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SENSITIVITY OF THE SEISMIC RESPONSE OF FULLY GROUTED REINFORCED MASONRY SHEAR WALLS WITH BOUNDARY ELEMENTS TO DESIGN PARAMETERS

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ABSTRACT

Reinforced concrete-masonry shear walls (RMSWs) with boundary elements (RMSW+BEs) were introduced as a seismic force-resisting system and found to achieve higher ductility levels without sudden loss of their strength compared to rectangular walls. The objective of this study is to investigate, numerically, the sensitivity of the seismic response of RMSW+BEs to the masonry compressive strain at peak stress, ε_{mu}, the masonry compressive strength, f'_m, and the vertical reinforcement ratio of the confined masonry boundary elements (MBE), ρ_{vBE}, for walls having different cross-section configurations and different aspect ratios. In this regard, a total of thirty RMSW+BEs are modeled and analyzed using static time history nonlinear analysis to predict the nonlinear seismic response of the RMSW+BEs. Two different aspect ratios, namely 1.66 and 4.16, were investigated, and three different boundary element cross-sections were studied. The selected wall heights (i.e., 6 m (19.69 ft) and 15 m (49.21 ft)) represent RMSW buildings with 2 and 5 storeys, respectively. The results showed that RMSWs with bigger boundary element sizes exhibited more sensitivity to the change of the BE vertical reinforcement ratio and the ultimate masonry compressive strain. On the contrary, it was inferred that walls with higher aspect ratios are less sensitive to changing ε_{mu}, and ρ_{vBE}. Furthermore, the ultimate lateral capacity of the RMSW+BEs was found more sensitive to the concentrated reinforcement in the boundary elements, whereas the ductility of the RMSW+BEs is highly sensitive to the ultimate masonry compressive strain. This study sheds light on some of the most critical parameters affecting the design of RMSW+BEs.

KEYWORDS: *boundary elements, concrete-masonry, ductility, reinforced masonry, sensitivity, shear walls*

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INTRODUCTION AND BACKGROUND

Reinforced concrete-masonry shear walls (RMSWs) have been widely used in the construction of many North American buildings. However, planar (i.e., rectangular) reinforced masonry shear walls were found to have stability, capacity, and ductility limitations due to the restricted arrangement of one row of vertical reinforcement rebars. As such, introducing a confined concrete masonry core (i.e., masonry boundary element, MBE) to the outermost ends of a rectangular shear wall enhances the stability and ductility of the RMSWs. This boundary element (BE) allows placing a steel cage of at least four reinforcing steel bars confined with hoops to be incorporated at the wall extremities. This contributes to alleviating the buckling of the vertical reinforcement bars in the compression zone at high displacement levels and enhancing the stability of the RMSWs. Moreover, increasing the confinement within the boundary elements enhances the shear wall's inelastic strain capacity and enhances the curvature ductility of the RMSWs. Thus, reinforced masonry shear walls with boundary elements (RMSW+BEs) were found to achieve higher ductility levels than their planar counterparts. Therefore, there is a need to investigate the most critical design parameters affecting the seismic performance of RMSW+BEs in order to facilitate optimizing the design of concrete-masonry buildings having RMSW+BEs in moderate and high seismicity zones. The literature showed that structural masonry walls with boundary elements exhibited ductile seismic response compared to rectangular RMSWs. Shedid et al. [1] reported that significant energy dissipation levels were associated with the inelastic response of the flanged walls and walls with boundary elements compared to their rectangular counterparts. Banting and El-Dakhakhni [2] investigated, experimentally, the seismic performance of five RMSW+BEs subjected to quasi-static reversed cyclic loading. The researchers inferred increasing the vertical reinforcement ratio of the walls increased the lateral capacity and the top drift, a significant drop in the displacement ductility, and a slight decrease in the tested walls' curvature ductility. The seismic performance of ductile reinforced masonry shear wall buildings was investigated by Aly and Galal [3]. In their findings, the researchers reported that the addition of the boundary elements to the wall toes using high strength C-shaped pilaster blocks combined with high strength grout greatly enhanced the overall system ductility and the seismic behavior. Aly and Galal [4,5] showed that using C-shaped MBE blocks enhanced the constructability and the seismic performance of the RMSW+BEs.

This study focuses on investigating, numerically, the sensitivity of the seismic response of RMSW+BEs to the design parameters, namely, the masonry compressive strain at peak stress (ε_{mu}), the masonry compressive strength, f_m', and the vertical reinforcement ratio of the confined MBEs (ρ_{vBE}). Furthermore, the wall configurations, namely, the MBE cross-section configuration and the wall aspect ratio (AR) were studied. The outcome of this numerical investigation provides essential data that helps better understanding and quantifying significant factors affecting the seismic design of RMSW+BEs buildings.

