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EFFECT OF ASPECT RATIO ON SENSITIVITY ANALYSIS OF A SIMPLIFIED MICRO-MODEL FOR PARTIALLY GROUTED REINFORCED MASONRY SHEAR WALLS

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ABSTRACT

A simplified finite element model is proposed using VecTor2 software to simulate the cyclic behavior of partially grouted reinforced masonry shear walls constructed with concrete-masonry blocks and having reinforced bond beams. Following the development of the validated model, a sensitivity analysis is conducted to study the relative effect of different grouted and ungrouted masonry modeling input parameters on the seismic response of the modeled walls. In this regard, four reference walls with different aspect ratios (1.0 and 2.0) and different vertical reinforcement spacings (600 mm and 1200 mm) are modeled. Afterwards, reference values of masonry modeling input parameters are changed within ±30% from the reference values. It is concluded that the parameters of the ungrouted masonry are the most influential ones, where the walls' behavior is mostly sensitive to the input value of the angle of internal friction between blocks and mortar. However, this effect diminishes as the aspect ratio of the wall increases and spacing between grouted cells decreases. Accordingly, for shorter walls and walls with larger spacing between grouted cells, more attention shall be given to the estimation of the parameters representing the material properties of ungrouted masonry, especially the angle of internal friction. This also concludes that better seismic response of PG-RMSWs can be achieved by increasing the friction between the mortar and blocks in the ungrouted portions of the walls.

KEYWORDS: *partially grouted, reinforced masonry, cyclic loading, simplified micro modeling, sensitivity analysis, tornado diagrams*

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INTRODUCTION

In general, cost effectiveness has stood as a burden on the full development of use of FG-RMSWs (Fully Grouted Reinforced Masonry Shear Walls) as a SFRS (Seismic Force Resisting System) in low and medium seismic zones in North America. Accordingly, the use of PG-RMSWs (Partially Grouted Reinforced Masonry Shear Walls), where only specific cells are grouted with vertical reinforcement inside and horizontal bars placed only in bond beams or placed as bed joint reinforcement. Although their behavior is relatively complex, they provide a very promising system to be used in low and mid-rise buildings [1, 2].

The development of reliable numerical modeling is required to allow for expanding the study of the behavior and the use of PG-RMSWs. A simplified micro-modeling approach can be used where some of the components are smeared together to produce a simplified model. In this approach, masonry units, grout and mortar are modeled together as a homogeneous material with zero-thickness interface elements to model shear and tensile failure of the bond between units and mortar [1, 3]. Numerical models, that are capable of simulating the behavior of PG-RMSWs, are limited, and the available studies are usually not generic and are limited to specific cases and materials properties, for example Maleki [4] and Bolhassani et al. [5]. Furthermore, the development of detailed finite-elements models requires complicated testing, which increases the complexity of such models. Referring to the simplified micro-models available in literature, they still require considerable development to be more reliable in simulating the cyclic behavior of PG-RMSWs. This is due to the several parameters that are not usually considered in the existing simplified micro-models, such as bar buckling, compression softening, and tension softening. Another concern is the large number of required input parameters that need experimental investigation; this is due to their influence on the behavior of the walls and the non-existence of sensitivity analysis that can illustrate the relative importance of the accurate estimation of different input parameters.

Accordingly, the first objective of this study is to develop a simplified-micro model to simulate the quasi-static cyclic behavior of PG-RMSWs using VecTor2 software [6] and validate it against experimentally tested walls available in the literature. The second objective of this study is to conduct a sensitivity analysis for a number of flexural dominated walls designed according to CSA S304-14 [7]. The aim of such sensitivity analysis is to investigate the effect of the accuracy of the estimation of grouted and ungrouted masonry properties on the prediction of seismic design parameters using the proposed model. The seismic design parameters include ultimate load and its corresponding displacement. In this regard, four PG-RMSWs are modeled in VecTor2 using the proposed modeling scheme with certain reference values for grouted and ungrouted masonry parameters. The four walls are selected such that each two walls have the same aspect ratio (1.0 and 2.0), but with different vertical reinforcement spacings (600 mm and 1200 mm). Afterwards, reference values of masonry input parameters are changed with ±30% from the reference value.

