

Stress-strain model for C-shape confined concrete masonry boundary elements of RM shear walls

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ABSTRACT

Reinforced masonry (RM) shear walls with boundary elements have been recently presented as a more ductile alternative to RM rectangular shear walls. Evaluating the complete (i.e. including the post-peak branch) compression stress-strain behavior of the confined and unconfined masonry is essential for predicting the seismic response of the RM walls with boundary elements. Recently, the authors investigated the effect of various volumetric ratios of transverse reinforcement, vertical reinforcement ratios, and grout strength on the axial stress-strain behavior of reinforced masonry boundary elements (RMBEs). However, all the specimens had a specific height to thickness ratio (i.e., $AR = 5$). This study presents the observed stress-strain relationship of seventeen half-scale fully grouted unreinforced and RMBE specimens, built using C-shape blocks, tested under concentric compression loading up to failure. Thus, quantifying the effect of various aspect (height to thickness) and confinement ratios on the RMBEs peak stress, strain corresponding to peak, and post-peak behavior. The results indicate that, as the hoop spacings and/or aspect ratio decreases, the peak stress and post-peak strains increase. Moreover, this study presents a stress-strain empirical model capable of predicting the RMBE stress-strain response by computing the confined and unconfined masonry stress-strain behavior. The model is calibrated using the experimental data of thirty-three RMBE specimens, tested in this study and literature. The proposed model presents an efficient tool that can be implemented in different analytical/numerical packages.

1. Introduction

Understanding the compressive stress-strain behavior of reinforced masonry boundary elements (RMBEs) is essential for predicting the lateral response of reinforced masonry (RM) shear walls with boundary elements. Limited studies, to date, focused on the confinement effect on the stress-strain response of reinforced masonry assemblages. RMBE is a kind of masonry column added towards the wall ends to increase the wall thickness in the wall's most stressed zone, subsequently allowing a reinforcement confinement cage to be added at the wall extremities and thus enhance the wall curvature ductility and lateral response (e.g., [1–4]). Unlike reinforced concrete (RC) structural elements, the cover to confined core ratio in masonry assemblage is much higher. Moreover, the cover in the reinforced masonry assemblage consists of masonry blocks, mortar and grout cover to the hoops. All these discrepancies are questioning the ability of the stress-strain models originally developed to predict the confined RC component response, to predict the stress-strain axial response of RMBE.

Adding confining hoops to the grout core of masonry prism was investigated by Shedid et al. [5]. Smith et al. [6] investigated incorporating the hoops in the block by utilizing Self-Reinforced concrete block. Other researchers focused on confining the end zone of RM walls, Sajjad [1] confined the end zone of RM wall by hoop reinforcement, confinement reinforcement Comb, and a spiral cage reinforcement. Shedid et al. [2] investigated the influence of adding flanges or boundary elements on the stability of the compression zone of the RM shear wall. Banting, and El-Dakhkhni [3] investigated the lateral cyclic response of RM walls integrated with boundary elements (BE) having different design parameters.

Abo El Ezz et al. [7] investigated the effect of hoops spacing on the axial compressive response of RMBEs built using standard concrete stretcher blocks. Unlike stretchers, C-shaped blocks allow placing the confinement hoops at any desired spacing. Thus, choosing the hoops spacing gives Engineers more control of the wall boundaries confinement level. Therefore, Obaidat et al. [8] investigated the effect of changing the confinement ratio introduced by transversal hoops on the

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axial stress-strain behavior of full-scale RMBEs built using C-shaped concrete masonry blocks. Moreover, Obaidat et al. [9] investigated the effect of changing grout strength, vertical and transversal reinforcement ratio on the axial stress-strain behavior of half-scale RMBEs built using C-shaped block.

The Canadian [10] and the American [11] material testing standards specify different height to thickness ratios, i.e. 5 and 2, respectively, in order to obtain the stress-strain relationship of masonry prisms. On the other hand, each standard presents a different correction factors to account for changing the aspect ratio. This implies that the sample aspect ratio has a direct effect on the resulting compressive stress-strain response. As such, this study investigates the effect of changing the aspect ratio (height to thickness) and confinement ratio (i.e. by changing the hoop spacing) on the compression stress-strain behavior of half-scale RMBE. Two aspect ratios will be investigated, namely, 2 and 3. Moreover, for each aspect ratio two hoops spacing will be utilized, namely, 30 and 60 mm. Also, unreinforced masonry boundary elements (BEs) with the same aspect ratios were tested. Therefore, six groups of RMBEs and masonry BEs were tested, each had at least two samples. A total of seventeen RMBE and BE specimens were tested under concentric axial loading up to failure in the structural laboratory at Concordia University. Furthermore, the experimental results will be compared to two other groups of RMBEs and one group of masonry BEs having an aspect ratio of 5 and similar hoops spacing tested by Obaidat et al. [9]. Therefore, by investigating the RMBE aspect ratio, this experimental and analytical study complements the parameters experimentally tested by Obaidat et al. [8] (i.e. vertical reinforcement ratio, the volumetric ratio of transverse reinforcement, and grout strength).

Although unconfined masonry numerical/analytical models are available in the literature (e.g. [9,10]), limited research was conducted for establishing the complete stress-strain relationship for confined masonry members. Priestley and Elder [11] proposed an analytical model capable of predicting the compression behavior of unconfined and confined masonry prisms. However, Priestley and Elder [11] model was conducted using standard blocks considering Priestly and Bridgeman [12] 3 mm confining steel plate. Abo El Ezz et al. [7] proposed a simplified stress-strain model for fully grouted unconfined and confined reinforced masonry boundary element built using standard concrete blocks. However, this model predicts the compression stress-strain curve of RMBE over the whole cross section smearing the transversal and the vertical reinforcement contributions. Obaidat et al. [13] investigated the ability of three existing stress-strain models ([7,11;14]) in predicting the compression stress-strain behavior of RMBEs built using C-shaped concrete blocks. It was concluded that these three models were not capable of capturing the post-peak response and the drop occurred due to the face shell spalling at the RMBE peak stress. Moreover, the available models were insensitive to the changing of aspect ratio and highly overestimated the enhancement in the RMBE peak stress and corresponding strain [13].

Based on the experimental data presented in this study and the data reported by Obaidat et al. [13] a stress-strain empirical model is developed. The proposed model was calibrated to best fit the experimental results of a total of thirty-three RMBEs using polynomial and linear regression techniques. This model aims at bridging the existing gap of computing the effect of different design parameters on the compressive stress-strain behavior of RMBEs.

