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ESTIMATING SLIDING SHEAR DISPLACEMENTS IN REINFORCED MASONRY SHEAR WALLS

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ABSTRACT: Sliding shear is often the governing failure mechanism in ductile reinforced masonry (RM) squat shear walls in low-rise buildings designed according to seismic design provisions of the Canadian masonry design standard CSA S304. Results of previous experimental studies also indicate that even for squat shear walls that experience flexural yielding, lateral displacements are the result of both flexural and sliding shear behaviour. Currently, there is a limited understanding of the sliding shear failure mechanism, magnitude of sliding displacements, and their impact on the overall building response. This paper presents the results of a comprehensive research study on the sliding shear mechanism and a novel approach for estimating sliding displacements. Three distinct mechanisms for Reinforced Masonry (RM) walls with sliding displacements have been identified in the study: sliding shear (SS) mechanism, dowel-constrained failure (DCF) mechanism, and combined flexural-sliding shear (CFSS) mechanism. In addition, a 2D analytical model was developed to simulate sliding behaviour in RM squat shear walls depending on their frictional resistance, dowel action, and flexural hinging. The model was calibrated using the results of experimental studies on wall specimens that experienced sliding shear displacements. Finally, as a result of several parametric studies, a design equation for estimating sliding shear displacements in RM squat shear walls was proposed in the paper.

1. Introduction

Reinforced Masonry (RM) squat shear walls characterized by a Height-to-Length (H/L) ratio below 1.0 are common in low-rise masonry buildings, such as school buildings and fire halls. Since fire halls are designated as post-disaster facilities, seismic design provisions of the National Building Code of Canada (NBCC) 2010 prescribe ductile design and detailing of RM shear walls corresponding to R_d value of 2.0 or higher. Consequently, RM squat shear walls need to follow provisions for moderately ductile squat shear walls outlined in the Canadian masonry design standard CSA S304-14.

The desired failure mechanism for RM shear walls subjected to seismic loading is a ductile flexural mechanism, characterized by yielding in plastic hinge zone. However, squat RM shear walls subjected to combined effect of lateral seismic forces and overturning bending moments are unlikely to develop a flexural yield mechanism since the sliding shear mechanism typically governs in these walls. This mechanism occurs in shear walls subjected to low axial stresses (typical for low-rise buildings) and relatively low amount of vertical reinforcement, and it is characterized by sliding interface at the base of the wall. This mechanism governs even when additional dowels are provided to increase sliding shear resistance at the base of the wall, however sliding interface moves up the wall height (Anderson and Brzev, 2009). Current CSA S304 design provisions do not address this problem and as a result, these walls are designed by assuming the sliding shear mechanism will have a ductile seismic performance. The provisions related to sliding shear mechanism are force-based and do not provide an approach for estimating sliding displacements.

This paper presents findings of a research study (Centeno, 2015) conducted to provide a methodology to accurately estimate the magnitude of sliding displacements that can develop in RM squat shear walls subjected to seismic loading. This study's goal was to provide a better understanding of the seismic performance of RM squat shear walls that experience this mechanism.

2. Background

According to the current approach for analysis and design of RM shear walls, it is expected that sliding shear displacements will occur when the sliding shear resistance is insufficient to develop the flexural yielding in the wall. However, experimental studies on RM shear walls subjected to lateral reversed cyclic loading have shown that in most cases sliding at the base of the wall occurred after the specimen had yielded in flexure (Priestley, 1977; Shing, 1989; Stavridis, 2011). Priestley (1977) performed tests on six RM squat shear wall specimens (H/L ratio of 0.75). The walls were heavily reinforced with horizontal reinforcement to prevent diagonal tension failure. Based on the results of this study the following explanation on sliding behaviour of RM shear walls was proposed (see Figure 1 for an illustration):

"*After the wall has suffered significant inelastic displacement in one direction, inelastic steel strains result in a wide open crack at the base course [..]. As the load direction is reversed, the crack becomes open over the full length of the wall. Since the base mortar course is very smooth, aggregate interlock is totally ineffective, and all shear has to be resisted by dowel action of the vertical steel. As the load is increased, the compression steel yields, the base crack closes at the compression end, and shear can once more be transmitted across the compression zone of the blockwork. Consequently, sliding ceases, and the load level rises rapidly*" (Priestley 1977).