PROPOSED SIMPLIFIED MICRO-MODEL

Model Development

In this study, simplified micro modeling approach is adopted as previously indicated. In modeling PG-RMSWs, large spacing between vertical reinforcement is usually expected as compared with reinforced concrete walls and FG-RMSWs. Accordingly, the effect of vertical bar buckling under compressive stresses is considered to ensure proper modeling of softening behavior of the walls after reaching its ultimate load and occurrence of crushing of masonry [4]. Furthermore, the simulation of masonry structures requires the definition of appropriate numerical strategies to include tensile and shear failures of block-mortar interface. This represents one of the main issues in modeling ungrouted masonry [8]. In this study, grouted masonry is modeled as a smeared material representing masonry blocks, grout and mortar as one material, while ungrouted masonry is modeled as solid units with thickness equal to the sum of the two face shell thicknesses along with the interaction between ungrouted masonry blocks using Mohr-Columb criterion by defining cohesion (c) and angle of internal friction (φ) to model the bonding behavior between units. Table 1 summarizes the models selected in VecTor2 to simulate the behavior of grouted and ungrouted masonry and reinforcement.

Table 1 Models used in VecTor2 to simulate different materials' behaviors

Material	Behavior Modeled	Used Model
Grouted and Ungrouted Masonry	Compression Pre-Peak	Hoshikuma et al [9]
	Compression Post-Peak	Modified Park-Kent [10]
	Compression Softening	Vecchio 1992-B [11]
	Tension Stiffening	Modified Bentz 2003 [6]
	Tension Softening	Nonlinear (Hordijk) [12]
	Dilation	Variable-Orthotropic [6]
	Cracking Criterion	Mohr-Coulomb (Stress) [6]
	Crack Slip	Not Considered
	Hysteretic Response	Nonlinear with Plastic Offsets
Reinforcement	Hysteretic Response	Bauschinger Effect (Seckin) [13]
	Dowel Action	Tassios [14]
	Buckling	Dhakal-Maekawa 2002 [15, 16]

Validation of the Proposed Model

In order to validate the adequacy of the proposed model to simulate the behavior of PG-RMSWs, a group of four walls from the literature [5, 4] are simulated using the proposed model in VecTor2 software. Comparing numerical results with experimental results of the walls used in validation, it can be concluded that the proposed model provides acceptable simulation of the behavior of PG-RMSWs. Figure 1 shows an example for the comparison of the experimental and numerical backbone curves for Wall 1 experimentally tested by Maleki [4] .

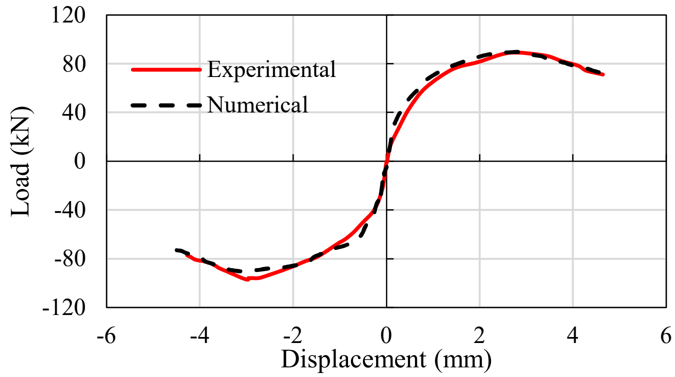


Figure 1: Experimental [4] and numerical backbone curves for validation Wall 1

SENSITIVITY ANALYSIS DEVELOPMENT

Structural response can be evaluated based on EDPs (Engineering Demand Parameters). Since these parameters are affected by the uncertainty of the estimation of input parameters, deterministic sensitivity analysis is developed to determine the relative significance of each of the input parameters on each of the EDPs. This can be presented in the format of what is called "Tornado Diagram". This diagram consists of a set of horizontal bars that are known as swings. These swings represent the variation of a selected EDP based on the variation in the investigated random variable or the input parameter. This means that larger swings represent larger expected variation in the EDP. To allow for a better presentation, all swings are measured from the reference values and then arranged in descending order from the top to the bottom giving the shape of a tornado [17].