2. Experimental program

2.1. Test matrix

Table 1 presents the nine test groups considered in this study, where each group consisted of at least two samples. A total of seventeen RMBEs having a various aspect (i.e. height to thickness) and confinement ratios and nine unreinforced BE were tested under concentric

axial compressive loading up to failure. It should be noted that all groups having an aspect ratio equal to 5 were tested earlier by Obaidat et al. [13]. For each group, the specimens were labeled with four terms of letters and numbers, e.g. BE-D4/60-AR2-A. The first term, BE, represents a boundary element. The second term (i.e. D4/60) is used to describe the transversal reinforcement size and spacing in mm. The third term (i.e. AR2) represent the sample's aspect ratio (i.e. height to thickness = 2 in this group). The letters A, B, or C follow the group name to identify the sample within each group. It should be noted that the confinement ratio, C_f , is calculated according to Eq. (1) and presented in Table 1.

$$C_f = \rho_l \sqrt{H/S_h} \quad (1)$$

where ρ_l is the volumetric ratio of the confinement reinforcement (i.e., the volume of confinement hoops to the volume of core concrete at spacing, S_h), H is the width of the confined core, and S_h is the spacing between the confinement hoops.

All samples were grouted with normal strength grout (i.e. 15 MPa). As shown in Table 1, the first three groups represented unreinforced BEs having aspect ratios of 2, 3 and 5. These three groups were tested to compare their stress-strain behavior with the corresponding RMBEs, and thus to quantify the vertical and transversal reinforcement influence on the RMBE stress-strain behavior. All the RMBE reinforced specimens had four vertical reinforcement #3 bars (71 mm²). The vertical bars were placed in each corner and confined with transverse reinforcement (i.e., hoops) of deformed D4 wires (25.8 mm²) having two different hoop's spacing of 60 or 30 mm. Groups 4 and 7 had the same aspect ratio of 2 and were confined with D4/60 mm and D4/30 mm hoops, respectively. Similarly, the remaining groups (5 and 8; 6 and 9) had aspect ratios of 3 and 5 and confined with D4/60 mm and D4/30 mm hoops, respectively. Therefore, this test matrix was designed to investigate the effect of different confinement levels and aspect ratios on the RMBE's compressive stress-strain behavior.

2.2. Construction of RMBEs

The construction of the RMBE specimens was performed by experienced masons following the Canadian construction practices. Half-scale concrete C-shaped blocks were used in all samples. Fig. 1(a–e) illustrates the RMBEs construction sequence. First, the rebars were cut and bent, then the reinforcement cage for each RMBE specimen was assembled. The cage consisted of four #3 (71 mm²) reinforcement bars, and deformed wire (D4) hoops tied at a particular spacing (30 or 60 mm). All hoops were anchored with 135° bends extending 55 mm into the grout's core. The reinforcement cage of each RMBE specimen was placed in a preassembled formwork to pour the bottom reinforced concrete footing with dimensions of 200 mm × 200 mm × 250 mm (length × width × height). However, the unreinforced BE specimens were placed on solid templates to provide equal elevation, and they did not have a top or a bottom footing. It should be noted that the hoops' size was increased to #4 (129 mm²) with 40 mm spacing to avoid any local failure in the bottom and top footing. The vertical reinforcement bars were continuous along the height of the RMBE specimen. There were no splices from the base of the bottom footing to the top footing. High strength concrete was poured in the wooden formwork; then the samples were permitted, approximately, one week to cure. Before laying the C-shaped concrete blocks, four strain gages were mounted on the mid height of the vertical reinforcing steel bars to track the axial strain on the vertical bars. A stacked bond pattern was utilized for each RMBE specimen. Each course had two C-block units placed face to face. The stacked bond pattern represented the layout envisioned for RMSW with boundary elements. All RMBE and unreinforced specimens had cross-sectional dimensions of 190 mm × 190 mm (length × width). Samples were assembled in four, six, and ten courses high for samples having aspect ratios of 2, 3, and 5, respectively. The RMBE specimens

Table 1
RMBE test specimen details.

Group #	RMBE ID	Number of tested specimens	Grout Strength (MPa)	Longitudinal Reinforcement		Transverse Reinforcement		Confinement ratio C_f
				Number-size of Bars	$\rho_l\%$	Bar size (spacing mm)	$\rho_t\%$	
1	BE-0-AR2	2	15	–	–	–	–	–
2	BE-0-AR3	3	15	–	–	–	–	–
3	BE-0-AR5*	4	15	–	–	–	–	–
4	BE-D4/60-AR2	3	15	4 – #3	0.79	D4 (60)	1.57	0.022
5	BE-D4/60-AR3	3	15	4 – #3	0.79	D4 (60)	1.57	0.022
6	BE-D4/60-AR5*	3	15	4 – #3	0.79	D4 (60)	1.57	0.022
7	BE-D4/30-AR2	3	15	4 – #3	0.79	D4 (30)	3.15	0.062
8	BE-D4/30-AR3	3	15	4 – #3	0.79	D4 (30)	3.15	0.062
9	BE-D4/30-AR5*	3	15	4 – #3	0.79	D4 (30)	3.15	0.062

* Tested by Obaidat et al. [6].

were strapped before grouting to avoid any cracks in the mortar head joints. Finally, once the masonry process was complete, a top footing, similar to the bottom one, was poured and left to cure in a preassembled formwork.

2.3. Material properties

RMBE's bottom and top footings were constructed using high strength concrete to eliminate any local failure and to ensure that failure occurs

within the test region. Table 2 summarizes the materials' compressive strength used for the construction of the RMBEs. The footings' strength was 83.8 MPa with a coefficient of variation (C.V.) of 6.2%. These results were based on the testing of twelve concrete cylinders. All RMBE specimens were constructed with C-shape half-scale concrete block units. Their nominal dimensions were 25 mm × 190 mm × 92.5 mm × 90 mm (thickness × length × width × height). According to the ASTM C140/C140M [15], fourteen coupons of half-scale concrete masonry blocks (100 mm × 50 mm × 25 mm) were tested under compressive loading.