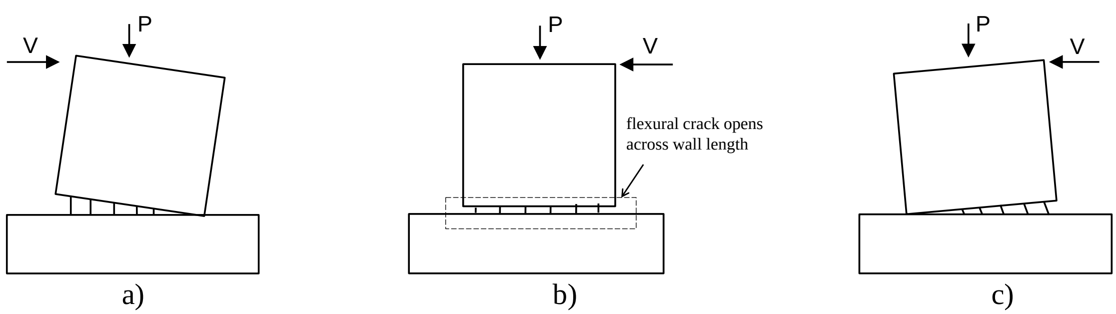


Fig. 1 - Sliding Shear in Combination with Flexural Yielding in RM Shear Walls: a) Flexural Yielding Occurs; B) Loading Direction Changes, and Sliding Starts at the Base, and C) Shear Force Transferred to the Base Through Dowel Action until a Flexural Crack is Closed

3. Analytical Model

3.1. Description

A novel 2D analytical macro model was developed to simulate sliding shear displacements in RM cantilever walls (Centeno, 2015). This model is able to simulate the interaction of the sliding shear and flexural behaviors in the development of a yielding mechanism in the wall. The model is based on the Multiple Vertical Line Element Model (MVLEM) approach which was originally proposed for simulating flexural response of reinforced concrete (RC) shear walls (Vulcano et. al., 1988). The wall cross-section in the plastic hinge zone is modelled as a series of axial springs which simulate the normal stress-strain relationship for the masonry and reinforcing steel. The MVLEM approach was modified to include into account the interaction between flexural compression and friction.

The proposed model is illustrated in Figure 2, on an example of a wall with height H and length L. The flexural compression and friction interaction is accounted for by friction bearing elements used to model masonry in compression (instead of axial springs used in the MVLEM model). The plastic hinge zone (height *h*) is modelled as a combination of multiple friction bearing elements and nonlinear axial springs, as well as a nonlinear shear spring. These elements are connected to two rigid beams, as shown in the figure. A portion of the wall above the plastic hinge zone (height H-*h*) is modeled using a beam-column element with elastic properties.

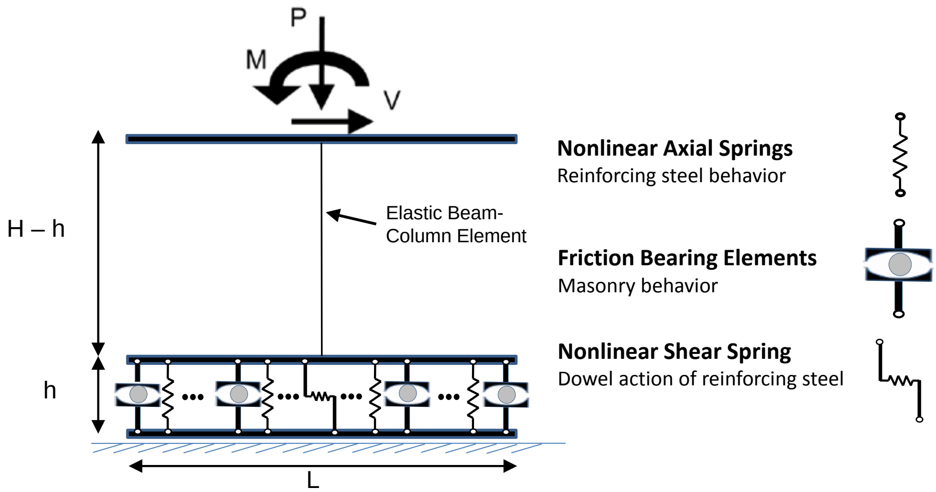


Fig. 2 - RM Cantilever Wall Model

3.2. Modeling Dowel Action

The nonlinear shear spring in the RM wall model was used to simulate dowel action of the vertical reinforcement across the sliding plane. Modeling of the vertical reinforcement's dowel action and its variation during cyclic loading is essential for accurate simulation of the sliding shear behavior. The monotonic envelope and hysteresis rules used to define the shear spring are shown in Figure 3.