In this study, RMSWs with different boundary elements cross-sections, namely, 390x400 mm (15.35x15.75 in), 390x600 mm (15.35x23.62 in), 390x800 mm (15.35x31.50 in), different story heights representing low and mid-rise masonry buildings (2 and 5 storeys) were examined. The sensitivity of the seismic response of RMSW+BEs to the change of ±30% of the design parameters ε_{mu}, f'_m, and ρ_{vBE} was studied. A 2D macro-modeling approach is utilized to predict the nonlinear seismic response of the RMSW+BEs using SeismoStruct software (2018). The numerical model is calibrated and validated using available experimental data of RMSWs in the literature. Quantification of the seismic response is conducted in terms of the RMSW+BEs lateral yield capacity (Q_y), lateral ultimate capacity (Q_u), and displacement ductility at 20% strength degradation ($\mu_{\Delta 0.8Qu}$). Comparisons of the walls' backbone curves and the tornado charts showing the influence of the design parameters on the seismic response of RMSW+BEs are reported.

TEST MATRIX AND DETAILS OF THE RMSW+BEs

Forty-two fully-grouted full-scale RMSW+BEs were modeled using SeismoStruct [6] . Table 1 describes the details of the six reference RMSW+BEs. The RMSW+BEs were designed according to the CSA S304-14 [7] provisions. It should be noted that the 4-20M bars in the webs of the walls were not changed with changing the masonry boundary elements′ sizes in order to satisfy the CSA S304-14 [7] provisions for the maximum spacing of vertical reinforcement in the plastic hinge region of ductile RMSWs. The wall configurations, namely, the wall aspect ratio (AR = height-to-length ratio; h_w/l_w), and the masonry boundary element size were investigated. As can be seen in Table 1, there are two wall aspect ratios (AR): 1.66 and 4.16 were considered. The RMSW+BEs cross-sectional configurations and the reinforcement details are illustrated in Figure 1 (dimensions are in mm). Among the studied walls, two different numbers of storeys were considered: 2 and 5. These numbers of storeys represent low-rise (2 storeys) and medium-rise (5 storeys) masonry shear wall buildings.

Table 1: Test matrix of the reference reinforced masonry shear walls with boundary elements (RMSW+BEs)

				Masonry Boundary element (MBE)			Web	
				Vertical reinforcement			Vertical reinforcement	
Wall No.	Wall identifier	Height (m) (ft)	Aspect ratio	Amount	$\rho_{v\,BE}$ (%)	cross-section	Amount	ρ_v (%)
1	Sq-BE-Low	6 (19.6)	1.66	4-25M	1.28	390x400	4-20M	0.22
2	Sq-BE-Mid	15 (49.21)	4.16	4-25M	1.28	390x400	4-20M	0.22
3	R1-BE-Low	6 (19.6)	1.66	6-25M	1.28	390x600	4-20M	0.26
4	R1-BE-Mid	15 (49.21)	4.16	6-25M	1.28	390x600	4-20M	0.26
5	R2-BE-Low	6 (19.6)	1.66	8-25M	1.28	390x800	4-20M	0.31
6	R2-BE-Mid	15 (49.21)	4.16	8-25M	1.28	390x800	4-20M	0.31

Sq = Square boundary element with dimensions 390x400 mm (15.35x15.75 in)
R1 = Rectangular boundary element with dimensions 390x600 mm (15.35x23.62 in)
R2 = Rectangular boundary element with dimensions 390x800 mm (15.35x31.50 in)