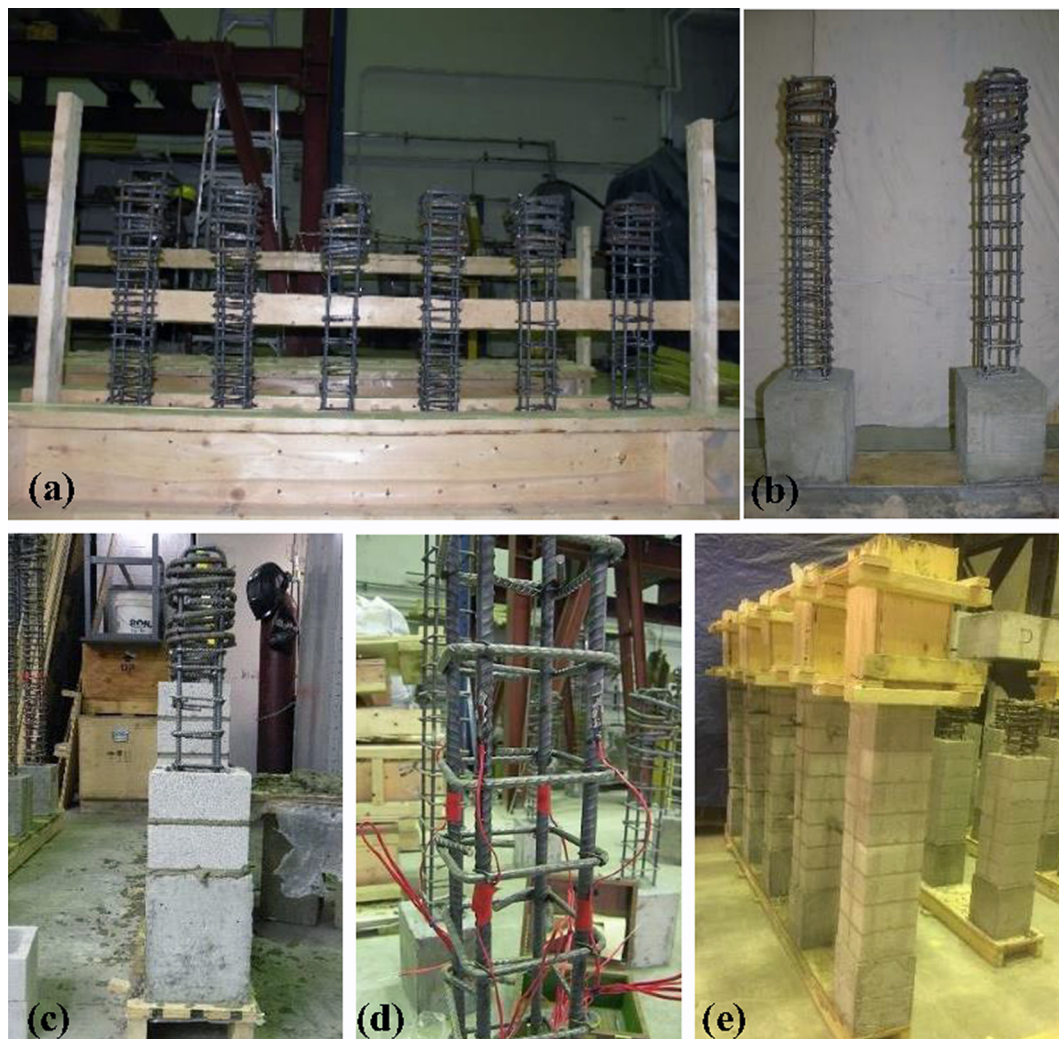


Fig. 1. Construction sequence of RMBEs.

Table 2
Materials properties.

Material	Notation	Average compressive strength (MPa)	C.V. (%)
Concrete cylinder (footings)	f_c	83.8	6.20
Masonry concrete block	f_b	22.0	13.8
Mortar cubes	f_{mc}	12.3	7.15
Grout cylinders	f_g	15.0	8.70

C.V.: coefficient of variation.

The average compressive strength, of the 14 tested coupons, was 22 MPa (C.V. = 13.8%). The C-shaped block units were joined in a stacked bond with an approximate thickness of 5 mm mortar joints (i.e., to meet the scaling requirements). Pre-bagged type S mortar was used for each specimen tested. From each batch, three 50 mm × 50 mm × 50 mm cubes were molded and cured. A total of fifteen mortar cubes were tested under compression. The average compressive strength of the mortar cubes was 12.3 MPa (C.V. = 7.15%). Fine grout was used for the construction of all specimens. The pre-mixed fine grout air treated in cylinders had an average compressive strength of 15 MPa (C.V. = 8.7%) tested according to CSA A179 [16].

Standard deformed reinforcement steel bars, sizes #3 and #4, were used for the vertical reinforcement and footing transversal reinforcement, respectively. On the other hand, deformed wire, D4, was utilized for the hoops. Average tensile yield strength of #3 and #4 was 455 MPa and 482 MPa, respectively. A clear yield region did not exist for the steel deformed wire (D4). Therefore, the proof yield strength corresponding to a 0.2% strain for D4 tested samples was 600 MPa.

2.4. Test setup and instrumentation

All RMBE specimens were tested under compressive concentric loading until failure. The test setup is illustrated in (Fig. 2). The compressive concentric loading was applied by a newly upgraded 3000 kN servo-controlled actuator operated at a constant displacement rate (i.e., 0.003 mm/sec). Using a displacement control loading enables the capturing of the post-peak stress-strain curve branch. This is essential to quantify the influence of the studied parameters on the behavior of the RMBE's post-peak behavior. The termination of the tests occurred when the specimens reach approximately 25% of its ultimate load (75%

strength degradation).

Two 50 mm thick rectangular steel plates and a spherical steel head were placed between the specimen and the actuator head. To ensure that the specimen's extreme ends remained parallel to one another and that the loads would be distributed uniformly, two layers of high strength plaster were added between the specimen's top and bottom surfaces and the steel plates. Fig. 2 displays typical dimensions of the RMBE specimens with different aspect ratios. The total height of the tested specimen having four courses (AR = 2), six courses (AR = 3), and ten courses (AR = 5) was 880, 1070, and 1455 mm, respectively, with an effective (gage) length of 380, 570, and 955 mm, respectively. The effective gage length was measured from the lower edge of the top footing to the upper edge of the bottom footing. In all RMBE specimens, four Linear Variable Differential Transducers LVDTs were used to measure the axial strain over the tested region.

3. Experimental results and discussion

Fig. 3 presents the compression stress-strain curves for all RMBE specimens. It should be noted that the stress was computed by dividing the reported load by the RMBE's cross-sectional area (190 mm × 190 mm). Also, the strain was calculated by dividing the average of the four LVDTs readings by the corresponding effective gage length. It can be noticed that the compressive stress-strain curve of confined RMBEs consists of three branches: rising curve up to the peak load, followed by a sudden drop, and gradually descending curve. However, the stress-strain curve of the unreinforced specimens has two branches: rising curve up to the peak load and descending post-peak curve. The sudden drop in the RMBE's stress was mainly attributed to the face-shell spalling of the concrete block, which resulted in a

