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EFFECT OF CHANGING VERTICAL REINFORCEMENT RATIO AND LEVEL OF AXIAL STRESS ON THE LATERAL RESPONSE OF REINFORCED MASONRY SHEAR WALLS WITH BOUNDARY ELEMENTS

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ABSTRACT

Reinforced masonry shear walls with boundary elements (RMSW-BE) showed enhanced lateral performance and displacement ductility compared to rectangular walls. However, few studies focused on the seismic performance of RMSW-BE. Predicting inelastic responses of RMSW-BE require accurate and effective numerical modelling tools that incorporate important material characteristics and behavioural response features. Therefore, there is a need for developing simplified numerical tools for reliable evaluation of the seismic response of RMSW-BE in order to facilitate the adoption of RMSW-BE in different design and assessment frameworks. In this paper, a numerical study is presented using a macro-modelling approach that is embedded in the software SeismoStruct to simulate the in-plane response of flexural dominated RMSW-BE. Model validation is conducted by comparing the lateral force-displacement responses computed from the model predictions against the experimental data of four RMSW-BE tested under quasi-static cyclic loading from the literature. A parametric study is performed to evaluate the influence of various levels of axial compressive stress, and vertical reinforcement ratio in BE on the load-displacement response of the RMSW-BE under quasi-static cyclic loading. All walls had a high level of displacement ductility under different levels of axial stress and vertical reinforcement ratio.

KEYWORDS: *axial stress level, boundary elements, masonry, parametric, shear walls, seismostruct, vertical reinforcement ratio*

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INTRODUCTION

Predicting the inelastic lateral responses of Reinforced Masonry Shear Walls with Boundary Elements (RMSW-BE) require accurate and simple numerical modelling tools that incorporate important material characteristics and behavioral response features. Consequently, simplified numerical tools are needed for reliable evaluation of the seismic response of (RMSW-BE) in order to facilitate their adoption in different design and assessment frameworks. Numerous studies have been conducted to simulate the nonlinear behavior of reinforced masonry shear walls. However, few studies investigated the seismic response of reinforced masonry shear walls with boundary elements (RMSW-BE).

Shedid et al. [1] tested seven half scale fully grouted RMSW and investigated the performance of walls with three different end configurations: rectangular, flanged and confined boundary elements. He observed an enhancement in ductility and ultimate displacements by flanged and end confined walls in comparison to rectangular walls subjected to the same level of axial stress. Banting et al.[2] tested five half scale fully grouted RMSW-BE with different design parameters such as aspect ratio, height, length and reinforcement ratio. He reported that the presence of BE in the walls delayed the buckling of the reinforcement as well as crushing of the grout. Experimental tests provide unique understandings on the damage pattern of masonry structures under earthquake loading. However, experiments are limited to scaled specimens, because of the limitations of available experimental facilities. Furthermore, experimental tests are costly and require immense facilities and resources. Accordingly, validated and reliable numerical modeling can be one of the effective solutions to investigate the performance of RMSW-BE having various design parameters.

The two main approaches for modelling RMSW are micro-modelling and macro modelling. Micro-modelling is based on discretization of a structure into a finite number of small elements interconnected at a finite number of nodes. Macro-modelling is based on representing the overall structure with larger elements, each which has properties that are equivalent to the sum of its components [3]. Although micro-modelling has high accuracy, it is a complex approach that needs high level of computational effort. Conversely, macromodelling is considered simpler and does not require the same level of detailed discretization used for micro-modelling.

This paper develops a 2D simplified numerical model utilizing Seismostruct package, using fiber based beam column elements, to simulate the behavior of RMSW-BE under cyclic loading. Experimental test results of four RMSW-BE reported by Shedid et al. [1] and Banting et al. [2] were used to validate the numerical model. In this study, the behavior of nine RMSW-BE was evaluated with different vertical reinforcement ratio in boundary elements (BE) and levels of axial compression stress. The objective of this paper is to illustrate through simplified numerical models the influence of these parameters on lateral load-displacement response of RMSW-BE in order to have a better understanding of the inelastic behavior of RMSW-BE.

