# SLIDING SHEAR RESISTANCE OF SQUAT REINFORCED MASONRY SHEAR WALLS UNDER SEISMIC LOADING

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## ABSTRACT

Current Canadian masonry design provisions for seismic design contained in CSA S304-04 standard of reinforced masonry (RM) shear walls often shows that sliding shear is the governing failure mechanism for squat walls with a height/length (H/L) aspect ratio below 1.0 at low axial load levels and subjected to lateral seismic forces and overturning moments. As a result it is estimated that the sliding shear mechanism prevents the development of ductile flexural response in these walls. However, previous experimental studies have shown cases of similar RM squat walls that have initially responded with a flexural yielding mechanism and after cycles of inelastic rotation have developed a sliding shear failure mechanism. Despite these observations, there currently are no recommendations on how to estimate the seismic performance of a RM squat wall with a sliding shear mechanism for a seismic design. The following presents the progress in a research study to model the sliding shear mechanism as a function of changes in friction resistance, dowel action and flexural hinging. This rationale model has been used to recreate the results observed in an experimental test and determine how the sliding shear resistance varied during the loading history.

**KEYWORDS**: reinforced masonry, sliding shear, seismic response, shear walls, squat walls

## INTRODUCTION

Squat shear walls made or reinforced concrete block masonry are most common in low-rise masonry construction, such as school buildings and fire halls. These walls are characterized by a height (H) to length (L) (H/L) aspect ratio of less than or equal to 1.0. Fire halls are designed as post-disaster facilities in the National Building Code of Canada 2010 (NBCC 2010) [1] and require the lateral resisting system to have a ductility capacity associated with a ductility force reduction 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" and use a capacity design approach.

Capacity design approach sets out to ensure that wall's shear strength corresponding to the diagonal tension failure mechanism is not less than the lateral force necessary to develop a flexural yielding mechanism in the plastic hinge zone of the wall, therefore ensuring a ductile seismic response. For the case of squat walls with low axial load the flexural failure mechanism cannot be guaranteed. Unlike their diagonal tension shear strength, the sliding shear strength of the above mentioned squat walls may be lower than the force required to develop the flexural mechanism. Moreover, if a design is revised and more vertical reinforcing bars (dowels) are added in the lower portion of the wall, sliding shear still remains the governing failure mechanism [2]. Current Canadian masonry design provisions contained in CSA S304-04 standard [3] do not address this issue, and there is a lack of guidance on rational criteria and shear capacity of squat shear walls with the predominant sliding shear mechanism.

In addition, there is a lack of agreement on whether sliding shear mechanism should be considered as a brittle or a ductile mechanism. This paper discusses the sliding shear mechanism and presents the results of an analytical study in which a rational model for simulating the sliding shear mechanism in reinforced masonry (RM) squat shear walls has been developed.

## MECHANICS OF THE SLIDING SHEAR MECHANISM

There are a very few reported research studies on the sliding shear mechanism in RM shear walls. However, it is believed that the sliding shear mechanism in RM shear walls is similar to shear friction mechanism in reinforced concrete flexural members, including beams and walls, and that the key parameters are the same. Shear friction mechanism is associated with the shear resistance along a sliding interface (plane), which depends on the friction due to gravity loads, aggregate interlock along the crack, and dowel action across the interface.

An explanation of the sliding shear mechanism in RM shear walls subjected to reversed cyclic lateral loading is based on the findings of previous experimental studies [4], [5]. When the wall is first forced to yield by applying a lateral load at the top, a flexural yielding mechanism initially develops, as shown in Figure 1a (provided that the capacity design approach has been followed in design and diagonal shear failure has been prevented). As a result of this mechanism, the reinforcement at the base of the wall yields in tension, leaving a gap between the base of the wall and the floor slab. After this, when the load direction is reversed, tension strains develop in the vertical reinforcement at the other end of the wall, and the gap between the base of the wall and the foundation propagates over the full wall length, as illustrated in Figure 1b. This results in an effective loss of friction resistance along the interface and forces shear to be resisted by shear deformation in the vertical reinforcement through dowel action. Once the flexural crack is closed, the sliding resistance increases rapidly and sliding ceases, as shown in Figure 1c. A literature review of previous experimental studies that have reported sliding shear mechanism in RM shear is presented in [6].