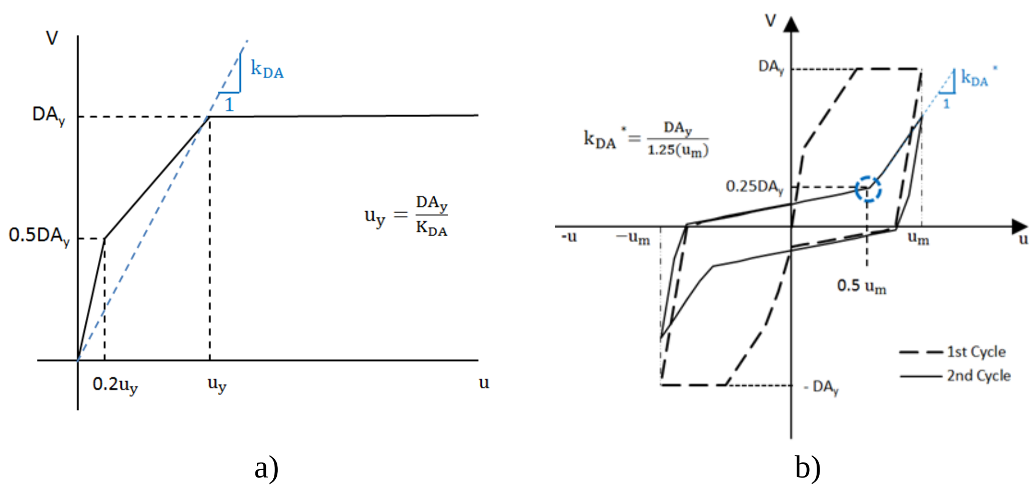


Fig. 3 – Modeling of Dowel Action Force Deformation Behavior: a) Monotonic Envelope, and b) Hysteretic Rules

Lateral force versus deformation behavior during the dowel action has been simulated by accounting for the interaction between transverse deformations of a reinforcing bar and the surrounding concrete (Dulascka, 1972; Pruijssers, 1988). This interaction can be analyzed using an approach similar to "beams on elastic foundations", where a reinforcing bar is treated as a beam supported by Winkler springs (Hetenyi, 1958). It should be noted that all previous studies were related to dowel action in RC structures. In this study, the same approach was adapted to RM structures and concrete properties were replaced by masonry grout properties.

Based on the above discussed approach, He and Kwan (2001) developed an expression for estimating the linear elastic stiffness for dowel action, k_{DA} (see Equation 1). The grout bearing stiffness, k_g, is determined using an expression based on experimental evidence (Soroushian, et. al., 1987), shown in Equation 2:

$$k_{DA} = E_s I_s \sqrt[4]{\left(\frac{k_g d_b}{4E_s I_s}\right)^3} \tag{1}$$

$$k_g = \frac{127\sqrt{f'_g}}{{d_b}^{2/3}} \quad \left(\frac{N}{mm^3}\right) \tag{2}$$

where:

k_{DA}: lateral stiffness

E_s: modulus of elasticity of steel

I_s: moment of inertia of the bar

d_b: diameter of the reinforcing bar

f'_g: masonry grout compressive strength

k_g: bearing stiffness of the masonry grout

Dowel action resistance equations were developed by following the assumption that the behaviour is characterized by local flexural yielding in the reinforcing bar and local crushing of the surrounding material (Dulascka, 1972; Priestley, 1977). The dowel action yield resistance, DA_y, can be determined from Equation 3, as follows

$$DA_y = C_{DA} A_s \sqrt{f'_g f_y} \tag{3}$$

where

DA_y: dowel action yield resistance

C_{DA}: coefficient of dowel action resistance

A_s: total area of vertical distributed reinforcement in the wall

f_y: steel yield strength

4. Calibration of the Analytical Model

The model was calibrated to match the test results from previous experimental studies on squat RM shear walls subjected to static reversed cyclic loading. The results used for the calibration consisted of five cantilevered walls (Hernandez, 2012), and five walls with fixed-fixed support conditions (Ahmadi, 2012). The available data set was used to calibrate the proposed model for different cases of effective shear-span/depth ratio, M/Vd, longitudinal reinforcement ratio, ρ_v, and axial load, P.