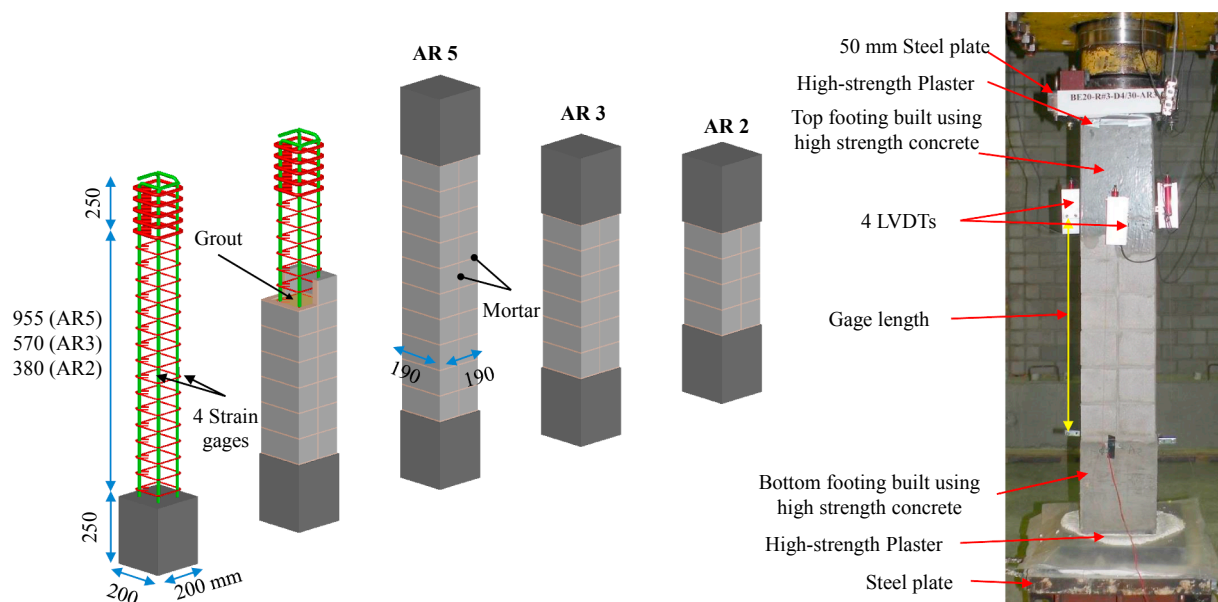


Fig. 2. Schematic of the test set-up, RMBE components, and instrumentations.

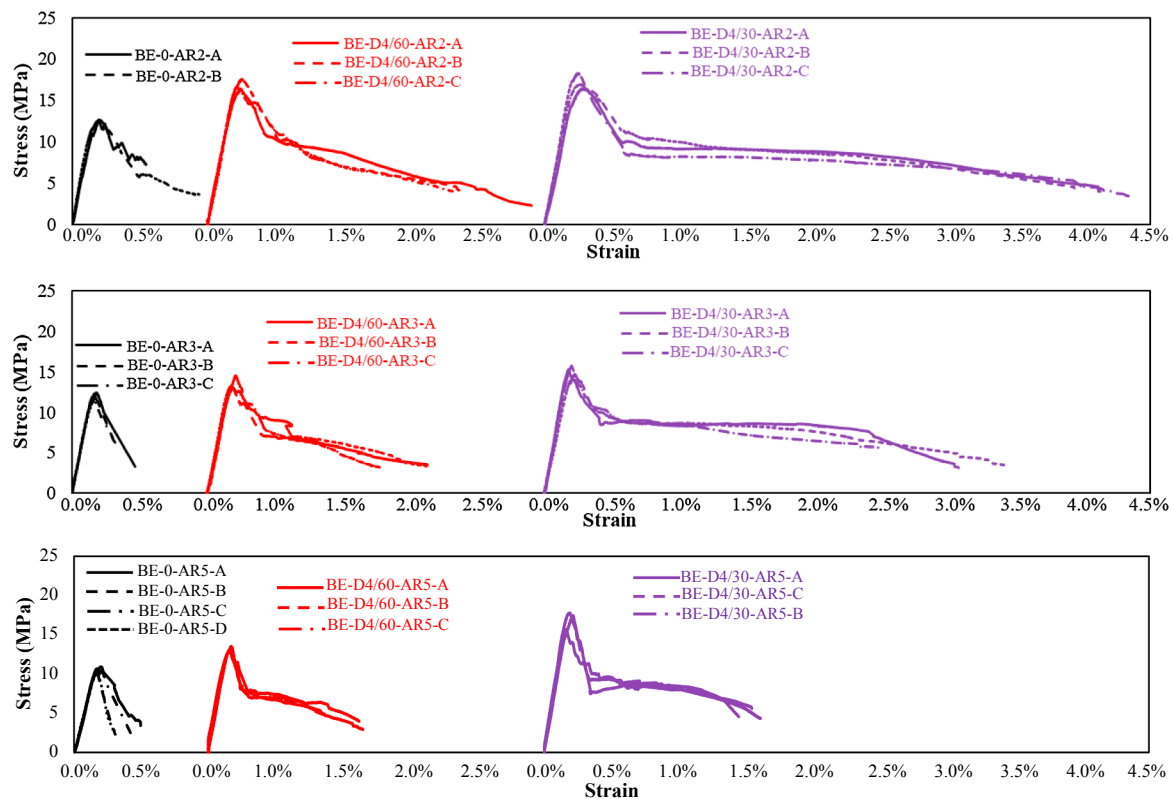


Fig. 3. Observed compression stress-strain curves for RMBE specimens having different height to thickness and confinement ratios.

40–50% loss of the RMBE strength, where the RMBE lost at least 55% of the cross-sectional area. Table 3 presents the experimental results of the peak stress (f_{max}), strain at the peak stress (ϵ_{max}), strain at 75% of the peak stress (ϵ_{75}), strain at 50% of the peak stress (ϵ_{50}), and strain

ductility ($\mu_{50\%}$) of the RMBE. The strain ductility is defined as the ratio between the strain at 50% of the peak stress on the descending curve (ϵ_{50}) and the strain at the peak stress (ϵ_{max}).

Table 3
Experimental results of the RMBEs.