## CURRENT DESIGN APPROACH FOR ESTIMATING THE SLIDING SHEAR RESISTANCE OF RM SHEAR WALLS

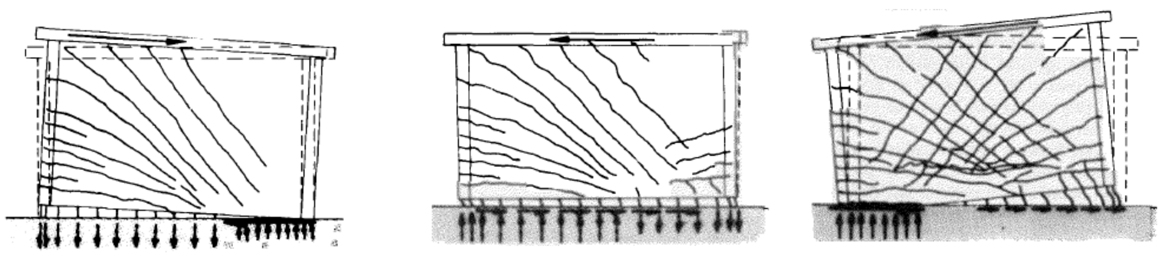
The current Canadian masonry design standard CSA S304-04, Cl.10.10.4 [3] provides the following equation for predicting the sliding shear resistance, $V_r$:

$$Vr = \phi_m \, \mu \, P_2 \qquad (1)$$

where:

$\phi_m$ = resistance factor for masonry

$\mu$ = 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 (area $A_s$)
$\phi_s$ = resistance factor for steel reinforcement
$f_y$ = steel yield strength



a) b) c)

**Figure 1: Sliding shear mechanism coupled with the flexural yielding:** a) **an onset of flexural yielding, b) an onset of sliding during the load reversal, c) shear resisted through dowel action until the flexural crack closes [5]**

**ANALYTICAL MODEL**

Current engineering practice can benefit from design tools that would be able to better predict the onset of sliding shear response, and establish whether it could be used as a ductile mechanism for seismic design. The goal of the proposed research is to develop a constitutive model that would be able to simulate the onset of the sliding shear mechanism based on the rational criteria.

A 2D analytical model has been developed in OpenSees software platform [7] for simulating the development of the sliding shear mechanism at the base of a RM cantilever shear wall. The key features of the model are: i) to account for coupling of the flexural and sliding shear mechanisms; ii) to simulate the variations in friction resistance, and iii) to identify criteria associated with triggering the dowel action. In addition, the model includes a nonlinear beam element that accounts for the contributions of shear and flexural deformations along the wall height.

The plastic hinge region at the base of a cantilever wall has been discretized to model the formation of a flexural yielding mechanism and a sliding shear mechanism, as shown in Fig 4. The base portion of the wall is modelled as a series of compression-only beam elements to simulate masonry in compression, and a series of nonlinear axial springs simulating the effect of vertical reinforcing bars.

The series of compression-only beam elements have been selected to model the friction resistance at the base of the wall. These elements have been modelled using the “Flat Slider Bearing” Beam (FSBB) element in OpenSees which calculates internally its shear resistance following the Mohr-Coulomb's friction model. When the residual strains in tension elements prevent compression on the FSBB element, its friction resistance becomes zero. As a result, the model is able to simulate a loss in friction resistance at the base, provided that none of its compression elements are loaded in compression. FSBB elements have been modelled as fixed at the top and pinned at the base in order to develop shear forces due to friction resistance and avoid undesirable bending moments at the base (as the wall's flexural resistance should be provided through axial forces).

One shear spring is added at the center of the plastic hinge region to simulate the dowel action in the vertical reinforcement. The spring is linked to the plastic hinge region using a constraint that sets its horizontal displacement to be equal to that at the node located at the top center of the plastic hinge. The range of suggested values obtained from experimental studies performed by others ( [4],[8], and [9]) for the dowel action force-deformation properties were: for the yield stress between 30% to 40% of the rebar's axial yield strength, $f_y$; and for the yield deformation between 1 to 5 mm. The hysteretic behaviour was modelled as pinched (shear-controlled), with stiffness degradation and without strength degradation; this was based on recommendation from a previous research study [10]. An example of the hysteretic behavior from the analytical model is presented in Figure 5.