Accordingly, the second objective of this study is to conduct a sensitivity analysis using tornado diagrams to investigate the sensitivity of the proposed model to different masonry material properties, as shown in Figure 2. Reference values are selected for each of these inputs and are then changed, one at a time, by ±30%, in order to see the effect of each of these parameters on the selected EDPs. The ±30% swing value for the input parameters is selected based on the expected coefficient of variation of the different investigated parameters, obtained during experimental testing. Knowing the effect of the selected input parameters on the selected EDPs will allow the user to pay special attention to the estimation of the most effective inputs based on the required EDPs.

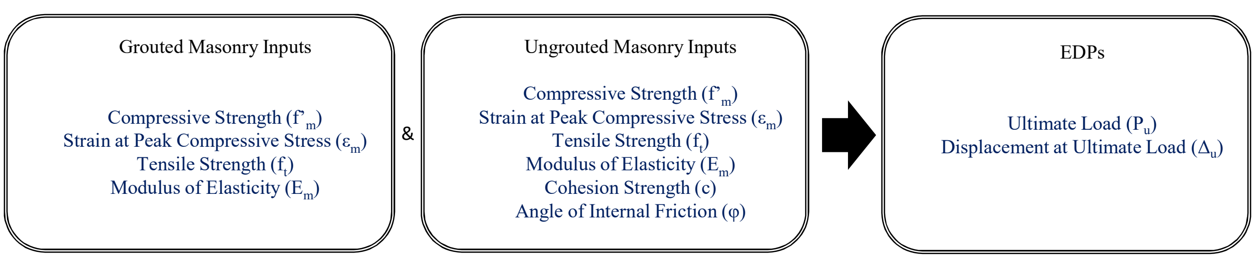


Figure 2: Inputs and EDPs of the sensitivity analysis

SELECTION OF PG-RMSWS FOR SENSITIVITY ANALYSIS

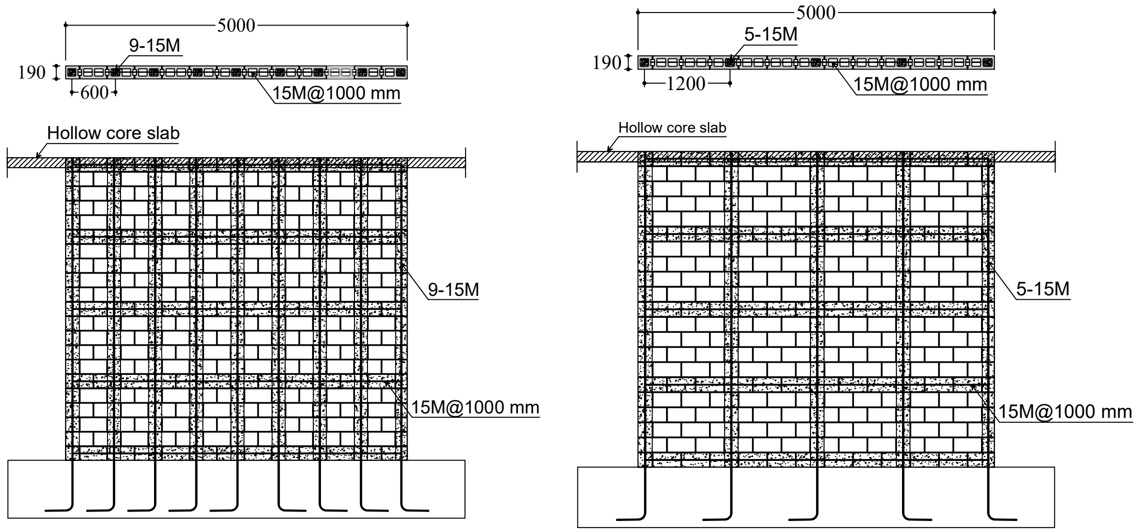
In order to conduct the sensitivity analysis of the proposed model, four full-scale PG-RMSWs are selected and designed according to CSA S304-14 [7]. The walls are selected such that each two walls are of the same aspect ratio but with different vertical reinforcement spacing. The selected walls are of aspect ratios 1.0 and 2.0 with spacing of vertical reinforcement of 1200 mm and 600 mm, as summarized in Table 2. In order to categorize the modeled walls, each wall is given a name consisting of two symbols (W-AR**x**-S**y**); x represents aspect ratio of the wall, while y represents the spacing between vertical reinforcement in mm. For example, W-AR1-S1200 means the wall with aspect ratio of 1.0 and spacing between vertical reinforcement of 1200 mm. Figure 3 shows elevations and cross sections of W-AR1-S600 and W-AR2-S1200 as examples of the modeled walls. In these four walls, reference values for the ten investigated parameters are selected as given in Table 3. In order to conduct sensitivity analysis of the proposed model for these parameters, each of them is increased and decreased by 30%, one at a time.