PARAMETRIC STUDY

Wall Details

Nine fully grouted RMSW-BE were modelled using SeismoStruct, according to the details provided in Table 1. The walls were designed according to CSA S-304-14 (Canadian standards Association (CSA)) [4]. Numerical wall models are used for the assessment of different parameters on the load-displacement response of RMSW-BE. The parameters under study are axial compressive stress, and vertical reinforcement ratio in BE. All walls were detailed with the same vertical reinforcement in web of four 20M bars [A_v=300 mm^2] spaced at 800 mm and horizontal reinforcement of 10M bars [A_h=100 mm^2] spaced at 190 mm. As indicated in Table 1, three vertical reinforcement ratios (0.79, 1.18, and 1.58%) in BE were also used to assess their effect on the load-displacement response of RMSW-BE. In addition, the axial stress of the walls is varied to represent the range of compressive stresses found in shear walls in typical reinforced masonry structures.Fig.1 shows the cross sections of the walls with different vertical reinforcements in BE.

Table 1: Test Matrix

Wall ID	**Length, (m)**	**Height, (m)**	**Aspect Ratio**	**Vertical Reinforcement (B.E)**		**Axial Compressive Stress (MPa)**
				Number and size	**ρ_v (%)**	
W1	4	6	1.5	4-20M	0.79	0
W2	4	6	1.5	6-20M	1.18	0
W3	4	6	1.5	8-20M	1.58	0
W4	4	6	1.5	4-20M	0.79	0.3
W5	4	6	1.5	6-20M	1.18	0.3
W6	4	6	1.5	8-20M	1.58	0.3
W7	4	6	1.5	4-20M	0.79	0.6
W8	4	6	1.5	6-20M	1.18	0.6
W9	4	6	1.5	8-20M	1.58	0.6