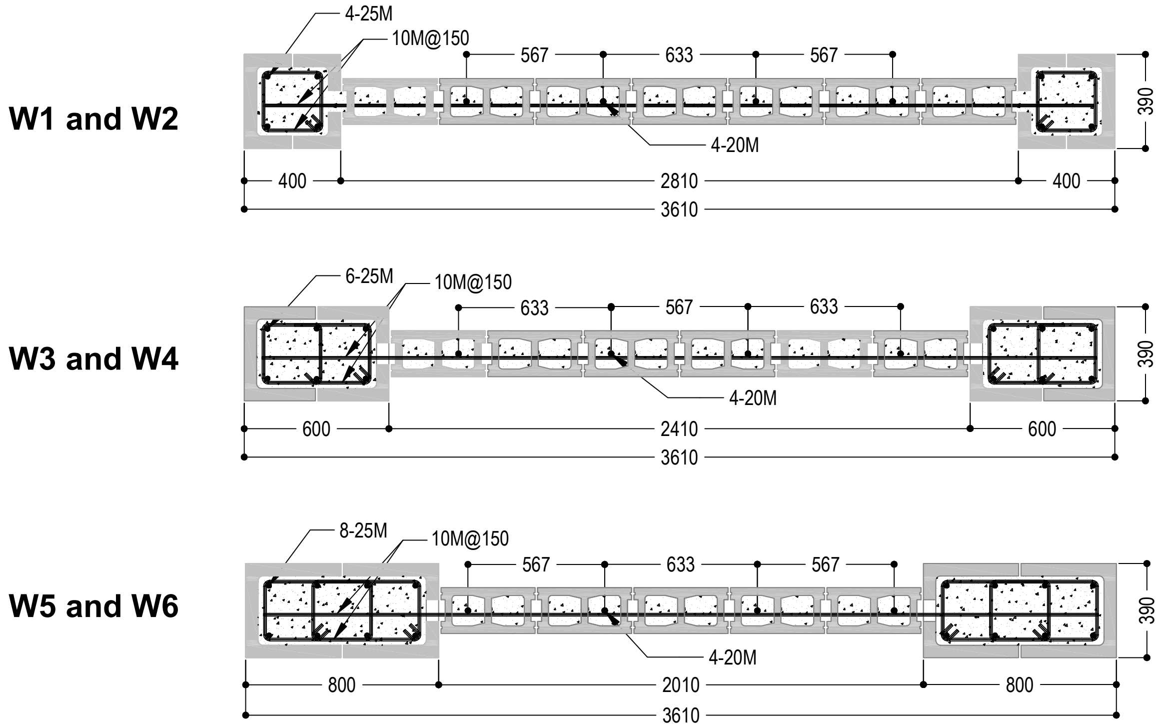


Figure 1: Details of the reinforced masonry shear walls with boundary elements

Each wall is given an identification to facilitate the comparison between the RMSW+BEs based on the boundary element shape and size (i.e., square versus rectangular), the wall height (i.e., Low and Mid). For example, the wall R1-BE-Mid represents a reinforced masonry shear wall with 390x600 mm (15.35x23.62 in) rectangular boundary elements with a total height of 15 m (49.21 ft).

The design parameters, namely, the masonry compressive strain at peak stress (ε_{mu}), the masonry compressive strength (f_m') and the MBE vertical reinforcement ratio (ρ_{vBE}) are utilized to develop the sensitivity analysis with upper and lower bounds of ±30% for each of the three above-mentioned parameters to investigate their effect on the seismic behavior of the studied RMSW+BEs. Each wall shown in Table 1 was modeled using ±30% of the reference design values ε_{mu}, f_m', and ρ_{vBE}. Hence, each wall has 7 models: the reference wall (listed in Table 1), and 6 other walls that have 2 variations (± 30%) for the three studied design parameters ε_{mu}, f_m', and ρ_{vBE}.

NUMERICAL MODELING APPROACH

In the current study, a macro-modeling approach is adopted to simulate the seismic response of the RMSW+BEs using the available tools of the SeismoStruct [6]. Displacement-based beam-column fiber-elements with distributed plasticity were utilized in the model. The displacement-based elements follow a standard finite-element approach, in which the element deformations are interpolated from an approximate displacement field that assume constant axial strain and linear curvature along the element length. The interpolation from an approximate displacement field results in concentration of strains at the first integration point near the wall base, not at the first element level as reported by Calabrese et al. [8]. Since each element has two integration sections, the first element length is chosen as twice as the plastic hinge length (i.e., $2l_p$) where each integration section accounts for one plastic hinge length (l_p). It is noteworthy that the plastic hinge length is calculated based on the equation suggested by Bohl and Adebar [9]. This equation accounts for the axial load effects and the moment-shear ratio of the walls. Figure 2 presents the discretization of the fiber-section of the RMSW+BEs with the material models used to calibrate the numerical model.

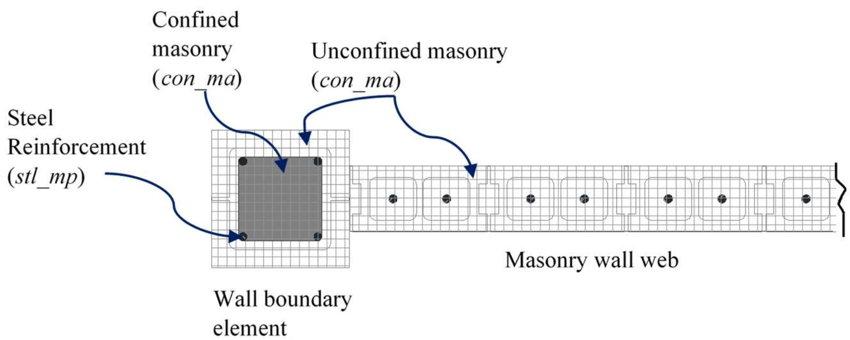


Figure 2: Cross-sectional nonlinear material models employed in the numerical model