The calibration was performed by following an iterative process, with the first iteration performed using the specimen dimensions and material properties. Subsequently, several iterations were made, and the model parameters were adjusted until the analysis results matched the experimental data to a satisfactory level. A comparison of the analytical results after calibration and experimental results is presented in Figure 4.

The value of effective coefficient of dowel action resistance, C_{DA}, was determined for each experimental test used in the calibration process. Proposed Equation 4 estimates the C_{DA} value and reflects the variation in resistance as a function of the H/L ratio which was observed in experimental studies. The equation is applicable to RM shear walls with uniformly distributed vertical reinforcement.

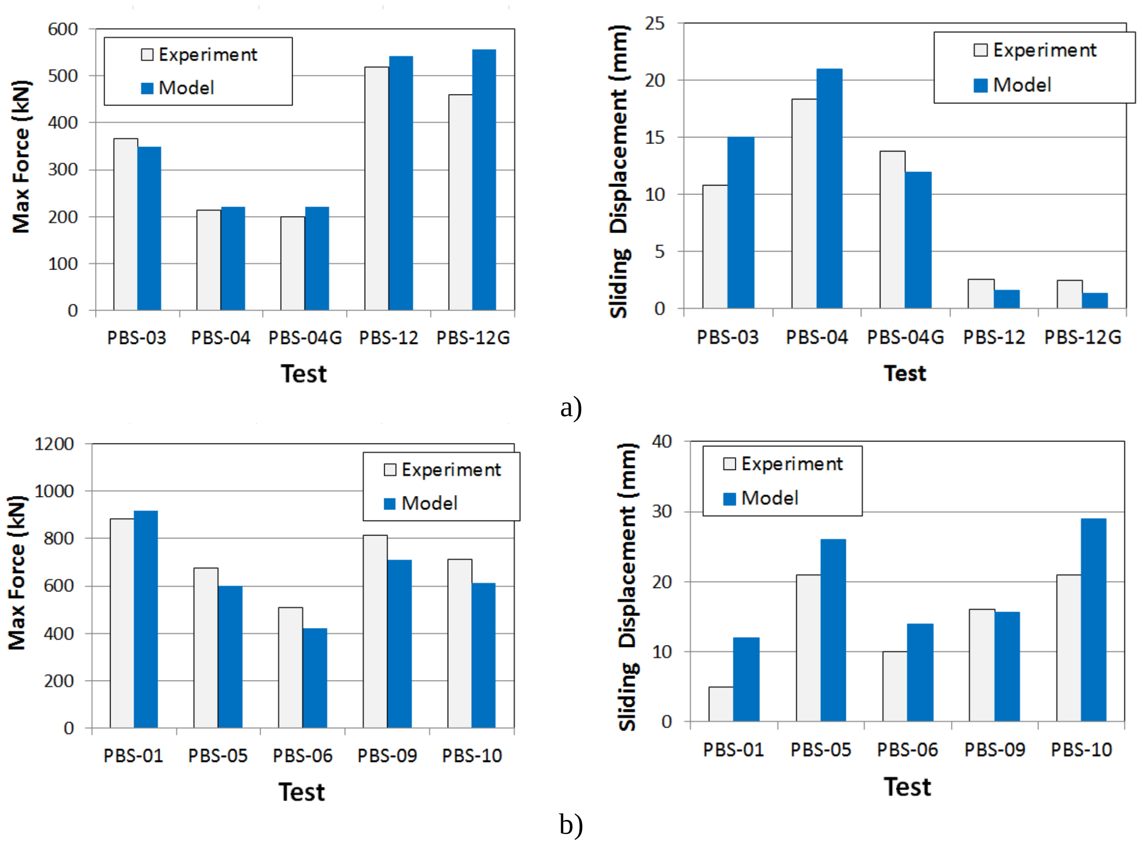


Fig. 4 – A Comparison of Peak Forces and Displacements From Calibrated Analysis Model vs Experimental Results: a) Cantilever Walls, and b) Fixed-Fixed Walls

$$C_{DA} = \begin{cases} 2.2, & H/L \le 0.5 \\ \left[2.2 - 2\left(\frac{H}{L} - 0.5\right)\right], & 0.5 < H/L < 1.0 \\ 1.2, & H/L \ge 1.0 \end{cases} \tag{4}$$