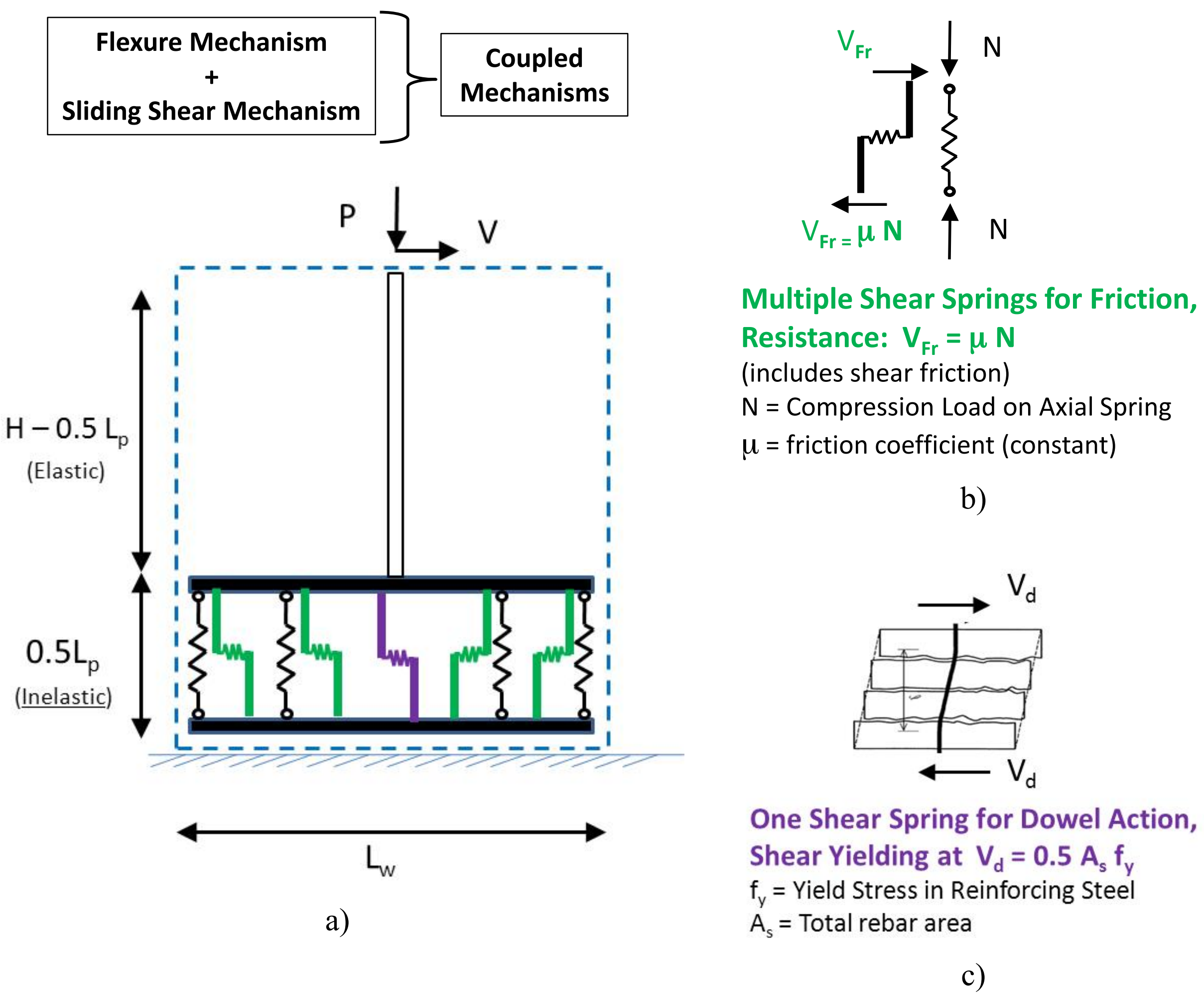



**Figure 4: Key Elements of the 2-D Analytical Model: a) Wall element model, b) Frictional resistance coupled with axial loading, and c) Dowel action model.**