RMBE ID	Maximum stress (MPa)		Strain at peak stress		Strain at 75% of the peak stress, ϵ_{75}		Strain at 50% of the peak stress, ϵ_{50}		Strain ductility, $\mu_{50\%}$
	f_{max}	Average (C.V. %)	ϵ_{max}	Average (C.V. %)	ϵ_{75}	Average (C.V. %)	ϵ_{50}	Average (C.V. %)	
BE-0-AR2-A	12.62	12.64	0.00209	0.002045	0.0034	0.0032	0.0047	0.0049	2.37
BE-0-AR2-B	12.65	(0.17%)	0.00200	(3.11%)	0.0030	(9.25%)	0.0050	(4.37%)	
BE-0-AR3-A	12.41	11.91	0.00180	0.001757	0.0026	0.0025	0.0037	0.0034	
BE-0-AR3-B	11.88	(4.16%)	0.00175	(2.30%)	0.0025	(3.03%)	0.0032	(7.33%)	1.95
BE-0-AR3-C	11.42		0.00172		0.0025		0.0034		
BE-0-AR5-A*	10.88	10.55	0.00195	0.00180	0.0022	0.0021	0.0037	0.0030	1.62
BE-0-AR5-B*	10.26	(2.77%)	0.00171	(7.91%)	0.0023	(4.30%)	0.0027	(19.05%)	
BE-0-AR5-C*	10.35		0.00200		0.0023		0.0032		
BE-0-AR5-D*	10.70		0.00174		0.0021		0.0024		3.31
BE-D4/60-AR2-A	16.39	16.88	0.00250	0.002367	0.0039	0.0042	0.0090	0.0078	
BE-D4/60-AR2-B	17.62	(3.86%)	0.00240	(6.45%)	0.0042	(7.65%)	0.0072	(12.91%)	
BE-D4/60-AR2-C	16.63		0.00220		0.0045		0.0073		3.50
BE-D4/60-AR3-A	13.00	13.65	0.00210	0.00210	0.0038	0.0035	0.0075	0.0074	
BE-D4/60-AR3-B	13.36	(6.15%)	0.00200	(4.76%)	0.0032	(8.07%)	0.0080	(10.41%)	
BE-D4/60-AR3-C	14.60		0.00220		0.0034		0.0065		3.77
BE-D4/60-AR5-A*	13.08	13.2	0.00156	0.00162	0.0022	0.0023	0.0066	0.0061	
BE-D4/60-AR5-B*	13.00	(2.12%)	0.00160	(4.45%)	0.0025	(6.55%)	0.0057	(7.51%)	
BE-D4/60-AR5-C*	13.52		0.00170		0.0023		0.0060		7.61
BE-D4/30-AR2-A	16.45	17.25	0.00260	0.002587	0.0044	0.0041	0.0220	0.0197	
BE-D4/30-AR2-B	18.30	(5.53%)	0.00240	(6.97%)	0.0040	(6.45%)	0.0200	(12.80%)	
BE-D4/30-AR2-C	16.98		0.00276		0.0039		0.0170		8.09
BE-D4/30-AR3-A	15.28	15.25	0.00220	0.002267	0.0035	0.0034	0.0180	0.0184	
BE-D4/30-AR3-B	14.70	(3.45%)	0.00230	(2.55%)	0.0034	(2.94%)	0.0200	(8.33%)	
BE-D4/30-AR3-C	15.75		0.00230		0.0033		0.0170		4.50
BE-D4/30-AR5-A*	17.78	16.97	0.00195	0.0020	0.0029	0.0028	0.0080	0.0090	
BE-D4/30-AR5-B*	15.70	(6.57%)	0.00190	(6.61%)	0.0027	(3.57%)	0.0100	(11.11%)	
BE-D4/30-AR5-C*	17.44		0.00215		0.0028		0.0090		

* Tested by Obaidat et al. [6].

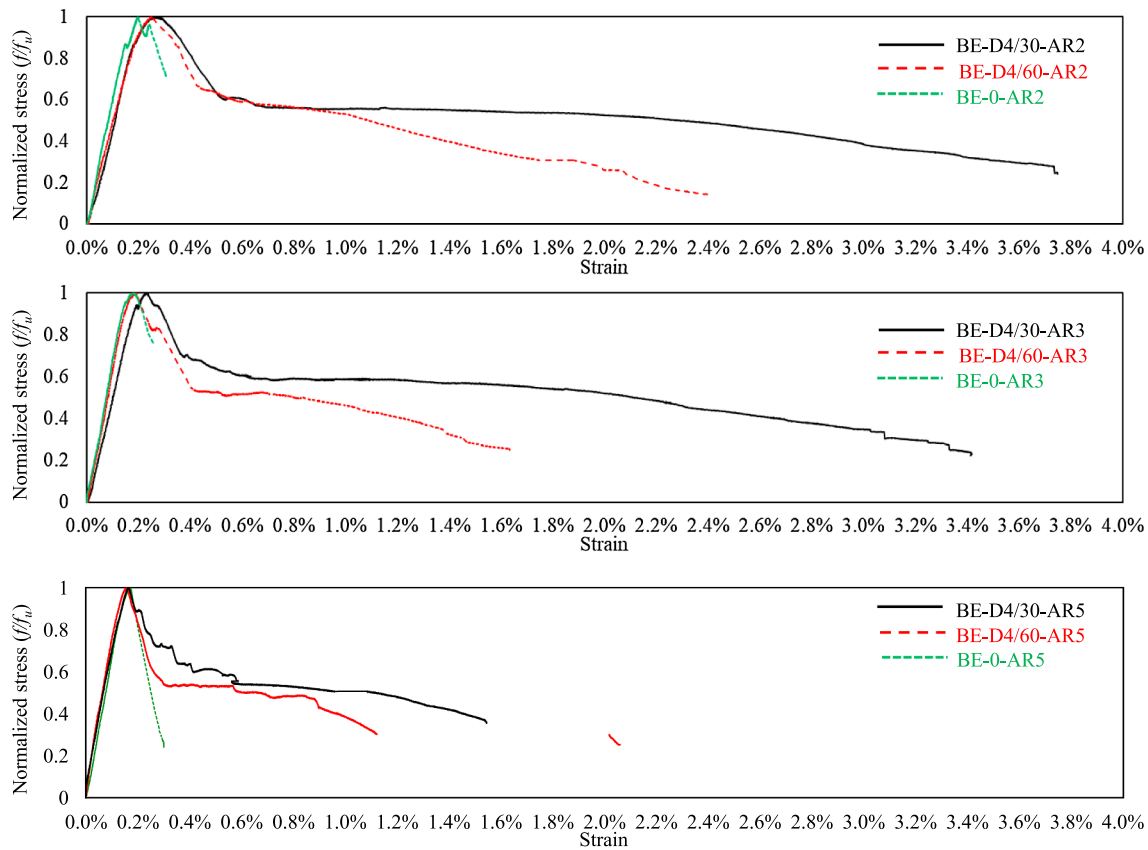


Fig. 4. Normalized compression stress-strain curves of RMBE having different confinement ratios.

3.1. Effect of changing aspect ratio (height to thickness) on the stress-strain response of RMBEs

The compressive stress-strain curves of three specimens, in three different groups having the same aspect ratio 2, 3, and 5, with various confinement ratios of transverse reinforcement ratios, can be seen in Fig. 3. It should be noted that the effect of the aspect ratio on the initial stiffness of the RMBE specimen was minimal. Fig. 3 shows that as the aspect ratio decreases, the peak stress increases. However, this was not the case for RMBEs having the highest confinement ratio (i.e., 30 mm hoops spacing). As such, as the aspect ratio decreased the confinement effect introduced by the specimen's capping resulted in increasing the RMBE peak stress. However, this confinement effect could be minimized in the RMBEs having the highest ratio of transversal reinforcement (i.e. RMBE become well confined). On average, as the aspect ratio decreased from 5 to 2, the strain corresponds to the peak strength increased by 14%, 46%, and 29% for unreinforced BEs, RMBEs having 60 and 30 mm hoops spacing, respectively.

Fig. 4 presents the RMBEs stress-strain results each normalized to its maximum stress in order to visualize the effect of the different parameters on the RMBEs post-peak response and ductility. As shown in Fig. 4, as the aspect ratio decreases the RMBEs developed a more gradual post-peak stress degradation. On average, as the aspect ratio decreased from 5 to 2, the strain corresponds to the peak strength increased by 14%, 46%, and 29% for unreinforced BEs, RMBEs having 60 and 30 mm hoops spacing, respectively. Moreover, the strain ductility (i.e. ratio of the strain at 50% of peak stress to strain at peak stress) increased as the aspect ratio decreased from 5 to 2 by 46%, and 69% for unreinforced BEs, RMBEs having 30 mm hoops spacing, respectively. However, the last observation was not the consensus of all, where for RMBEs having 60 mm hoops spacing as the aspect ratio decreased from 5 to 2 the displacement ductility decreased by 12%.