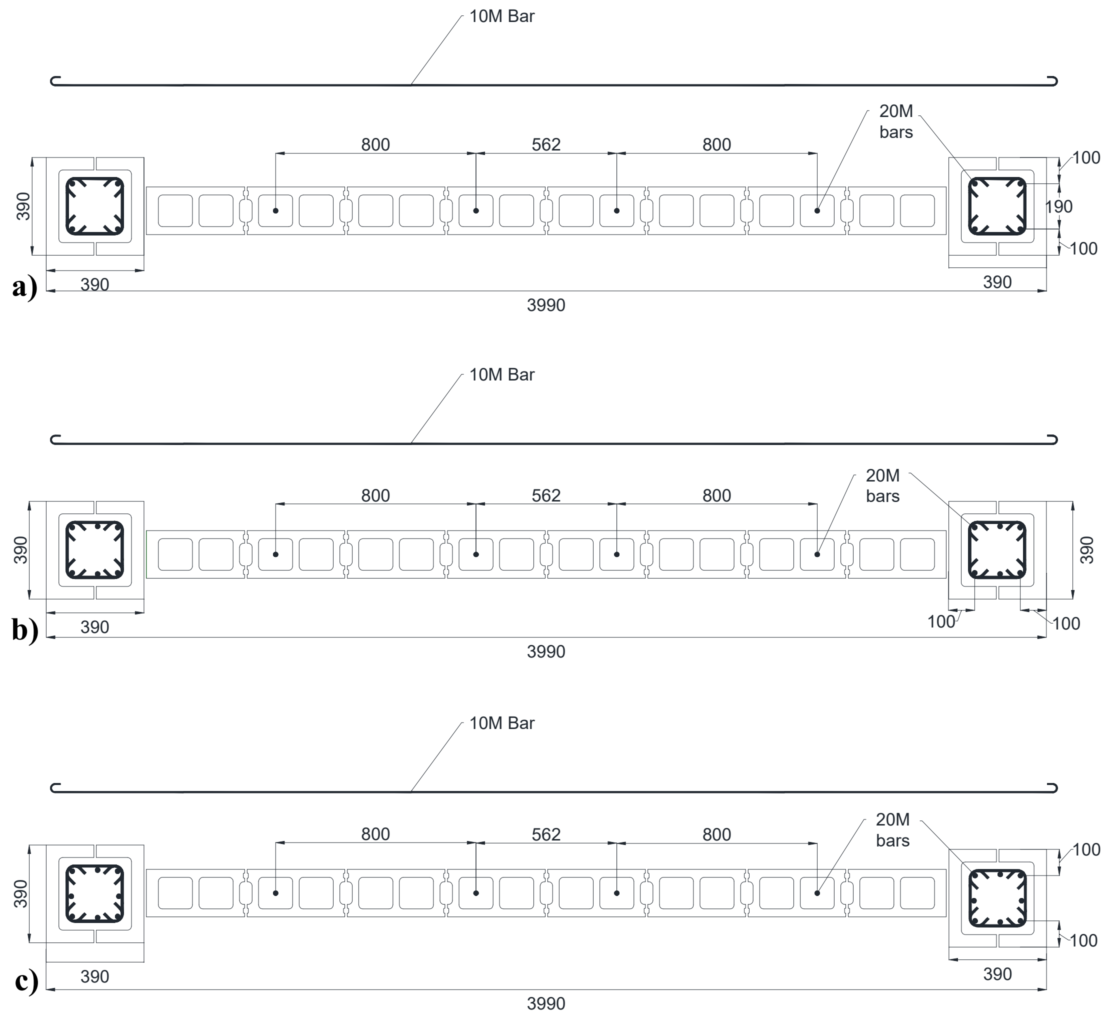

Figure 1: Cross section of walls: (a) 4 bars in B.E; (b) 6 bars in B.E; (c) 8 bars in B.E

Element Size and Boundary Conditions

Each wall was divided into four elements based on recommendations of Calabrese et al. [5] that a good approximation to the response can be obtained with a mesh discretization of at least four elements. Several formulas are available in the literature to estimate L_p of shear walls [6, 7, 8]. The formula proposed by Bohl and Adebar [8], which is based on nonlinear finite-element analysis results of 22 reinforced concrete shear walls, was found to give the closest estimate of the plastic hinge length, L_p, for RMSW-BE [9]. Therefore, the L_p is calculated as proposed by Bohl and Adebar [3] as shown in Eq. (1), whereas, this equation gives a lower bound estimate of plastic hinge length.

$$L_p = (0.2 l_w + 0.05 z)\left(1 - \frac{1.5P}{f'_c A_g}\right) \leq 0.8 l_w \quad (1)$$

where, l_w is the wall length, z is the moment shear ratio, A_g is the gross area of the wall cross section, f'_c is the concrete compressive strength (i.e. f'_m will be used instead for masonry walls), P is the axial force on the section. Fiber discretization is adopted to represent the behavior at the section level, where each fiber is associated with a uniaxial stress-strain law. A sufficient number, around 150 to 400 fibers can lead to good estimates of the load-displacement hysteresis response according to Boulanger et al. [10]. Consequently, based on sensitivity analysis, the RMSW-BE sections were divided into 300 fibers. The RMSW-BE considered in the current study were modeled as cantilevers, and thus, this was represented in the model by perfectly fixing the base degree of freedoms. Consequently, the axial loads are held constant and reversed cyclic horizontal displacements were applied at the top of the wall using the same loading protocol as the experimental tests from literature. Two load cycles were conducted for each wall at increments of yield displacement until a drop of 20% from the peak resistance was reached.

Material Models and Mechanical Properties

The consideration of nonlinear material behavior in the prediction of RMSW-BE requires accurate modelling of the uniaxial material stress-strain cyclic response. Table 2 shows the mechanical material properties of steel and masonry used in the numerical modeling of the walls.