5. Yield Mechanisms for RM Shear Walls

Several nonlinear static analyses on the calibrated model were performed to study the sliding behaviour of RM cantilever walls subjected to cyclic loading and the effect of design parameters. It was assumed that diagonal shear failure mechanism was prevented by design. Results of the study showed that the following four yield mechanisms are possible for RM shear walls subjected to cyclic loading: i) Sliding Shear (SS) mechanism, ii) Combined Flexural-Sliding Shear (CFSS) mechanism, iii) Dowel-Constrained Failure (DCF) mechanism, and iv) Flexural (Fl) mechanism.

5.1. Sliding Shear (SS) Mechanism

The sliding shear mechanism will develop when the sliding shear resistance, V_{SS}, is less than the lateral force, V_{Fl}, required to induce flexural yielding in a RM shear wall. As a result, the wall does not experience flexural yielding and its inelastic deformations are only due to inelastic sliding shear displacements.

5.2. Combined Flexural-Sliding Shear (CFSS) Mechanism

An RM shear wall will experience a CFSS mechanism when the sliding shear resistance, V_{SS}, exceeds V_{Fl}, and the wall is able to experience yielding through a flexural yield mechanism. During load reversals, base sliding displacements develop due to elastic dowel action deformations, while a lateral force V_o is transferred across an open flexural crack along the wall length (see Figure 1). The wall switches back to a flexural mechanism when the flexural crack is closed. The magnitude of sliding displacements increases at higher ductility demands due to degradation of dowel action shear stiffness.

5.3. Dowel-Constrained Failure (DCF) Mechanism

An RM shear wall will experience a DCF mechanism when the dowel action yield resistance is insufficient to resist the lateral force, V_o, developed while the flexural crack is open along the wall length. This behaviour is considered as failure, because it prevents closure of the flexural crack and the development of a flexural yield mechanism. Instead, the DCF mechanism develops significant inelastic dowel action deformations, and is characterized by a low lateral load resistance (equal to the dowel action yield resistance, DA_y).

5.4. Flexural (Fl) Mechanism

Fl mechanism is characterized by base sliding displacements which occur due to elastic dowel action deformations when the shear force, V_o, is transferred across the open flexural crack. However, dowel action shear demands are low and do not cause a degradation of dowel action shear stiffness. Therefore, base sliding displacements are expected to be insignificant (on the order of 1 mm or less).

6. Estimating Sliding Displacements in a CFSS Mechanism

In this study, an expression was developed for estimating the base sliding displacement in RM walls that experience a CFSS mechanism. The expression is based on the assumptions i) that sliding displacements develop while the flexural crack is open across the wall length and ii) that sliding displacements are a function of the shear force, V_o , and the dowel action shear stiffness, k_{sec}.

6.1. Shear Force, V_o and Overturning Moment, M_o

In RM walls that experience a CFSS mechanism, the in-plane shear force and overturning moment are resisted by the vertical reinforcing bars through dowel action and axial forces, respectively, when the flexural crack is open across the wall length, as shown in Figure 5 . This flexural crack can close if sufficient shear resistance can be provided through dowel action. The corresponding overturning moment, M_o, would cause vertical reinforcement on one end of the wall to yield in compression (Priestley, 1977). This overturning moment, M_o, is a function of the cross-sectional area of the vertical reinforcing bar, A_{db}, the axial stress in the reinforcement f_s, and the vertical bar's lever arm, d, as shown in Figure 5b.

Through parametric studies it was determined that the M_o value is influenced by: i) the axial compression level, $P/(A_s f_y)$, and ii) the spacing of the reinforcing bars, s. Equations 5 and 6 can be used to determine the M_o value for RM walls with uniformly distributed reinforcement, as follows

$$M_o = [C_o] A_s f_y L \tag{5}$$

Where:

$$C_o = \left[0.21\left(1 + \frac{s}{L}\right)\left(1 - \frac{P}{A_s f_y}\right)\right] \tag{6}$$