3.2. Effect of confinement ratio on the stress-strain response of RMBEs

Fig. 3 shows that, as the confinement ratio of transverse reinforcement increases, the peak stress increases. The increase in peak stress is more noticeable in the RMBE specimens having an aspect ratio of 5. On average, as the confinement ratio of transverse reinforcement increased from 0.022 (i.e. 60 mm hoops spacing) to 0.062 (i.e. 30 mm hoops spacing), the peak stress increased by 2%, 12%, and 29% for RMBEs with AR of 2, 3 and 5, respectively.

The RMBEs developed more gradual post-peak stress degradation as the confinement ratio of transverse reinforcement increases (Fig. 4). On average, as the confinement ratio of transverse reinforcement increased from 0.022 to 0.062, the strain corresponds to the peak stress, ϵ_{max} , increased by 9%, 8%, and 23% for RMBEs with AR of 2, 3 and 5, respectively. Moreover, the strain ductility, $\mu_{50\%}$, increased by 130%, 131%, and 19%, as the confinement ratio of transverse reinforcement increased from 0.022 to 0.062, for RMBEs with AR of 2, 3 and 5, respectively.

3.3. RMBEs damage propagation

Fig. 5 shows the typical failure modes of the unreinforced BE and RMBE specimens with various aspect ratios. Prior to the peak strength, both unreinforced BE and RMBE specimens showed similar damage characterized by surface hair cracks. However, the unreinforced BEs failed in a brittle manner, and sudden splitting occurred at the onset of the peak stress. On the other hand, face shell spalling was observed in RMBE following the peak stress. This was followed by vertical reinforcement bars buckling outwards at high strains. It should be noted, no fracture in the transversal hoops was observed in any of the tested samples. Steel-masonry strain compatibility was observed up to the peak-stress as observed by Obaidat et al. [9]. Subsequently, vertical reinforcement bars yielding was observed following the RMBE's peak

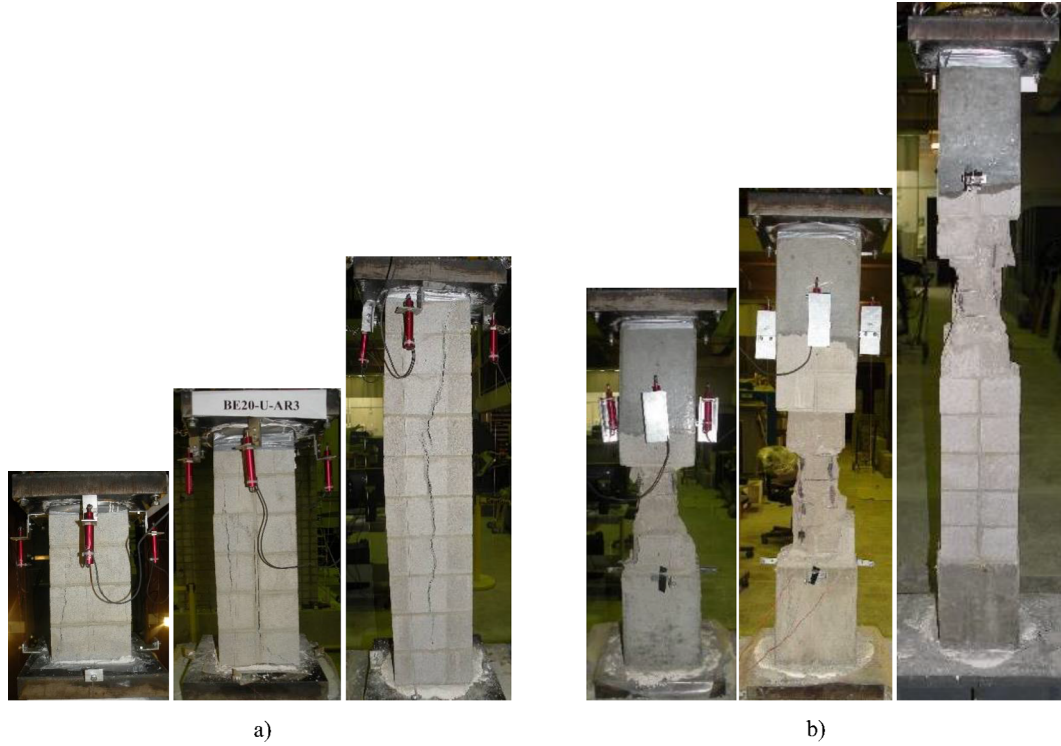


Fig. 5. Observed damage of BE specimens with various aspect ratios: (a) unreinforced BEs, and (b) RMBEs.

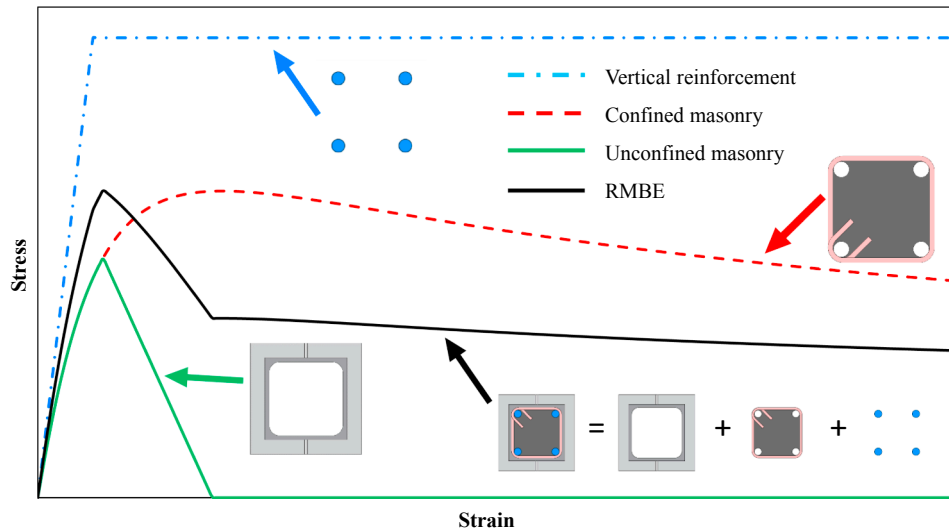


Fig. 6. Stress-strain relationship of RMBE components.

stress. Finally, failure occurred when the grout between the hoops was crushed, as seen in (Fig. 5).