The concrete-masonry material was simulated using the available concrete material model, *con_ma*, by Mander et al. [10] adopted in SeismoStruct [6]. The Mander et al. nonlinear concrete material model is calibrated using the maximum masonry compressive strength (f'_m)and its corresponding strain (ε_{mu}), the maximum tensile strength (f_{tm}), and the masonry modulus of elasticity (E_m). This model is also adaptable to the confinement factor of the confined reinforced MBE, based on which, the cyclic rules, the masonry compressive strength, and its corresponding strain are modified. In the current study, the value of the masonry compressive strength (f'_m) was selected as 20 MPa and its corresponding strain (ε_{mu}) was chosen as 0.002, and the masonry modulus of elasticity (E_m) was computed based on the CSA S304-14 [7] provisions (i.e., $E_m = 850 f'_m$).

The nonlinear cyclic response of the reinforcing steel bars is attained using the Menegotto and Pinto [11] material model (*stl_mp*) that is available in SeismoStruct [6]. This model is simple, readily calibrated, and capable of capturing the yield strength, the strain hardening effects, the Bauschinger effect, and the strength degradation due to cyclic loading. Moreover, this model is mainly defined using the reinforcement steel modulus of elasticity (E_s), the yield strength (f_y), the strain hardening parameter, the fracture/buckling strain, and other calibrating coefficients. For the current study, the yield strength (f_y) of 400 MPa (58015 psi) and the modulus of elasticity (E_s) of 200 GPa (29007.5 ksi) were employed.

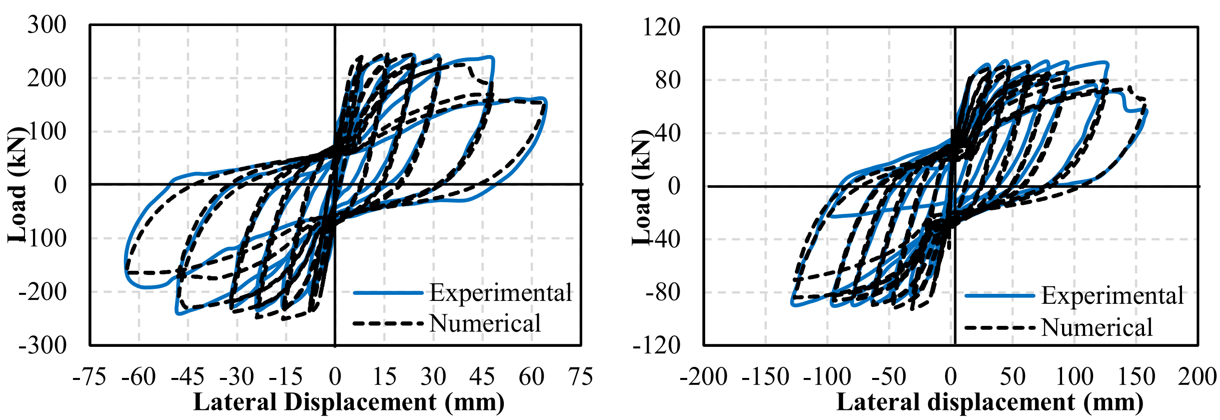
Model Validation

To ensure the robustness of the numerical modeling approach, the numerical model and its calibrated material models were validated against experimental results of RMSWs (i.e., rectangular and with boundary elements) available in the literature. The experimental results of the RMSWs were selected based on the studies conducted by Banting and El-Dakhakhni [2] and Shedid et al. [1] on the seismic response of RMSWs with boundary elements using quasi-static cyclic loading. RMSW+BEs W6 from Shedid et al. [1] and W2 from Banting and El-Dakhakhni [2] were chosen to be validated against the developed numerical model. Table 2 describes the details and the reported material properties of the RMSWs adopted from the literature to be used to validate the numerical model. Figure 3 depicts the load-displacement hysteresis of the tested RMSWs by Banting and El-Dakhakhni [2] and Shedid et al. [1] and that of the numerical model.