Table 2: Material Mechanical Parameters for the Numerical Models

Parameter		**Value**
Compressive strength f_c (MPa)		17
Elasticity modulus of masonry E_m (MPa)		14450
Strain at peak strength ε_c		0.0015
Elasticity modulus of steel E_s (MPa)		200,000
Yield strength f_y (MPa)		400
Strain hardening parameter r (%)		0.005
Transition curve initial shape R_0		18.8
Transition curve shape	a_1	18.5
	a_2	0.25
Isotropic hardening	a_3	0
	a_4	1
Confinement factor, C_f		1.1

The masonry was modelled using Mander et al. [11] nonlinear model for concrete (con_ma in SeismoStruct). This is a uniaxial nonlinear constant confinement model. The confinement effects provided by the lateral transverse reinforcement are incorporated through the rules proposed by

Mander et al. [11] whereby constant confining pressure is assumed throughout the entire stress-strain range. The input parameters of the model for the masonry are: the compressive strength (f'_m); the strain at peak strength (ε_m); and the modulus of elasticity (E_m). The elastic modulus, E_m, was calculated according to the MSJC code (Masonry Standards Joint Committee (MSJC)) [12] as 850f'm, where f'_m is the masonry compressive strength. RMW-BE have the vertical reinforcement near the extreme compression fiber confined by stirrups. Therefore, the compressive strength of the masonry at boundary elements is higher than that of the wall web. This was taken into consideration within the numerical model, by adjusting the masonry material model accordingly by defining the confinement factor employed by Mander et al [11] to take the effect of confinement of the closed ties. It is defined as the ratio between the confined and unconfined compressive stress and used to scale up the stress-strain relationship throughout the entire strain range. The steel reinforcement was modeled using Menegotto-Pinto's [13] nonlinear steel model (stl_mp in Seismostruct). This model is a uniaxial steel model proposed by Menegotto and Pinto [13] coupled with the isotropic hardening rules proposed by Filippou et al. [14]. The input parameters are: the elastic Young modulus (E_s); the yield strength (f_y); the strain hardening ratio (r) and five coefficients representing the transition from elastic to plastic zone (R_0, a_1, a_2, a_3 and a_4).

Model validation Details

Model predictions were validated using experimental data of half-scale RMSW-BE tested by Banting et al. [2], and Shedid et al. [1]. Four RMSW-BE specimens experimentally tested under fully reversed displacement controlled quasi-static cyclic loading were used for the numerical model validation. The selected RMSW-BE specimens have different aspect ratios, ranging from 1.48 to 3.23. Table 3 summarizes the dimensions, aspect ratios and reinforcement details of the walls.

Table 3. Summary of Wall Details Used for the Model Validation

Wall ID	Length (mm)	Height (mm)	Vertical reinforcement		Horizontal reinforcement		Aspect ratio	Axial stress (MPa)	References
			No. of bars and bar size	ρ_v (%)	No of bars at spacing (mm)	ρ_h (%)			
W1	1235	3990	10 M10	0.69	1 at 95	0.3	3.23	0.89	Banting et al.[2]
W2	1235	2660	10 M10	0.69	2 at 95	0.6	2.15	0.89	Banting et al.[2]
W3	1800	3990	11 M10	0.55	1 at 95	0.3	2.21	0.89	Shedid et al. [1]
W4	1800	2660	11 M10	0.55	2 at 95	0.6	1.48	0.89	Shedid et al. [1]

The computed load-displacement hysteresis of the four RMSW-BE were validated against the experimental results reported by Banting et al. [2], and Shedid et al. [1]. Results show that there is a good agreement between the experimental hysteresis loops and the corresponding loops from the cyclic analyses using SeismoStruct. The model is able to simulate the most relevant characteristics of the cyclic response, including the initial stiffness, peak load, stiffness degradation, strength degradation over the loading history as shown in Fig.2.