## AN APPLICATION OF THE MODEL

The proposed analytical model was calibrated using the results of an experimental study on a RM squat shear wall specimen subjected to reversed cyclic loading [4]. The specimen A4, tested as a part of the larger study, demonstrated significant sliding at the base. The specimen was a RM concrete block wall (140 mm block thickness), had a height of 1820 mm, and the length of 2430 mm. The vertical reinforcement consisted of 6-16mm diameter bars and horizontal reinforcement consisted of 8-16mm bars, using high strength steel deformed bars (454 MPa yield strength). 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 10 MPa with added confinement plates to allow some ductility in the post-yielding range. The sliding shear resistance for the specimen based on the CSA S304-04 provisions (Cl.10.10.4) was $V_r$=558 kN, as estimated using Equation 1.

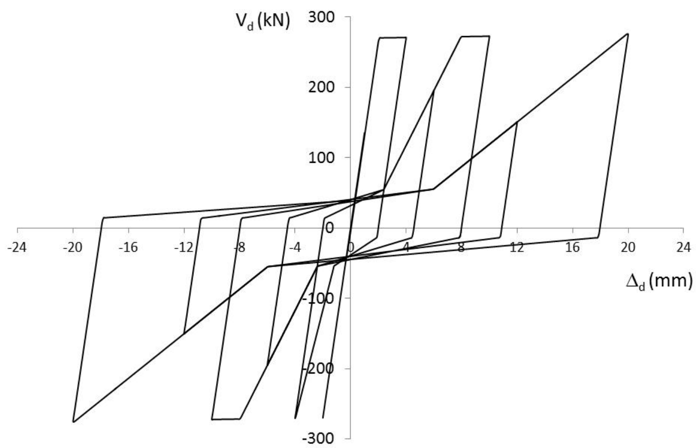
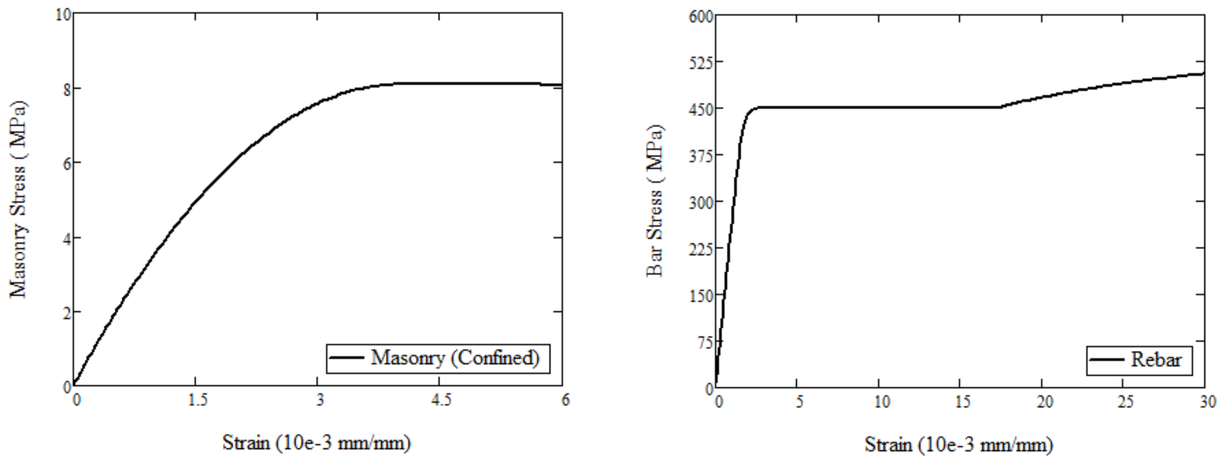



**Figure 5**: **Force-deformation response of a shear spring model used to simulate the dowel action**

The analytical model for this specimen was developed using the same wall dimensions. Cracked section properties of the beam element were used, with a 0.50 and 0.25 coefficients effectively reducing the cross-sectional area and inertia, respectively; and an elastic modulus, $E_m$, of 40,000 MPa.