Table 2: Details and material properties of the RMSWs utilized for the validation

Wall ID	Reference	Length (mm) (in)	Height (m) (ft)	Vertical reinforcement		Horizontal reinforcement		Masonry
				Amount	f_y (MPa) (psi)	Amount	f_y (MPa) (psi)	f'_m (MPa) (psi)
W6	[1]	1802 (70.9)	2.66 (8.7)	11-M10	495 (71794)	2-D4@95	534 (77450)	16.4 (2379)
W2	[2]	1235 (48.6)	3.99 (13.1)	10-M10	496 (71939)	D4@95	582.5 (84484)	17.3 (2509)

It can be seen there is good agreement between the experimental results and that of the numerical model where the model is seen to have the capability to capture the most significant parameters of the seismic response such as the yield strength, the lateral capacity, the stiffness and strength degradation with different displacement increments, and the pinching behavior of the walls. Hence, the model was found to be reliable and able to capture the cyclic response of the RMSW+BEs.



(a) (b)

Figure 3: Validation of the numerical model against experimental results from (a) wall W6 from Shedid et al. (2010); and (b) wall W2 from Banting and El-Dakhakhni (2014)

ANALYSIS OF THE RESULTS

The tornado charts of the sensitivity analysis show the influence of changing the design parameters on the seismic response components of each studied wall (i.e., Q_u, Q_y, and $\mu_{\Delta 0.8Qu}$) normalized to their corresponding components (i.e., $Q_{u,ref}$, $Q_{y,ref}$, and $\mu_{\Delta 0.8Qu,ref}$) of the reference walls listed in Table 1. The RMSW+BEs were subjected to fully-reversed displacement-controlled cycling loading using the static time history nonlinear analysis in SeismoStruct (2018). The fully reversed cycling loading was applied using multiples of the yield displacement (Δ_y), at which, yielding of the outermost vertical reinforcement bars of the RMSW+BEs is captured. The cycles were performed until the RMSW+BEs reach 80% of its lateral ultimate load, $0.8Q_u$ (i.e., 20% strength degradation). The displacement ductility ($\mu_{\Delta 0.8Qu}$) of the RMSW+BEs was calculated based on the ratio between the lateral displacement at 20% strength degradation ($\Delta_{0.8Qu}$) and the lateral yield displacement (Δ_y).

Effect of The Wall Aspect Ratio

The aspect ratio of the walls greatly affected the ultimate capacity (Q_u) of the RMSW+BEs, which decreased significantly when the aspect ratio increased, as can be seen from the difference between Figures 4(a) and 4(b). For walls with a square MBE, the ultimate capacity (Q_u) of wall W2 decreased by 55% when the aspect ratio increased from 1.66 to 4.16 compared to wall W1. For walls with a rectangular MBE R1, Q_u of wall W4 decreased by 55% as the aspect ratio surged from 1.66 to 4.16 compared to wall W3. Also, increasing the aspect ratio from 1.66 to 4.16 yielded a decrease of 57% in Q_u of wall W6 compared to their wall W5 counterpart. Increasing the aspect ratio of the RMSW+BEs resulted in a significant drop in their displacement ductility. For walls with square MBE, increasing the aspect ratio from 1.66 to 4.16 resulted in a decrease of 52% in the displacement ductility ($\mu_{\Delta 0.8Qu}$) for wall W2, when compared to wall W1. Similar results were observed for walls W4 and W6 when compared to W3 and W5, respectively. It is worth noting that the displacement ductility of the walls with higher aspect ratios significantly dropped due to attaining the 20% strength degradation rapid than the walls with lesser aspect ratios.