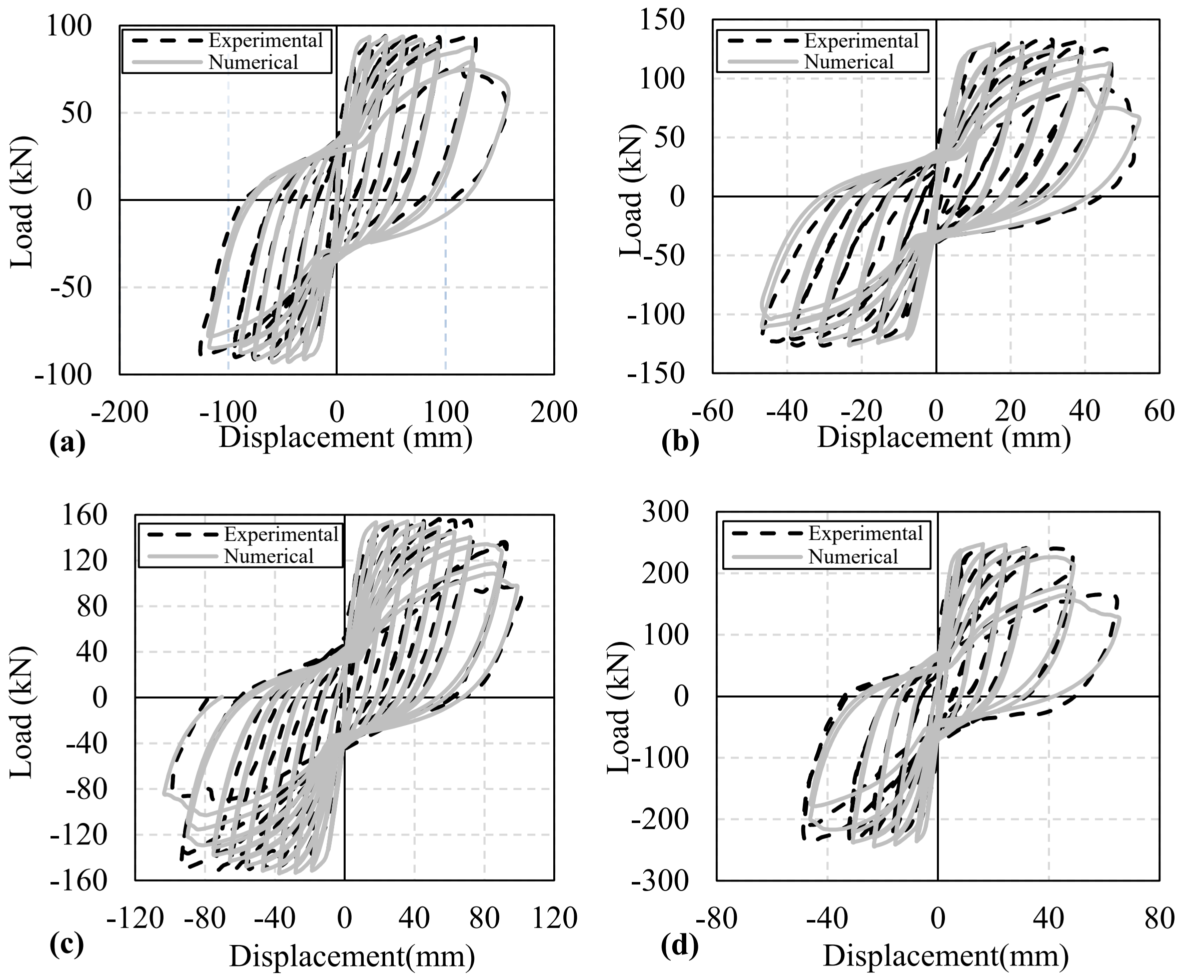

Figure 2: Experimental and numerical hysteresis loops: (a) Wall 1; (b) Wall 2; (c) Wall 3; (d) Wall 4

RESULTS

Load-Displacement Response

After the validation of the numerical model, a parametric study was performed to assess the influence of different parameters on the lateral behavior of the RMSW-BE. All walls were subjected to fully reversed displacement controlled quasi-static cyclic loading and were cycled up to failure at 20% strength degradation. The envelopes of the load-displacement relationships for 9 walls are presented in Fig.3. In addition, analytical calculations using equilibrium and compatibility principles were carried out using CSA S304-14[4] to predict the walls yield strength, $Q_{y(pred)}$, and peak flexural strength, $Q_{u(pred)}$ to further validate the numerical model calculations. Force equilibrium and plane section strain compatibility were used to determine $Q_{y(pred)}$ and $Q_{u(pred)}$. The theoretical yield strength $Q_{y(pred)}$ was determined assuming elastic strength in the masonry, $f_m=\varepsilon_m x E_m$, and the extreme reinforcement at its average yield strain (ε_y=0.0025). The theoretical peak flexural strength, $Q_{u(pred)}$ was determined assuming an equivalent stress block of strength 0.85*f'm* over a compression block depth of 0.8c with a limiting strain of ε_{mu}=0.0025 as prescribed in the CSA S304-14 [4].