The wall's plastic hinge was modelled using 34 equally spaced FSBB elements for the compression elements and six uniaxial springs (one spring per vertical rebar). For the compression-only beam elements, different concrete material properties were used to model axial compression, with an elastic modulus, $E_m$, of 44,000 MPa, and the stress-strain constitutive relationship for confined concrete (to simulate the effect of confining plates). The vertical reinforcement was modelled using the reinforcing steel material element with the yield strength $f_y$ of 454 MPa and strain hardening range. Figure 6 illustrates stress-strain curves for both the masonry compression and the reinforcing steel material models.

The plastic hinge length ($L_p$) was estimated to be 50% of the total height, $H_w$, following recommendations in [2,11]. The inelastic displacements at the top of the wall due to flexural hinging are equal to the product of the inelastic rotation times the height of the wall measured above the center of the plastic hinge ($H_w - 0.5L_p$).




a) b)

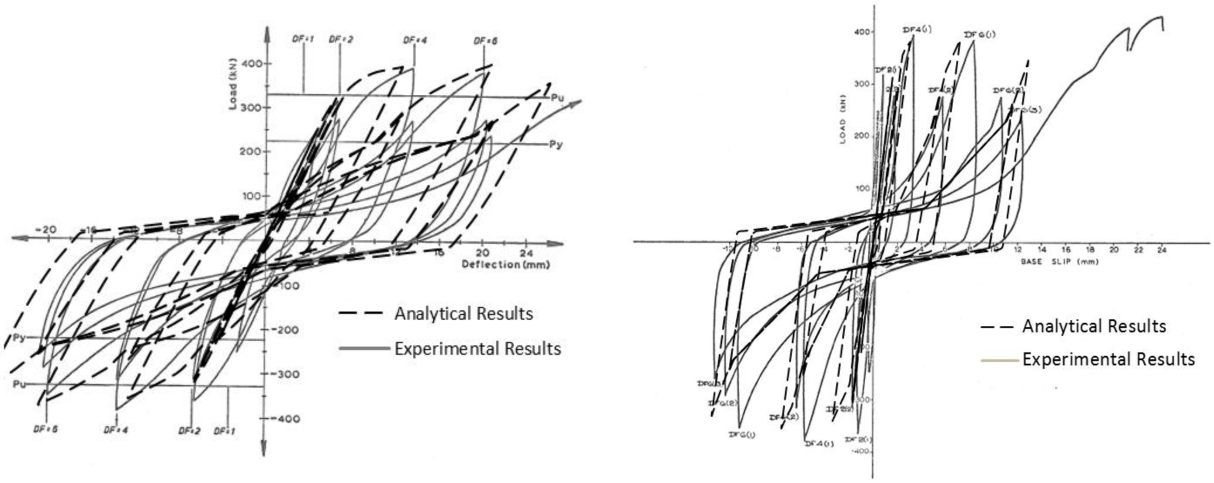
**Figure 6**: **Stress-strain curves used for material models: a) Masonry with Confinement Plates, b) Reinforcing Steel**

The frictional resistance was determined using a frictional coefficient (μ) of 1.00 and shear yielding displacement of 1.0 mm. For the dowel resistance, the values of yielding stress and yielding deformations were set equal to 50% of the yield strength, $f_y$, and 2 mm, respectively. These values were calibrated based on a satisfactory match between the analysis results and the experimental data.

A comparison of the analytical and experimental results is shown in Figure 7. It can be seen that the analytical model was able to simulate the force-deformation behavior of the wall specimen fairly well. The analytical model matched the force-deformation slope of the wall specimen, and maximum force and displacements recorded during the testing. The model was able to capture the apparent loss of lateral strength observed during the second cycle of displacement corresponding to ductility factors (DF) of 2, 4, and 6 (where DF is defined as a ratio of the maximum displacement reached at a specific load cycle and the yielding displacement). The model was also able to reach similar residual strength after unloading as the test specimen.