Where

C_o: coefficient of overturning moment M_o P: Axial force

s: spacing of vertical reinforcing bars

The lateral force V_o required to develop overturning moment M_o in a cantilevered RM shear wall can be determined from Equation 7. Flexural crack that causes sliding can close when the dowel action yield resistance, DA_y, is sufficient to resist the lateral force, V_o, where

$$V_o = \frac{M_o}{H} \tag{7}$$

6.2. Dowel Action Secant Stiffness, k_{sec}

In a CFSS mechanism, sliding displacements develop due to dowel action deformations, which are required to enable shear transfer across the open flexural crack along the wall length. Approximately 80% of these displacements correspond to elastic dowel action and 20% correspond to inelastic dowel action. In addition, after each increase in displacement ductility, μ, higher elastic dowel action deformations develop for each subsequent loading cycle due to degradation in the dowel action shear stiffness, as shown in Figure 6a. For instance, at a displacement ductility, μ, equal to 2, the dowel action deformation is equal to 2.5 times the dowel action deformation developed at a μ value of 1.

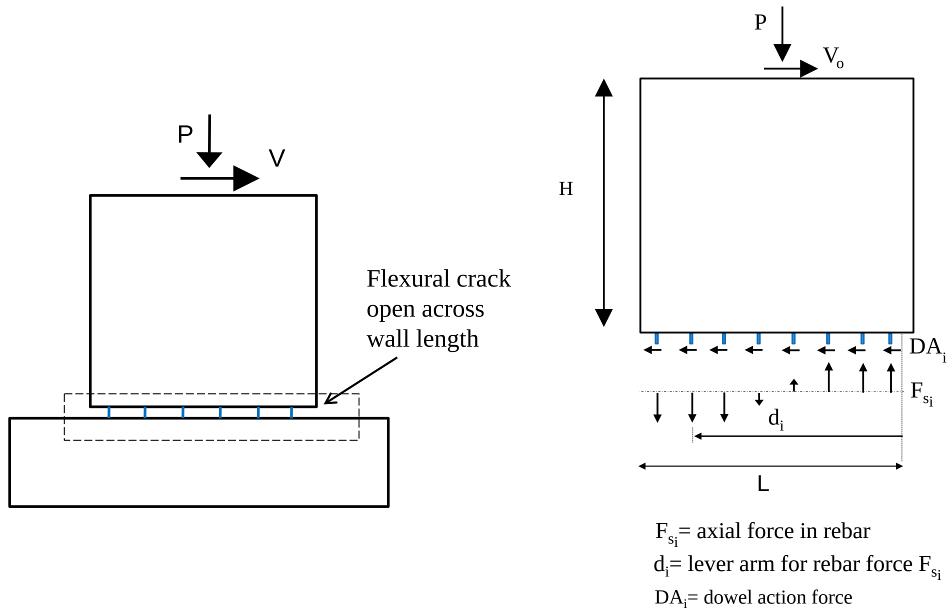


Fig. 5 – Lateral resistance of an RM shear wall with open flexural crack: a) Wall loading and cracked at wall-foundation interface, and b) Vertical reinforcement resisting external loading through dowel action, DA, and axial forces, F_s.

To measure the degradation in dowel action shear stiffness, a secant stiffness value, k_{sec}, was determined for each displacement ductility demand value, µ, applied during cyclic loading. Figure 6b shows that at a µ value of 2, the k_{sec} value is equal to 49 kN/mm; this corresponds to 39% of the elastic dowel action stiffness, k_{DA}. The k_{sec} parameter at each loading cycle is determined from Equation 8 as follows

$$k_{sec} = \frac{DA}{u_{DA}}, \qquad DA \leq DA_y \tag{8}$$

Where:

DA: shear force transferred through dowel action.

u_{DA}: dowel action deformation.

The dowel action stiffness ratio, C_k, is a ratio of the dowel action secant stiffness, k_{sec}, and the elastic dowel action stiffness, k_{DA}, and it is determined from Equation 9. For RM walls that experience a CFSS mechanism, the dowel action stiffness ratio, C_k, is less than 1.0.