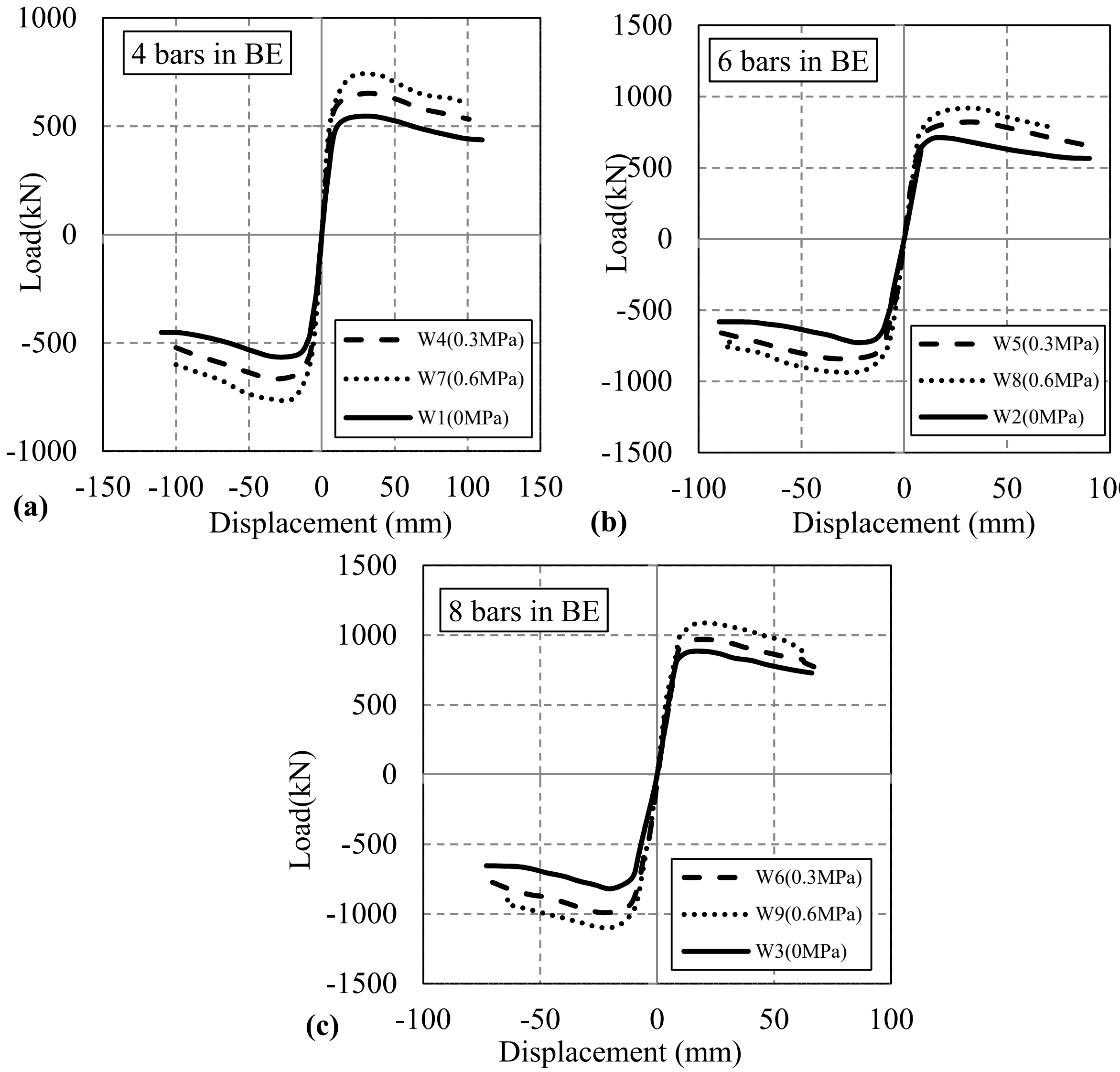

Figure 3: Load-displacement hysteresis' Envelopes for RMSW-BE

The predicted analytical and numerical lateral capacity at yield and at peak of all walls are listed in Table 4. For all walls, the ratio between the analytical and the numerical strength Q_{Num}/Q_{Pred} ranged between 0.91 to 1.17 for yield load and 0.89 to 1.15 for ultimate load calculations, respectively. Consequently, a good agreement between the analytical and numerical predictions is achieved. The displacement ductility, μ_Δ is a measure of the ability of the member to withstand large deformations beyond its yielding point without breaking. It is defined as the ratio between the top displacement at a specified limit and the idealized yield displacement using elastic-plastic idealization of the load-displacement method suggested by Tomazevic [15]. The numerical values of idealized yield displacement (Δ_{yi}), and ductility at 20% strength degradation ($\mu_{\Delta 0.8u}$) are presented in Table 4. The effect of different design parameters on the displacement ductility is also discussed below.

Table 4: Lateral capacity and Displacement Ductility

Wall ID	Lateral Capacity At yield Q_y			Lateral Capacity At peak Q_u				
	Q_{Num} (kN)	Q_{Pred} (kN)	(Q_{Num}/Q_{Pred})	Q_{Num} (kN)	Q_{Pred} (kN)	(Q_{Num}/Q_{Pred})	Δ_{yi} (mm)	$\mu_{\Delta 0.8u}$
W1	387.2	348.5	1.11	556.0	612.0	0.91	9.46	11.6
W2	520.4	482.6	1.08	711.6	791.9	0.89	8.74	10.30
W3	652.6	616.5	1.06	857.1	747.0	1.15	8.97	7.82
W4	474.0	517.5	0.92	655.4	721.8	0.91	8.84	11.30