Table 2: Dimensions and reinforcement configurations for walls used in the sensitivity analysis

Wall ID	**L (mm)**	**H (mm)**	**t (mm)**	**Vertical Reinforcement**	**Horizontal Reinforcement**	**H/L**	**Axial Load (kN)**	**Cycle Increment (mm)**
W-AR1-S1200	5000	5000	190	15M@1200 mm	15M@1000 mm	1	50	3
W-AR1-S600				15M@600 mm				
W-AR2-S1200		10000		15M@1200 mm		2	141	5
W-AR2-S600				15M@600 mm				

Table 3: Input reference parameters for walls used in sensitivity analysis

Parameter		**Value**	**Reference**
Grouted Masonry	f'_m (MPa)	10	Table 4 of CSA S304-14 [7] assuming block strength = 20 MPa and Type S mortar
	E_m (MPa)	8500	CSA S304-14 [7]
	ε_m	0.0015	Priestley et al. [18]
	f_t (MPa)	0.4	Table 5 of CSA S304-14 [7] assuming Type S mortar
Ungrouted Masonry	f'_m (MPa)	13	Table 4 of CSA S304-14 [7] assuming block strength = 20 MPa and Type S mortar
	E_m (MPa)	11050	CSA S304-14 [7]
	ε_m	0.001	Zhou et al. [19] assuming mortar strength = 8.5 MPa as the minimum value specified by CSA S304-14 [7]
	f_t (MPa)	0.65	Table 5 of CSA S304-14 [7] assuming Type S mortar
	JSR = c/f'_m	0.001	Default values assumed by VecTor2 [6]
	φ	37^o	
$F_{y,hz}$ (MPa)		400	Normal strength steel is used
$F_{y,vl}$ (MPa)		400	



(a) (b)

Figure 3: Elevations and cross sections for walls with aspect ratio 1.0 used in sensitivity analysis: a) W-AR1-S600, b) W-AR1-S1200 (dimensions are in millimeters)

The axial load applied on the walls is selected by assuming that walls of aspect ratio one and two are supporting one and three, respectively. The sensitivity analysis is performed such that axial load on the walls is calculated by assuming walls are internal and the structure is divided into 5 m by 5 m panels. This means that change in the aspect ratio is accompanied with change in the applied axial load. It is assumed that the floor is composed of precast prestressed concrete hollow-core slabs with thickness of 150 mm (self-weight = 2.15 kPa). Superimposed dead loads are assumed to be 1.5 kPa. The building is assumed to be at Toronto, Ontario giving a snow load of 1.28 kPa. Load combinations are selected based on NBCC 2015 [20]. The walls are then designed as moderately ductile shear employing capacity design principles. As such, the walls are designed according to CSA S304-14 [7] such that diagonal shear capacity and sliding shear capacity are at least 10% more than the shear force corresponding to nominal moment capacity. For walls supporting more than one story, the shear force is assumed to be applied at two-thirds of the wall height measured from the base of the walls, representing the location of the resultant of all story shear forces and at the top of the wall for one-story wall. The previously discussed walls are modeled in VecTor2 under fully reversed cyclic loading with each cycle applied twice to capture cyclic and in-cycle strength and stiffness degradation.

RESULTS AND DISCUSSIONS

Figures 4 to 7 show the tornado diagrams of the sensitivity analysis. They are arranged such that results of the walls with the same spacing between vertical reinforcement are given in the same Figure. It can be concluded that both the ultimate load and the corresponding displacement are mostly affected by the angle of internal friction then ungrouted masonry compressive strength.