**DISCUSSION**

Once the analytical model was calibrated with the results n relevant experimental study in a satisfactory manner, the next step is associated with studying the properties of the sliding shear mechanism in the tested specimen. The main focus of this section is to discuss the coupling of sliding shear and flexural behaviour in the wall specimen, and the effect of the direction of loading the ductility demand, and the repeated loading cycles.




a) b)

**Figure 7**: **Cyclic loading results from proposed nonlinear model compared to experimental results of a RM squat shear wall : a) Wall A4 load vs top deflection b) Wall A4, load vs base sliding**

Figure 8 shows the estimated time history response at the base and at the top of the cantilever wall during cyclic loading. The time history of the top displacements represents the imposed cyclic loading set as input loading for the displacement-controlled static analysis. The displacement protocol includes cycles of loading representing ductility factors, DF, equal to 2 (2 cycles), 4 (2 cycles) and 6 (3 cycles). This diagram also shows that the base wall sliding was significant during the testing.

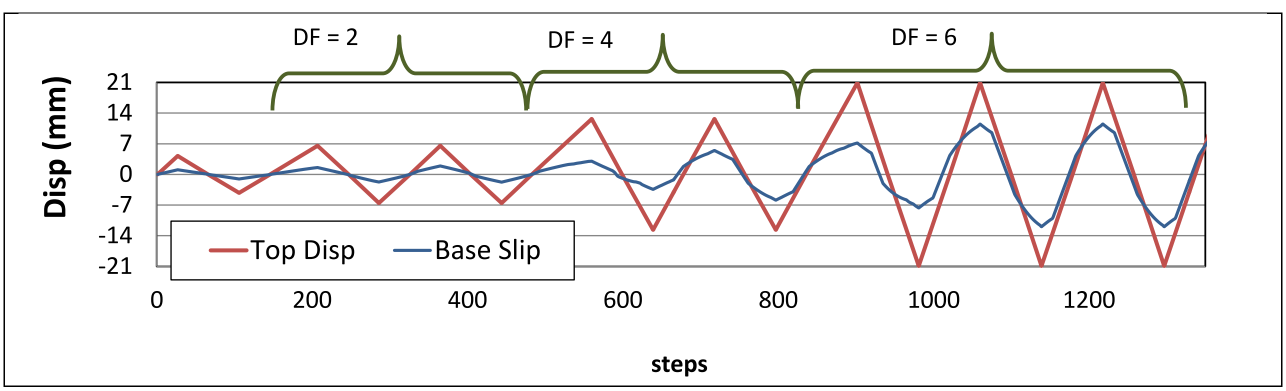
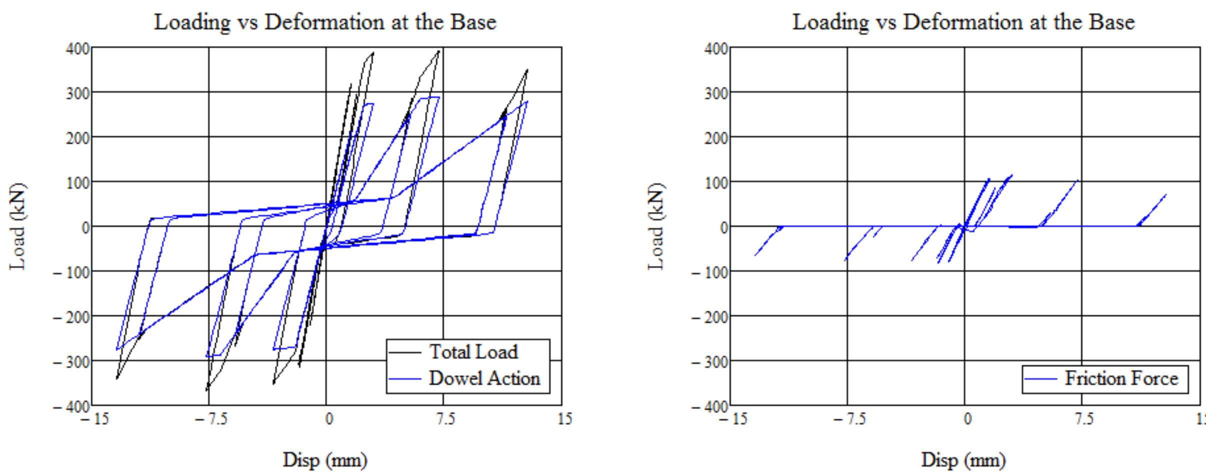



**Figure 8: Time history response, showing displacements at the top and the base of the wall**

Hysteresis curves corresponding to the dowel action force and the total force at the base of the wall are plotted vs the base displacement , as shown in Figure 9a. It can be seen from the figure that, according to the analysis, the majority of the sliding resistance is due to dowel action. The friction resistance can be calculated by subtracting the dowel action force from the total force.