$$C_k = \frac{k_{sec}}{k_{DA}} \tag{9}$$

Where

C_k: dowel action stiffness ratio

k_{sec}: dowel action secant stiffness

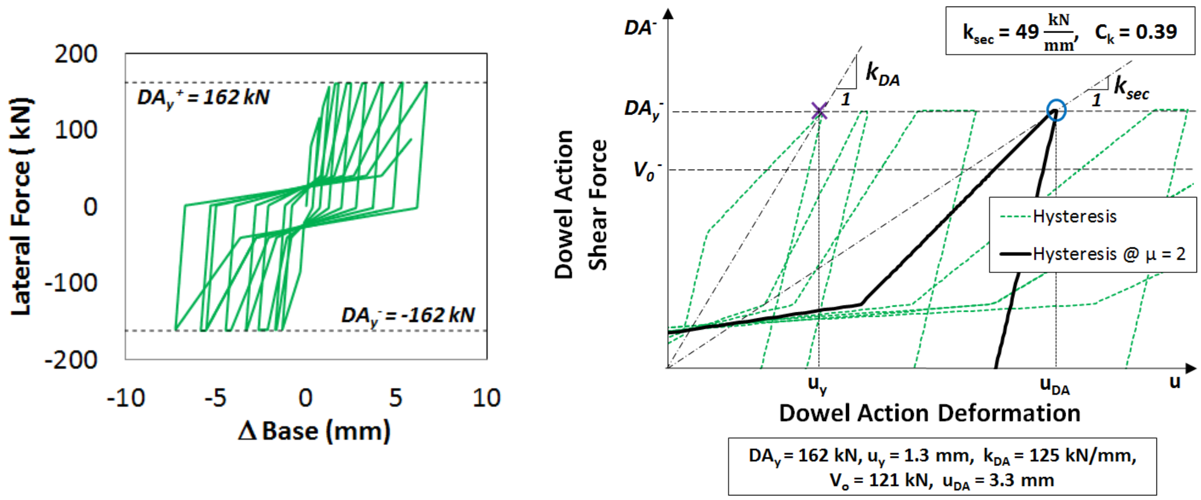
k_{sec}: dowel action secant stiffness

6.3. Sliding Shear Behavior of Lightly Reinforced RM Shear Walls

Cyclic loading analyses were performed on RM wall models to measure a variation in sliding shear behavior depending on various parameters. The results presented in this section correspond to several RM walls with H/L ratios less than 2.0, with H/L increments of 0.1. All walls were assigned a constant height of 3 m and thickness of 190 mm. Vertical reinforcement ratio, ρ_v, was set at 0.2%, assuming 10M bar size. The level of axial compression, $P/(A_s f_y)$, was set at 0%. The masonry compression strength, f'_m, was taken as 10 MPa, masonry grout strength, f'_g, was 35 MPa, and steel reinforcement strength, f_y, was 400 MPa.

The results of this parametric study show the RM shear wall's yield mechanism varies depending on the H/L ratio. RM shear walls with H/L ratios less than 0.6 developed a SS mechanism, RM shear walls with

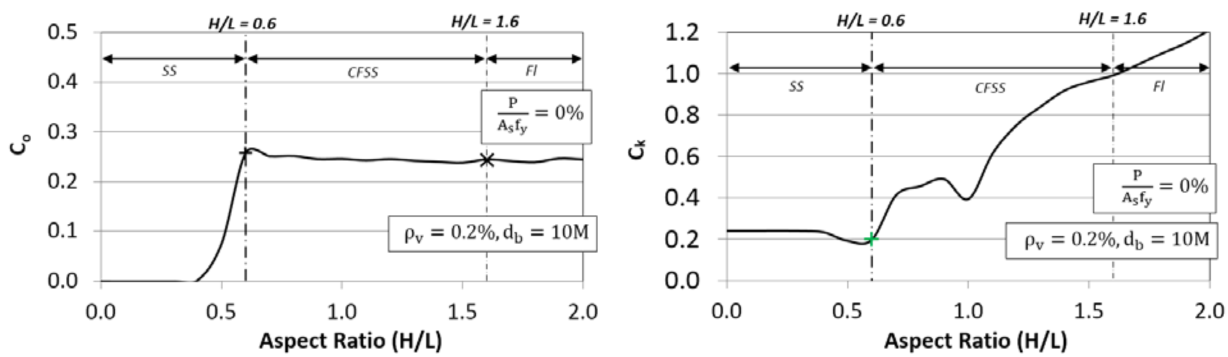
H/L ratio ranging from 0.6 to 1.6 developed a CFSS mechanism, and RM shear walls with H/L ratios greater than 1.6 developed a Fl mechanism.



a) b)

Fig. 6 – Cyclic response of an RM shear wall with H/L ratio of 1.0 experiencing CFSS mechanism: a) Dowel action hysteresis, and b) Estimation of dowel action secant stiffness, k_{sec}, at μ value of 2.