W5	629.0	559.2	1.12	830.3	912.8	0.91	9.00	9.88
W6	760.6	692.4	1.10	976.9	1106.9	0.88	9.49	7.20
W7	430.4	474.8	0.91	750.8	827.7	0.91	11.8	8.53
W8	693.8	635.0	1.09	924.1	1021.3	0.90	10.3	7.51
W9	899.0	767.2	1.17	1098.6	1214.3	0.90	9.79	6.48

Effect of Axial Compressive Stress

The effect of changing the axial compressive stress on the load-displacement behavior is assessed. In Fig.4 (a), results show that the lateral ultimate capacity of walls increases with higher level of axial load ratios. It is also seen in Fig.3 that walls with higher axial load experienced a more rapid strength degradation than that for walls with lower axial load ratios. In addition, it is observed that displacement ductility decreased with increased axial stress, as shown in Fig.4 (b). The displacement ductility tends to decrease slightly with increases in axial compressive, which is attributed to a slight increase in the displacements at yield with increased axial stress. Similar observations were recently reported by Banting et al. [16] after testing RMSW under different levels of axial loads.

Effect of Vertical Reinforcement Ratio in B.E

The effect of varying the vertical reinforcement ratio in the boundary element on the load-displacement behavior can be observed in Fig. 4(c). Where the ultimate capacity of walls increases as the vertical reinforcement ratio in B.E increases. The displacement ductility was highly dependent on the amount of vertical reinforcement. The results plotted in Fig.4 (d) show that as the vertical reinforcement ratio in B.E increases; displacement ductility decreases.