The friction force vs base displacement is presented in Figure 9b. Note that the frictional resistance values include the contribution of the dead load (13 kN) and the shear friction. The maximum frictional force was 107 kN in the positive direction of loading and 82 kN in the negative direction; this represents 20% and 15% of the code value for sliding shear resistance, $V_r$, respectively.

The analysis results show that the sliding shear response of the wall specimen was not equal for both loading directions. Both the frictional resistance and the base displacement were different when the results in the positive and negative load direction were compared. It was found that the frictional resistance was higher and the displacements were lower for the direction in which the first load was applied (positive direction) compared to the opposite (negative) direction.

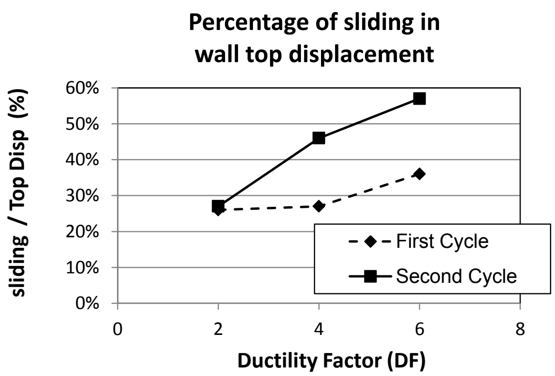



a) b)

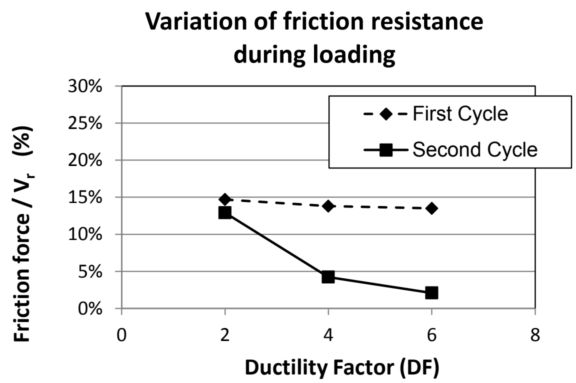
**Figure 9: Load vs displacement hysteresis curves at the base of the wall: a) Dowel Action only, and b) Friction only**

Figure 10a shows a ratio of the base sliding displacement at the base of the wall and the total peak top displacement for each loading cycle. The sliding shear contribution is affected by the increase in ductility demand, and the loading cycle (it was not the same for the first and second cycle corresponding to the same loading). The contribution of sliding displacements is higher at the higher ductility demands; this was reported as an important characteristic of the sliding shear mechanism in the experimental study [4]. When a cycle of loading for a given ductility demand is applied for a second time, the contribution of sliding is more significant than in the first cycle, with the sliding displacements close to 60% of the imposed displacement at the top of the wall. As a result, the sliding shear mechanism becomes the dominant failure mechanism in the wall that has initially developed a flexural mechanism.

Figure 10b shows that frictional resistance in the negative direction is at 15% of the expected sliding shear resistance, $V_r$, when a cycle of loading is applied for a first time, for all ductility factor, DF, levels. When a cycle of loading with the same displacement amplitude is applied for the second time, the frictional resistance is shown to decrease, reaching 2% of the $V_r$ for the DF = 6. As a result, during repeated loading cycles the sliding shear hysteresis is controlled by the hysteretic behaviour of dowel action alone. Note that the values presented in Figure 10 correspond to the negative loading direction, which was characterized by larger sliding displacements.




a)




b)

**Figure 10: Degradation in sliding stiffness: a) Sliding displacements, and b) Frictional resistance**

The time history of the masonry strains at the two extreme ends of the wall are shown in Figure 11. Here this plot is used to establish at what instances both ends of the wall have positive strains, which indicates that a full horizontal crack is formed along the section. The time history shows that the first flexural crack is formed at DF=4, observed in the plot at the first cycle of loading, when the end x/L=0 begins loading in tension. This plot shows that for the repeated cycles for ductility demands, DF=4 and 6 both ends of the wall are in tension for approximately the entire duration of the cycle, which explains why the measured contribution of friction resistance drops when a cycle is repeated.