This is true even when the spacing between grouted cells decrease or aspect ratio increases. However, this effect is less significant relative to other parameters when reducing the spacing between grouted cells or increasing the aspect ratio. This is attributed to the fact that the shear component of the walls' resistance is significant especially for walls of smaller aspect ratio. In addition, failure of PG-RMSWs is usually expected to be accompanied by major stepped cracks in the mortar-block interface as previously discussed since this interface is weak in shear. As the aspect ratio increases, the flexural component of the behavior becomes more dominant and the effect of the strength of block-mortar interface becomes less significant. This is true in case of reducing the spacing between grouted cells since the area of block-mortar interface is reduced.

Based on the previous discussion, it can be concluded that the properties of ungrouted masonry, especially the angle of internal friction, have the most significant effect on the investigated EDPs as compared with all other investigated input parameters. This effect becomes more significant as the spacing between grouted cells increases and aspect ratio decreases. This means that accurate estimation of such parameters is critical to ensure an acceptable simulation of PG-RMSWs using the proposed model. In addition, this can be extended to a conclusion that better seismic response of PG-RMSWs can be achieved by increasing the friction between the mortar and blocks in the ungrouted portions of the walls. Despite being very simple, it can result in more economic design with reduced cross-sectional dimensions and less reinforcement area. In addition, it can allow for reduced seismic design forces as it improves the displacement ductility. This improvement is more influential in the case of shorter walls and smaller spacing between vertical reinforcement.

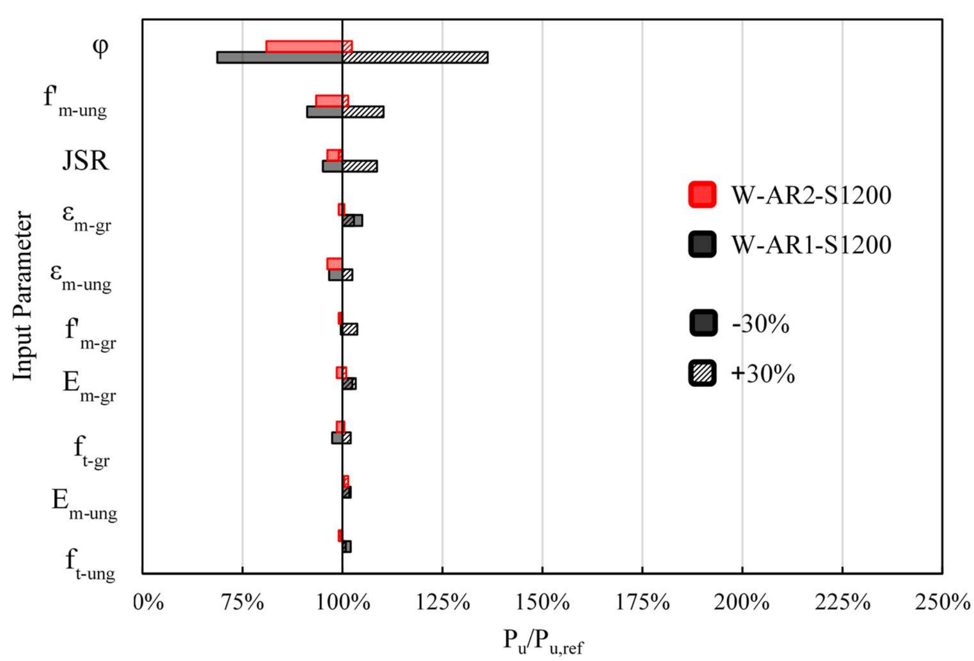


Figure 4: Sensitivity of the proposed numerial model in the estimation of P_u for PG-RMSWs with different aspect ratios and verical reinforcement spacing of 1200 mm