4. Empirical compressive stress-strain material model for RMBEs

4.1. Model overview

Based on the experimental data of the current study and the study by Obaidat et al. [9] an empirical stress-strain relationship is proposed for the confined and unconfined masonry zones considering different grout strength, aspect ratio, vertical, and transversal reinforcement ratios. As shown in Fig. 6, at a given strain the RMBE total stress is computed by adding the stress of the unconfined masonry, confined masonry and the vertical reinforcement each weighted to its cross-

sectional area according to Eq. (2). Therefore, this model provides the flexibility of predicting the stress-strain relationship for RMBEs built using a various reinforcement bar sizes, block, and core dimension combinations.

$$f = f_{mu} \frac{A_{mu}}{A_t} + f_{mc} \frac{A_{mc}}{A_t} + f_s \frac{A_s}{A_t} \quad (2)$$

where f is the compressive stress, f_{mu} is the unconfined stress, f_{mc} is the confined stress, f_s is the vertical steel reinforcement stress, A_{mu} is the unconfined zone area, A_{mc} is the confined zone area, A_s is the vertical reinforcement steel area, and A_t is the total cross section area.

In this study, a mathematical expression similar to the one proposed by Mander et al. [16] is utilized to produce a smooth continuous curve for the compression stress-strain behavior of RMBE unconfined and confined masonry zones. This expression was calibrated with the

Table 4
RMBE specimen details used for calibrating an empirical model.

RMBE #	RMBE ID	Grout Strength (MPa)	Longitudinal Reinforcement		Transverse Reinforcement		Aspect ratio AR
			Number-size of Bars	$\rho_v\%$	Bar size (spacing mm)	$\rho_t\%$	
1	BE15-R#3-D4/60-A*	15	4 – #3	0.79	D4 (60)	1.57	5.03
2	BE15-R#3-D4/60-B*	15	4 – #3	0.79	D4 (60)	1.57	5.03
3	BE15-R#3-D4/60-C*	15	4 – #3	0.79	D4 (60)	1.57	5.03
4	BE15-R#3-D4/45-A*	15	4 – #3	0.79	D4 (45)	2.1	5.03
5	BE15-R#3-D4/45-B*	15	4 – #3	0.79	D4 (45)	2.1	5.03
6	BE15-R#3-D4/45-C*	15	4 – #3	0.79	D4 (45)	2.1	5.03
7	BE15-R#3-D4/30-A*	15	4 – #3	0.79	D4 (30)	3.15	5.03
8	BE15-R#3-D4/30-B*	15	4 – #3	0.79	D4 (30)	3.15	5.03
9	BE15-R#3-D4/30-C*	15	4 – #3	0.79	D4 (30)	3.15	5.03
10	BE15-R#4-D4/60-A*	15	4 – #4	1.40	D4 (60)	1.57	5.03
11	BE15-R#4-D4/60-C*	15	4 – #4	1.40	D4 (60)	1.57	5.03
12	BE15-R#4-D4/45-A*	15	4 – #4	1.40	D4 (45)	2.1	5.03
13	BE15-R#4-D4/45-B*	15	4 – #4	1.40	D4 (45)	2.1	5.03
14	BE15-R#4-D4/45-C*	15	4 – #4	1.40	D4 (45)	2.1	5.03
15	BE15-R#4-D4/30-A*	15	4 – #4	1.40	D4 (30)	3.15	5.03
16	BE15-R#4-D4/30-B*	15	4 – #4	1.40	D4 (30)	3.15	5.03
17	BE45-R#3-D4/60-A*	45	4 – #3	0.79	D4 (60)	1.57	5.03
18	BE45-R#3-D4/60-C*	45	4 – #3	0.79	D4 (60)	1.57	5.03
19	BE45-R#4-D4/60-A*	45	4 – #4	1.40	D4 (60)	1.57	5.03
20	BE45-R#4-D4/60-B*	45	4 – #4	1.40	D4 (60)	1.57	5.03
21	BE45-R#4-D4/60-C*	45	4 – #4	1.40	D4 (60)	1.57	5.03
22	BE-D4/60-AR2-A	15	4 – #3	0.79	D4 (60)	1.57	2.00
23	BE-D4/60-AR2-B	15	4 – #3	0.79	D4 (60)	1.57	2.00
24	BE-D4/60-AR2-C	15	4 – #3	0.79	D4 (60)	1.57	2.00
25	BE-D4/60-AR3-A	15	4 – #3	0.79	D4 (60)	1.57	3.00
26	BE-D4/60-AR3-B	15	4 – #3	0.79	D4 (60)	1.57	3.00
27	BE-D4/60-AR3-C	15	4 – #3	0.79	D4 (60)	1.57	3.00
28	BE-D4/30-AR2-A	15	4 – #3	0.79	D4 (30)	3.15	2.00
29	BE-D4/30-AR2-B	15	4 – #3	0.79	D4 (30)	3.15	2.00
30	BE-D4/30-AR2-C	15	4 – #3	0.79	D4 (30)	3.15	2.00
31	BE-D4/30-AR3-A	15	4 – #3	0.79	D4 (30)	3.15	3.00
32	BE-D4/30-AR3-B	15	4 – #3	0.79	D4 (30)	3.15	3.00
33	BE-D4/30-AR3-C	15	4 – #3	0.79	D4 (30)	3.15	3.00

* Tested by Obaidat et al. [6].

experimental results of thirty-three RMBEs having a different aspect ratio, grout strength, vertical and transversal reinforcement ratios. The specimens' details are presented in Table 4. The following sections introduce the calibration process, the computed model, and the model predictions compared to the experimental data.

4.2. Model calibration

In the first two curves in the legend of Fig. 7, the contribution of the vertical bars to the RMBE's stress-strain behavior was subtracted assuming steel-masonry strain compatibility (Obaidat et al. [13]). The load carried by the vertical reinforcement, P_s , was subtracted from the total load, P_{exp} ,

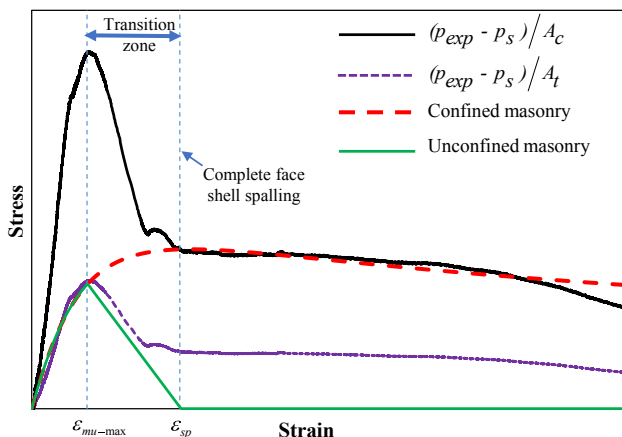


Fig. 7. Calibration of the proposed model with the experimental data.

considering an elastic-perfect plastic response. The elastic modulus and the yield stress for the two studied vertical bar sizes (i.e. #3 and #4) were measured experimentally. The resulting load ($P_{exp} - P_s$) is divided once by the total area of the RMBE, A_b , and once by only the core area, A_c , as shown in Fig. 7. As discussed earlier, the sudden stress drop was mainly attributed to the spalling of the block face shell which represent approximately 55% of RMBE specimen cross section. Hence, the applied load was resisted by the whole RMBE cross-section up to the peak stress.