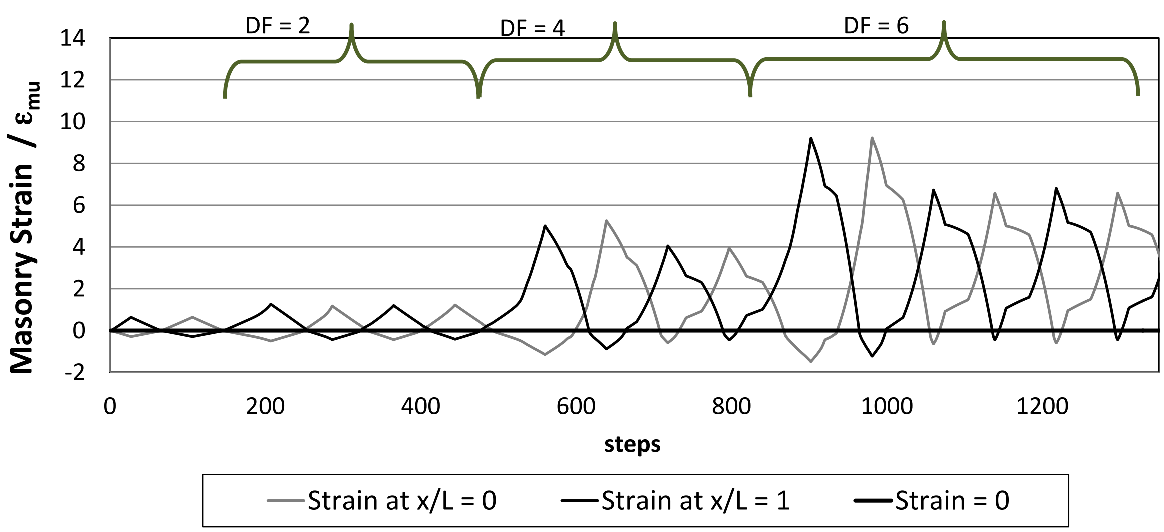



**Figure 11: Time history results of strains in rebar at wall ends**

Based on the current analysis, the estimated maximum frictional resistance and dowel resistance account for 20% and 50% of the total sliding shear resistance estimated based on CSA S304-04 design provisions ($V_r$=558 kN), respectively. Therefore, a combined frictional and dowel resistance account for 70% of the shear total resistance ($V_r$). Based on this, the ratio of friction resistance to total shear resistance, was on the order of $\frac{2}{7}$. This indicates that the current sliding resistance equation in CSA S304-04 needs to be revised to assign a reduced coefficient to the frictional resistance contribution and possibly account for dowel action. In addition, the results of the analyses performed to date show that shear friction mechanism may contribute only a fraction of the expected $V_r$ value and it needs to be studied further.

## CONCLUSIONS

This research study has set out to develop an analytical model that can simulate the sliding shear mechanism in RM shear walls. The model allows monitoring the sliding and the flexural deformations developing at the plastic hinge location of the wall. The model was calibrated to simulate the structural response of a wall specimen subjected to reversed cyclic lateral loading, and estimate changes in sliding resistance during opening and closing of flexural cracks.

Based on the results of the analytical study, it was found that the relative contribution of sliding displacement relative to the total displacement increased with the ductility demand and the number of repeated cycles of loading. Friction resistance was found to contribute to sliding resistance for the first cycle of a given ductility demand, however the resistance was reduced to smaller contributions for further cycles at the same ductility demand level. A loss of frictional resistance and an increase in sliding contribution towards the total wall displacement were found to be associated with the slip and degradation in stiffness of dowel action. Further studies will be performed to identify critical parameters affecting the contribution of shear friction to the total sliding resistance of RM shear walls.

## ACKNOWLEDGEMENTS

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