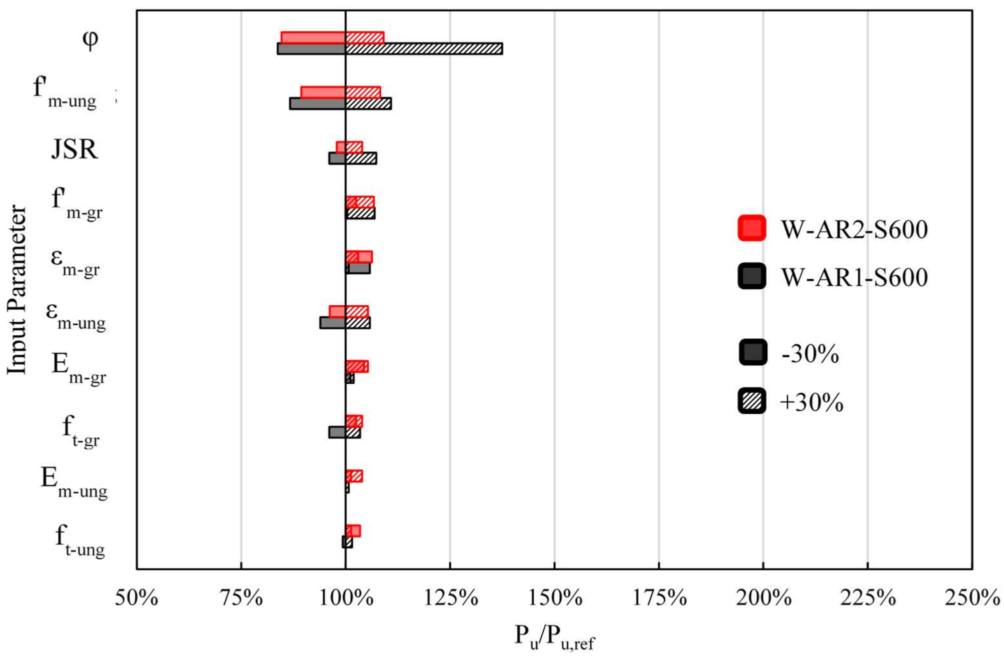


Figure 5: Sensitivity of the proposed numerical model in the estimation of P_u for PG-RMSWs with different aspect ratios and verical reinforcement spacing of 600 mm

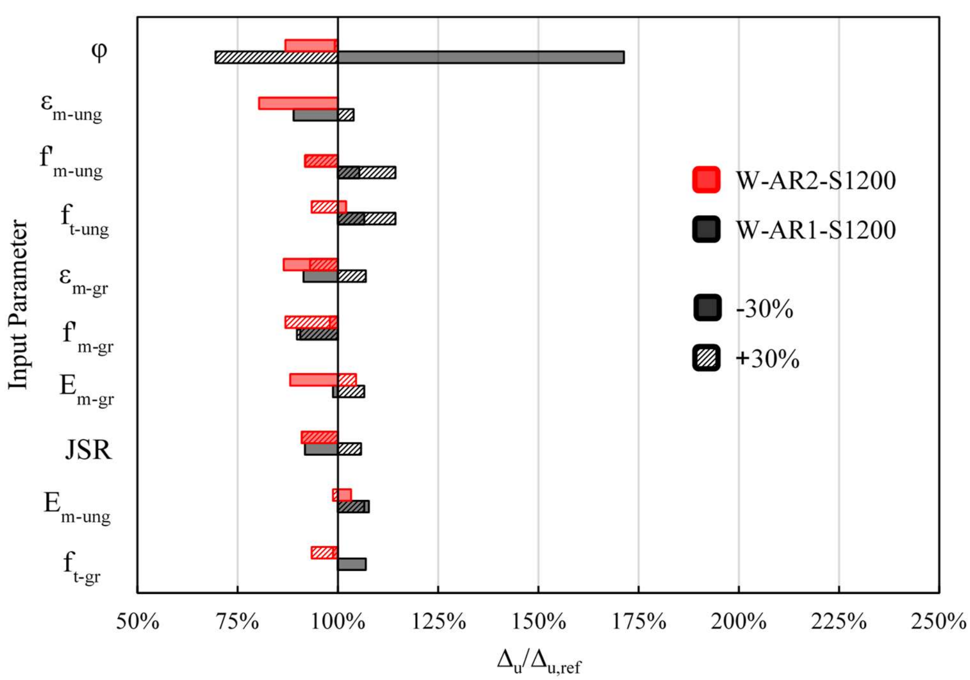


Figure 6: Sensitivity of the proposed numerical model in the estimation of Δ_u for PG-RMSWs with different aspect ratios and verical reinforcement spacing of 1200 mm