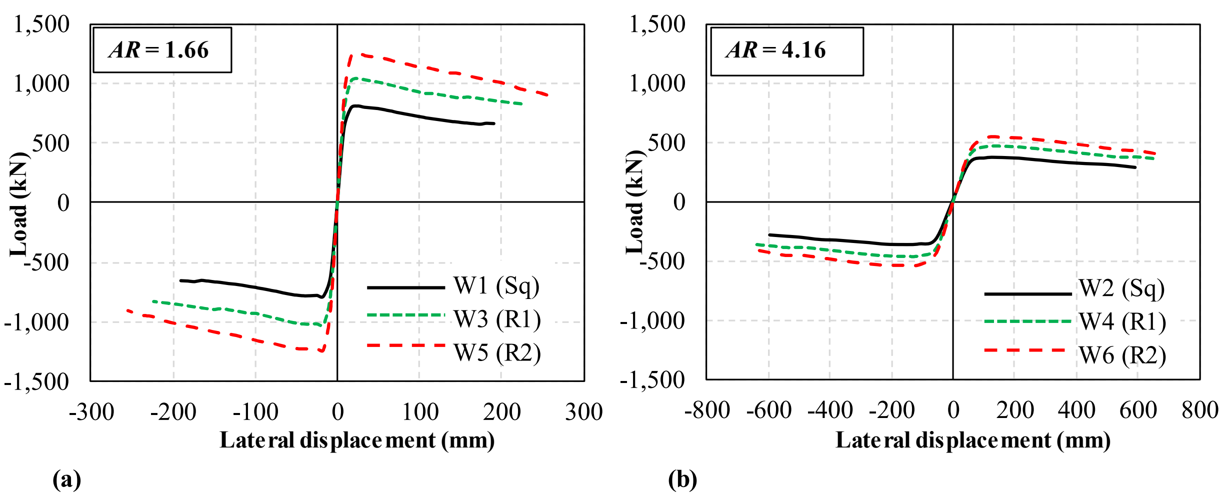


Figure 4: Load-displacement envelopes for RMSWs (a) *AR* = 1.66; and (b) *AR* = 4.16

Effect of The Wall's Masonry Boundary Element Configuration

Figure 4(a and b) show the lateral load-displacement envelopes for RMSW+BEs W1 to W6 having three different boundary elements configurations, namely, square, rectangular R1, and rectangular R2. Figure 4(a) shows a comparison of the lateral load-displacement envelopes of W1, W3, and W5, whereas Figure 4(b) depicts the load-desplacments curves of those with higher aspect ratio (AR = 4.16). As shown in Figure 4(a), increasing the MBE size resulted in a significant increase in the ultimate capacity (Q_u) of the RMSW+BEs. For walls with an aspect ratio (AR) of 1.66, Q_u increased by 29% and 55% for walls W3 and W5, respectively, when the MBE size increased to rectangular R1 and R2 compared to their square MBE wall W1. Also, for walls with AR = 4.16, Q_u of walls W4 and W6 improved by 24% and 47% as the MBE section increased to rectangular R1 and R2, respectively, when compared to that of the wall W2. Increasing the MBE size in RMSW+BEs resulted in an enhancement in their respective displacement ductility ($\mu_{\Delta 0.8Qu}$). For walls with AR = 1.66, increasing the MBE size to rectangular R1 and R2 for W3 and W5 enhanced $\mu_{\Delta 0.8Qu}$ by 24% and 14%, respectively, when compared to wall W1. On the other hand, increasing the MBE size for walls with AR = 4.16 had no substantial influence on their displacement ductility.

Sensitivity of The Wall's Lateral Yield Capacity (Q_y) to The Design Parameters

Figure 5 shows the tornado charts that illustrate the sensitivity of the RMSW+BEs yield strength (Q_y) to the design parameters with different walls' aspect ratios and MBE sizes. As indicated in Figure 5, the vertical reinforcement ratio of the boundary element (ρ_{vBE}) is the most influential parameter affecting Q_y, whereas the masonry compressive strain at peak stress (ε_{mu}) has no substantial influence on Q_y. Also, Q_y was more sensitive to the change of ρ_{vBE} for walls with a lower aspect ratio AR = 1.66, as shown in Figures 5(a and b).

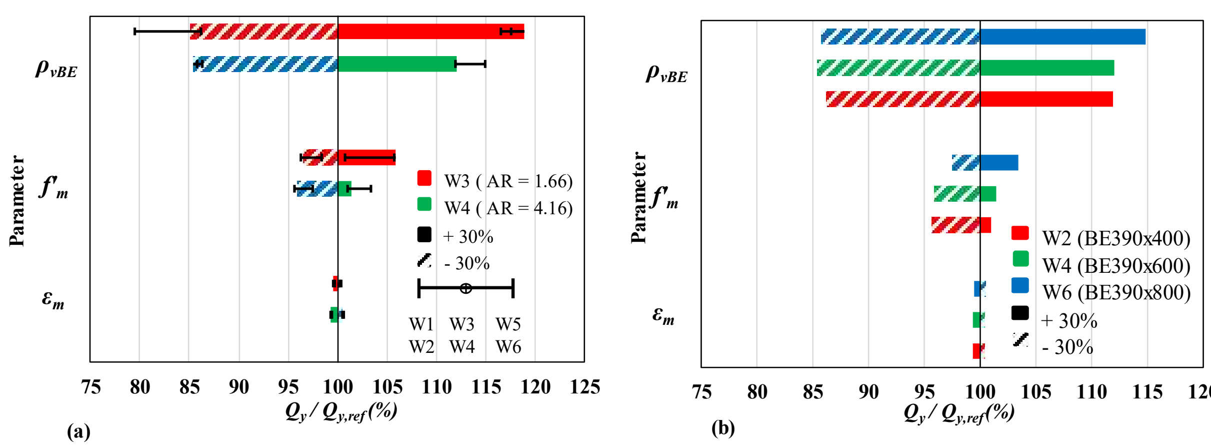


Figure 5: Sensitivity of the lateral yield capacity (Q_y) to ±30% changing of ε_{mu}, f'_m, and ρ_{vBE} for RMSW+BEs having different (a) aspect ratios; and (b) BE sizes

The ±30% change in ρ_{vBE} resulted in nearly ±20% change in Q_y for walls with AR = 1.66, respectively. This change declined to almost ±15% for walls with AR = 4.16. It can be inferred that there is a directly proportional relationship between ρ_{vBE} and Q_y which can be attributed to the increase/decrease of the yield moment capacity of the walls as the reinforcement ratio increases/decreases, respectively.