For each RM wall considered, the values of overturning moment, M_o, and the corresponding coefficient, C_o, were measured. As shown in Figure 7a, for RM walls that experienced a CFSS mechanism or an Fl mechanism, the C_o value was equal to 0.25, irrespective of their respective H/L ratio.



a) b)

Fig. 7 – Cyclic response of RM shear walls with low axial stress and vertical reinforcement ratio of 0.2% at μ=2: a) C_o vs H/L ratio, and b) C_k vs H/L ratio.

The dowel action secant stiffness ratio, C_k, in each RM wall is influenced by the H/L ratio and the wall's yield mechanism, as shown in Figure 7b. In RM walls experiencing a SS mechanism, the C_k ratio ranges between 0.19 and 0.23. For RM walls with a CFSS mechanism, the C_k ratio follows a trend of increasing values that start at approximately at 0.20 for H/L ratio of 0.6, and reach 1.0 for H/L ratio of 1.6. For RM shear walls that experience a Fl mechanism, the C_k ratio is greater than 1.0. This indicates that dowel action deformations are less than the dowel action yield deformation, u_y.

This study has determined two parameters that influence the magnitude of sliding displacements in RM shear walls with a CFSS mechanism: the shear force, V_o, and the dowel action secant stiffness, k_{sec}. Using these parameters, the following empirical expression is proposed for estimating sliding displacements for CFSS mechanism:

$$\Delta_{Base} = 1.25\frac{V_o}{k_{sec}} \tag{10}$$

Equation 10 and the results shown in Figure 7 were used to estimate the sliding displacements for RM shear walls considered in the analyses. The sliding displacements determined from Equation 10 were compared with those from the analysis results of RM shear walls experiencing a CFSS mechanism at a displacement ductility corresponding to a μ value of 2. This comparison shows that Equation 10 generated similar results to those obtained from nonlinear analysis.

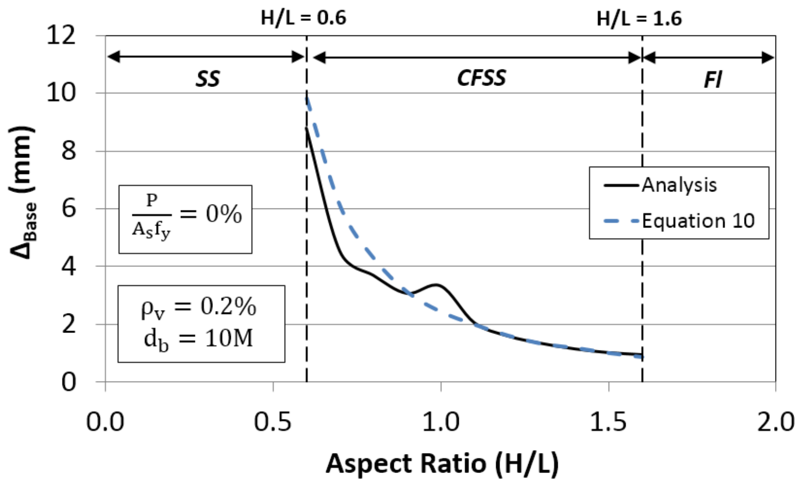


Fig. 8 – Sliding displacements in RM shear walls with low axial stresses and vertical reinforcement ratio of 0.2% at a μ value of 2.

7. Conclusions

This study has proposed a modeling approach for estimating sliding displacements in RM shear walls subjected to in-plane lateral loads. The onset of sliding is determined by modeling the wall's sliding shear resistance as the sum of frictional and dowel action resistances, and by accounting for their nonlinear behaviour during cyclic loading.

The following three yield mechanisms for RM shear walls that develop sliding displacements at the wall base were identified in the study: i) Sliding Shear (SS) mechanism, ii) Combined Flexural-Sliding Shear (CFSS) mechanism, and iii) Dowel-Constrained Failure (DCF) mechanism.

The sliding response parameters studied in this paper were the C_{DA} coefficient, the C_o coefficient, and the the C_k coefficient. These parameters are required to predict the yield mechanism and to estimate the base sliding displacements in a RM shear wall subjected to cyclic loading.

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