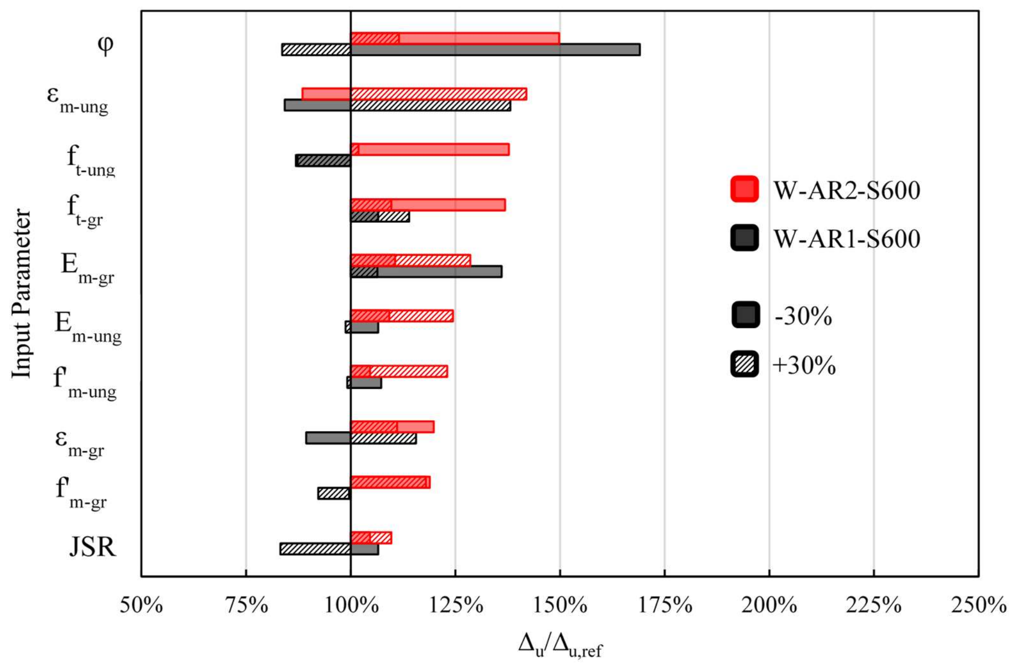


Figure 7: Sensitivity of the proposed numerical model in the estimation of Δ_u for PG-RMSWs with different aspect ratios and verical reinforcement spacing of 600 mm

SUMMARY AND CONCLUSION

In this research, a simplified micro-model is proposed to simulate the cyclic behavior of PG-RMSWs. The proposed model is validated against several walls' experimental results in the literature and is proven to provide acceptable behavior. A sensitivity analysis is conducted to study the influence of different input grouted and ungrouted masonry parameters on the engineering demand parameters of PG-RMSWs. The sensitivity analysis aims at providing guidelines to balance between the required effort and accuracy in estimating the input parameters. To do so, four walls are modeled in VecTor2 using the proposed modeling scheme with certain reference values for grouted and ungrouted masonry parameters. These four walls are selected such that each two walls have the same aspect ratio (1.0 and 2.0) with different vertical reinforcement spacings (600 mm and 1200 mm). Afterwards, reference values of masonry input parameters are changed with ±30% from the reference value.

The sensitivity analysis reveals that ungrouted masonry properties, especially the angle of internal friction, are the most influential parameters on the behavior of the walls. This effect is more obvious for shorter walls and for walls with larger reinforcement spacings. This demonstrates that more attention shall be given to the estimation of the masonry parameters for shorter walls, especially block-mortar interface properties using the proposed equations and experimental methods available in literature in order to ensure appropriate modeling of PG-RMSWs. This also leads to the conclusion that the behavior of PG-RMSWs, including strength and ductility can be enhanced by ensuring better bond between masonry block and mortar since this interface is relatively weak and has a significant effect on the behavior of such walls. This opens the area for future research to improve the seismic response of PG-RMSWs by enhancing the bond between mortar and masonry blocks.