Sensitivity of The Wall's Lateral Ultimate Capacity (Q_u) to The Design Parameters

Figures 6 (a and b) show the tornado charts depicting each of the design parameters' influence on the lateral ultimate capacity (Q_u) of the RMSW+BEs. It is observed that the change of the boundary element vertical reinforcement ratio (ρ_{vBE}) is the most influencing parameter on Q_u. A change of ±30% in ρ_{vBE} yielded a direct change of nearly ±20% in Q_u. Besides, it was found that the masonry compressive strength (f'_m) and the masonry compressive strain (ε_{mu}) had a negligible effect on Q_u. Like the yield strength (Q_y) of the RMSW+BEs, Q_u was more sensitive for walls with aspect ratio AR = 1.66 compared to those with higher aspect ratios AR = 4.16. Furthermore, Q_u was more sensitive for walls with greater MBE size (i.e., rectangular R2) than those with smaller MBE sizes, as illustrated in Figure 6(b).

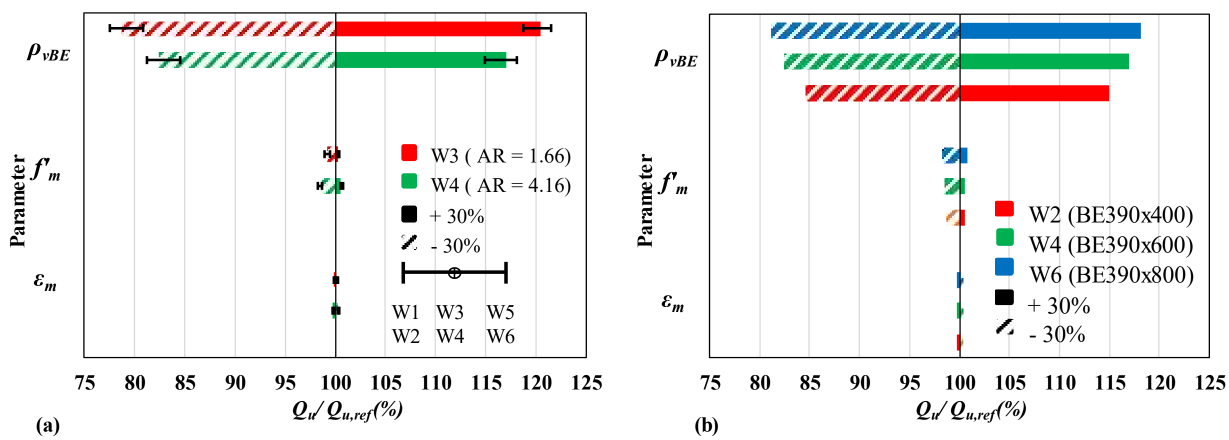


Figure 6: Sensitivity of the lateral ultimate capacity (Q_u) to ±30% changing of ε_{mu}, f'_m, and $\rho_{v\,BE}$ for RMSW+BEs having different (a) aspect ratios; and (b) BE sizes

Sensitivity of The Wall's Displacement Ductility ($\mu_{\Delta 0.8Qu}$) to The Design Parameters

Figure 7 shows that, in general, the displacement ductility, $\mu_{\Delta 0.8Qu}$, was extremely sensitive to the change of ε_{mu}. Besides, $\mu_{\Delta 0.8Qu}$ was intensively sensitive to the 30% reduction in ε_{mu} rather than their 30% increase. Figures 7(a and b) shows that a reduction of 30% in the masonry compressive strain (ε_{mu}) resulted in a tremendous drop of nearly 60% in $\mu_{\Delta 0.8Qu}$ for all the studied walls. On the contrary, $\mu_{\Delta 0.8Qu}$ experienced an improvement of just 10~15% as ε_{mu} increased by 30%. It is worth noting that $\mu_{\Delta 0.8Qu}$ was higher sensitive for walls with aspect ratio AR = 1.66 compared to those with higher aspect ratios: AR = 4.16. It is also noticeable that the 30% reduction of f'_m had a significant effect of around 15-20% on $\mu_{\Delta 0.8Qu}$, whereas the change of ρ_{vBE} had an effect of 10% on $\mu_{\Delta 0.8Qu}$. The directly proportional relationship of the masonry compressive strain at peak stress (ε_{mu}) with the displacement ductility ($\mu_{\Delta 0.8Qu}$) can be attributed to the former's critical effect on the displacement ductility. The reduction in the masonry strain at peak stress (ε_{mu}) greatly reduces the ultimate curvature of the RMSW+BE, which in turn lowers its curvature ductility and displacement ductilities.

