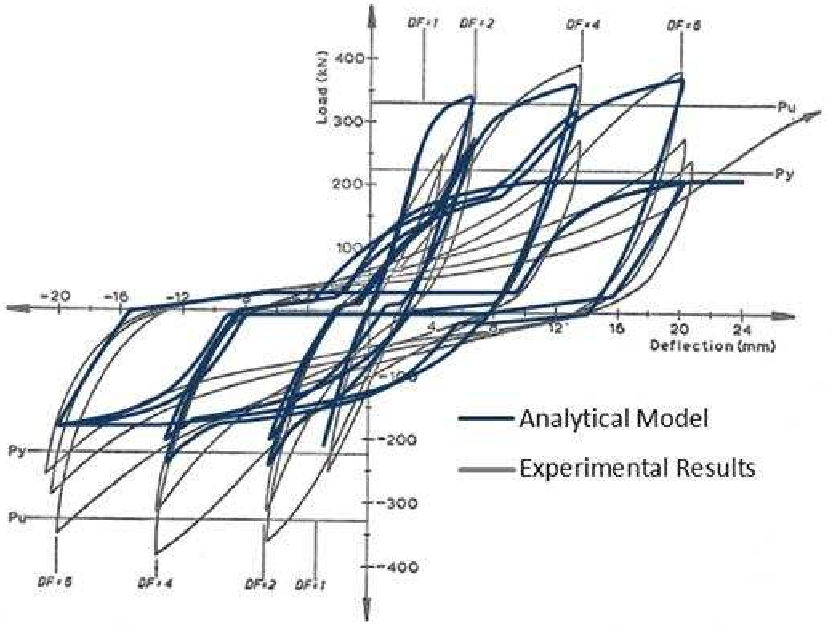
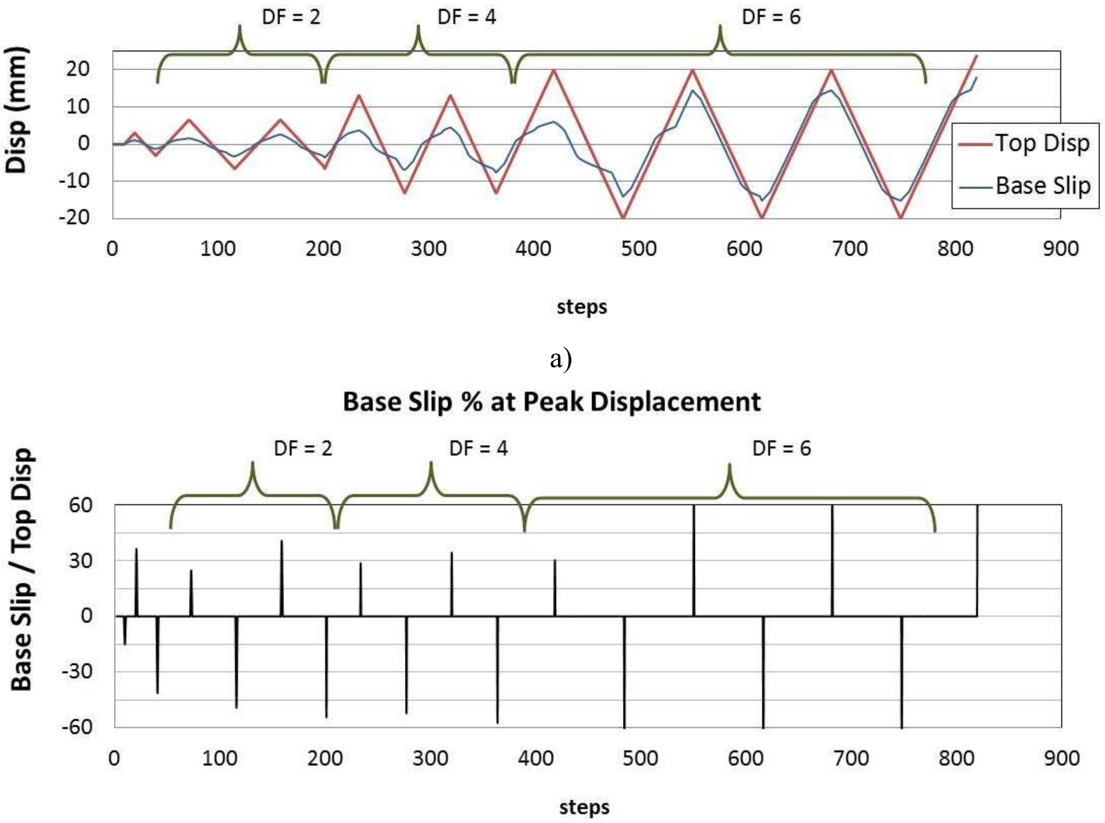


Figure 6. Cyclic loading results from proposed nonlinear model compared to experimental results of RM squat wall (specimen A3).

The displacement time history results of the model show it is able to simulate the increasing level of base wall sliding when the applied ductility factor is increased. The model shows that for ductility factor, DF, equal to 2.0, the base wall sliding can be as much as 54% of the total top displacement; and for a DF equal to 6.0, the contribution can increase to 76%.

The force-deformation behaviour is shown to be asymmetric, unlike that of the experimental specimen. Additional work is required to improve the capability of the model to simulate a more symmetric behaviour. In addition, the results of the model show a regain in lateral stiffness which occurs for a smaller deformation demand than that reported by the experimental results.

It is proposed to perform a sensitivity study to identify the consequences of the sliding shear mechanism in RM shear walls.



a)

b)

c) **Figure 7.** Cyclic loading displacement time history results: a) displacement time history at the top and base of modelled wall, and b) time history of the ratio of base slip and the top displacements for the wall.

5. CONCLUSIONS

This research study has set out to obtain a better understanding of the sliding shear mechanism in squat RM shear walls and update the current design method. A 2-D analytical model has been developed to simulate the sliding shear mechanism based on findings from previous experimental studies. A significant progress has been made in developing the model that can reproduce the formation of a flexural crack and its effects on the sliding shear resistance at the base of the wall. Further work is required to improve the simulation and modelling of the force-deformation relationship for dowel action.

It is expected that, when finalized, the proposed model will enable improved estimates of sliding shear resistance and associated sliding displacements in RM squat walls.

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