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REFERENCES

[1] El-Dakhakhni, W., & Ashour, A. (2017). Seismic Response of Reinforced-Concrete Masonry Shear-Wall Components and Systems: State of the Art. Journal of Structural Engineering, 03117011.

[2] Schultz, A. E. (1996). Seismic Performance of Partially Grouted Masonry Shear Walls. Eleventh Conference on Earthquake Engineering, (p. Paper No. 1221).

[3] Arnau, O., Sandoval, C., & Murià-Vila, D. (2015). Determination and validation of input parameters for detailed micro-modelling of partially grouted reinforced masonry walls. Proceedings of the Tenth Pacific Conference on Earthquake Engineering. Sydney, Australia.

[4] Maleki, M. (2008). Behaviour of Parially Grouted Reinforced Masonry Shear Walls Under Cyclic Reversed Loading. PhD Thesis, McMaster University, Department of Civil Engineering, Hamilton, Ontario.

[5] Bolhassani, M., Hamid, A. A., & Moon, F. (2016). Enhancement of lateral in-plane capacity of partially grouted concrete masonry shear walls. Engineering Structures, 108, 59-76.

[6] Wong, P. S., Vecchio, F. J., & Trommels, H. (2013). VecTor2 & Formworks User's Manual; Second Edition. University of Toronto, Department of Civil Engineering.

[7] CSA Group (2014). Design of Masonry Structures. Mississauga, Ontario, Canada: CSA Group.

[8] Bolhassani, M., Hamid, A. A., Lau, A. C., & Moon, F. (2015). Simplified micro modeling of partially grouted masonry assemblages. Construction and Building Materials, 83, 159-173.

[9] Hoshikuma, J., Kawashima, K., Nagaya, K., & Taylor, A. W. (1997). Stress-Strain Model for Confined Reinforced Concrete in Bridge Piers. Journal of Structural Engineering, 123(5), 624-633.

[10] Scott, B. D., Park, R., & Priestley, M. J. (1982). Stress-Strain Behavior of Concrete Confined by Overlapping Hoops at Low and High Strain Rates. ACI Journal, 79(1), 13-27.

[11] Vecchi, F. J. (1992). Finite Element Modeling of Concrete Expansion and Confinement. Journal of Structural Engineering, 118(9), 2390-2406.

[12] Cornelissen, H. A., Hordijk, D. A., & Reinhardt, H. W. (1986). Experimental determination of crack softening. HERON, 13(2).

[13] Seckin, M. (1981). Hysteretic Behaviour of Cast-in-Place Exterior Beam-Column-Slab Subassemblies", PhD Thesis. Toronto, Ontario, Canada: Department of Civil Engineering, University of Toronto.

[14] He, X. G., & Kwan, A. K. (2001). Modeling Dowel Action of Reinforcement Bars for Finite Element Analysis of Concrete Structures. Computers and Structures, 79(6), 595-604.

[15] Dhakal, R. P., & Maekawa, K. (2002). Modeling for post-yield buckling of reinforcement. Journal of Structural Engineering, 128(9), 1139-1147.

[16] Dhakal, R. P., & Maekawa, K. (2002). Reinforcement Stability and Fracture of Cover Concrete in Reinforced Concrete Members. Journal of Structural Engineering, 128(10), 1253-1262.
[17] Binici, B., & Mosalam, K. M. (2007). Analysis of Reinforced Concrete Columns Retrofitted with Fiber Reinforced Polymer Lamina. Composites: Part B, 38, 265–276.
[18] Priestley, M. J., & Elder, D. M. (1983). Stress-Strain Curves for Unconfined and Confined Concrete Masonry. ACI Journal, 80(3), 192-201.
[19] Zhou, Q., Wang, F., Zhu, F., & Yang, X. (2017). Stress–strain model for hollow concrete block masonry under uniaxial compression. Materials and Structures, 50(106), 1-12.
[20] Institute for Research in Construction. (2015). National Building Code of Canada (NBCC). Ottawa, Ontario, Canada: National Research Council of Canada.
[21] Ramírez, P., Sandoval, C., & Almazán, J. L. (2016). Experimental study on in-plane cyclic response of partially grouted reinforced concrete masonry shear walls. Engineering Structures, 126, 598-617.