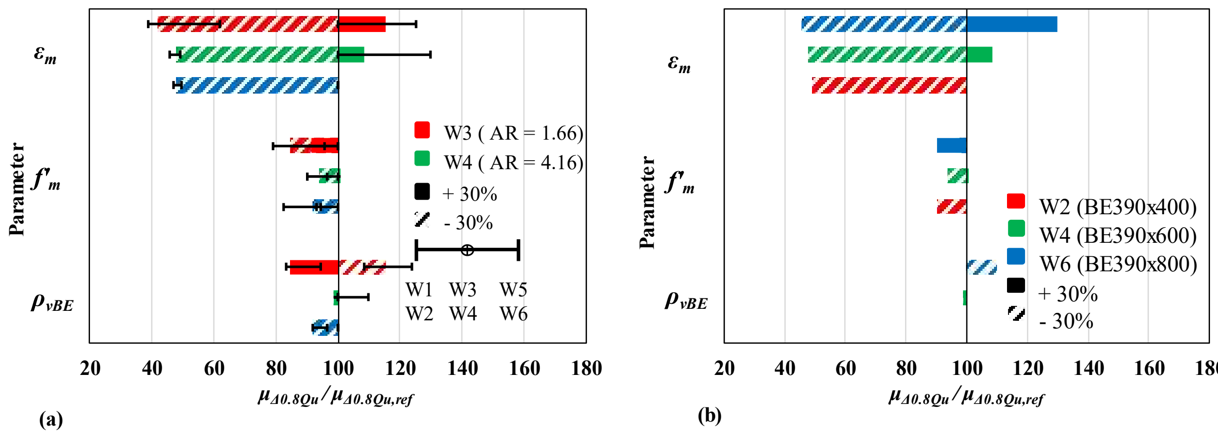


Figure 7: Sensitivity of the displacement ductility ($\mu_{\Delta 0.8Qu}$) to ±30% changing of ε_{mu}, f'_m, and $\rho_{v\,BE}$ for RMSW+BEs having different (a) aspect ratios; and (b) BE sizes

CONCLUSIONS

A sensitivity analysis was performed to quantify the influence of three design parameters, namely, the masonry compressive strain at peak stress (ε_{mu}), the masonry compressive strength (f'_m), and the vertical reinforcement ratio of the boundary elements (ρ_{vBE}) on the seismic response components of the RMSW+BEs. This study also investigated the influence of two wall configurations, namely, the aspect ratio and the boundary element size on the seismic performance of RMSW+BEs. The results showed that increasing the wall aspect ratio from 1.66 to 4.16 signifcantly decreased the lateral ultimate capacity (Q_u) and the displacement ductility ($\mu_{\Delta 0.8Qu}$) of the RMSW+BEs with different wall configurations. As the masonry boundary element (MBE) size increased, both the lateral ultimate capacity (Q_u) and the displacement ductility ($\mu_{\Delta 0.8Qu}$) increased. The lateral yield capacity (Q_y) of the RMSW+BEs was susceptible to changing the boundary elements' vertical reinforcement ratio (ρ_{vBE}). However, the influence of the masonry compressive strength (f'_m), and the masonry compressive strain at peak stress (ε_{mu}) had an insignificant effect on Q_y. Changing the vertical reinforcement ratio (ρ_{vBE}) by ±30% was found to significantly affect the lateral ultimate capacity (Q_u) of the RMSW+BEs. The masonry compressive strength (f'_m) was found to have a more significant influence on Q_u compared to the effect of ε_{mu}. Decreasing the masonry compressive strain at peak stress (ε_{mu}) by 30% had a detrimental effect on the displacement ductility ($\mu_{\Delta 0.8Qu}$) of the RMSW+BEs compared to is 30% increase. Moreover, $\mu_{\Delta 0.8Qu}$ was found to be extensively affected by the reduction of ε_{mu} and f'_m, respectively. On the contrary, the change of ρ_{vBE} had a marginal effect on $\mu_{\Delta 0.8Qu}$.

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