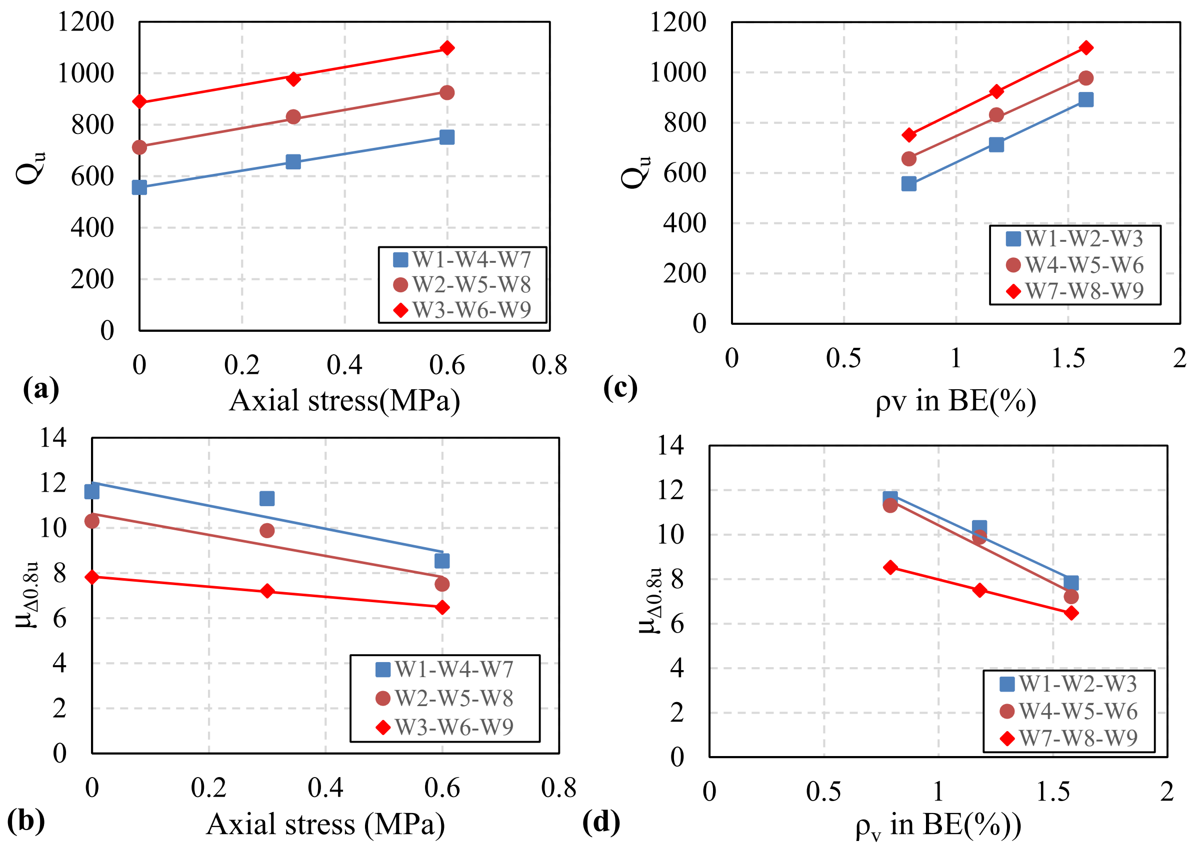

Figure 4: Effect of axial stress: (a) lateral capacity; (b) displacement ductility, Effect of ρ_v in BE: (c) lateral capacity; (d) displacement ductility

CONCLUSIONS

This paper presented a macro model using SeismoStruct for the numerical simulation of the behaviour of RMSW-BE under cyclic loading. The numerical model was validated based on selected experimental results from the literature of RMSW-BE tested under cyclic loading. The model predictions showed a good agreement between the numerical and experimental load-displacement responses. In addition, a parametric study has been performed aiming at assessing the influence of vertical reinforcement ratio in BE and axial stress on the in-plane behavior of masonry walls. Axial stress and vertical reinforcement ratio had a significant effect on the displacement ductility and ultimate strength. The displacement ductility for walls with high axial stress (0.6MPa) and heavily reinforced walls (8 bars in BE) decreased by 23% and 31% respectively in comparison to walls with zero axial loads, and lightly reinforced walls (4 bars in BE). The ultimate capacity Q_u increased by 29% for walls with high axial stress (0.6MPa) and increased by 52% for walls with high vertical reinforcement ratio (ρv=1.58%). Ongoing research is applying this modeling technique to develop fragility curves to be used for the seismic performance based assessment of RMW-BE.

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