Fig. 7 shows the technique used to calibrate the proposed stress-strain model to the experimental results. It is assumed that both the confined and unconfined masonry models will have the same stress up to the ultimate stress that corresponds to ϵ_{mu-max} , where the strain in the confined hoops is not high enough to confine the core as explained by Yong et al. [17]. Following the face shell spalling at strain ϵ_{sp} , the load will be totally carried by the confined core. Consequently, the transition zone between the strain corresponding to maximum stress, ϵ_{mu-max} , and the spalling strain, ϵ_{sp} , is assumed to have a linear decay in the unconfined masonry model and a smooth transition curve for the confined masonry model, as shown in the last two curves in the legend of Fig. 7. This calibration process was conducted for each RMBE and the required parameters that will be defined in the following section for the unconfined and confined models were computed for different grout strength, aspect ratio, vertical and horizontal reinforcement ratios.

4.3. Model formulation

The complete compressive stress-strain relationship of the **confined masonry** is computed using Eq. (3) that represents a mathematical expression similar to the one proposed by Mander et al. [14]. (see Fig. 8).

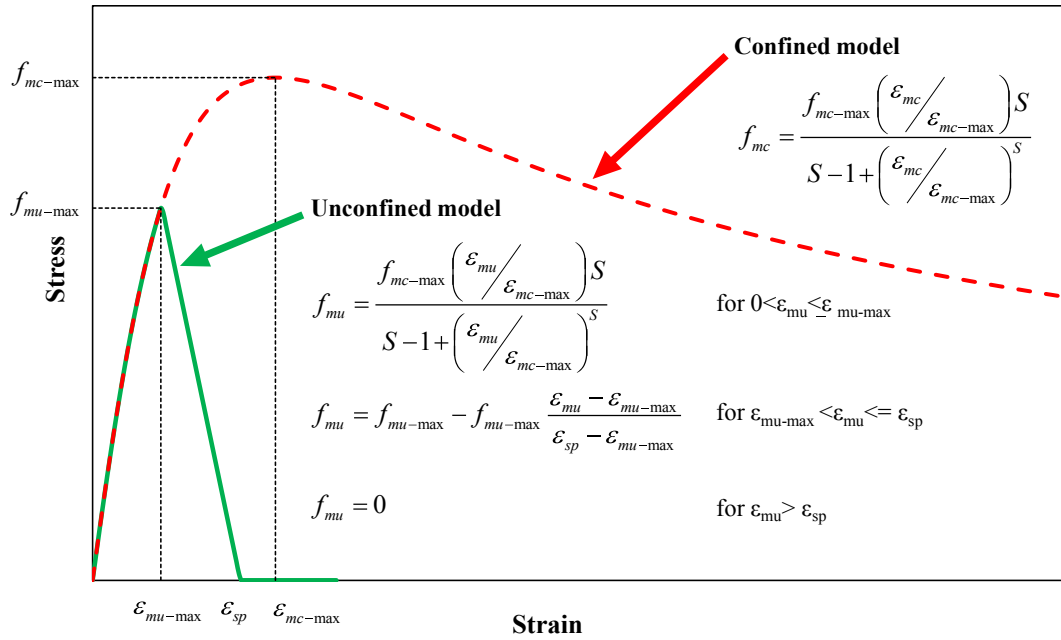


Fig. 8. Proposed empirical stress-strain model formulations.

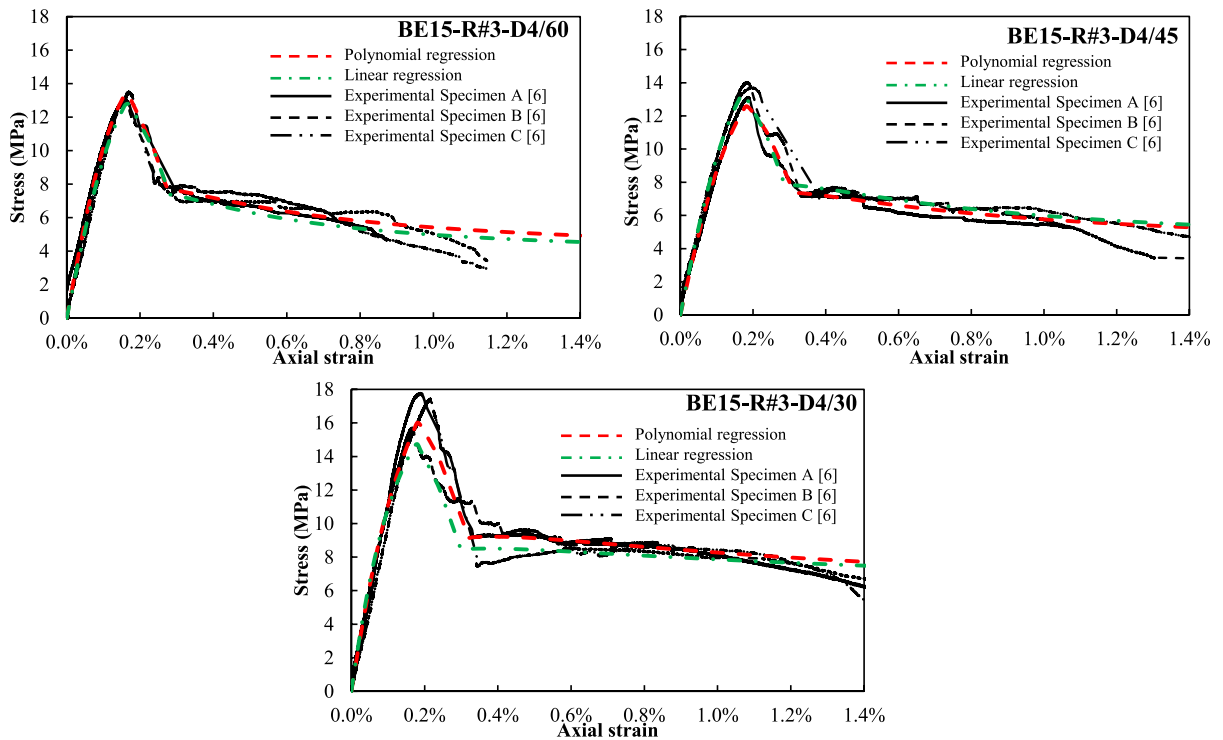


Fig. 9. Model predictions versus the experimental results for RMBE built using #3 vertical bars.

$$f_{mc} = \frac{f_{mc-max} (\epsilon_{mc}/\epsilon_{mc-max})^S}{S - 1 + (\epsilon_{mc}/\epsilon_{mc-max})^S} \quad (3)$$

where f_{mc} is the confined compressive stress corresponding to a particular strain ϵ_{mc} , f_{mc-max} is the confined masonry peak stress, ϵ_{mc-max} is the strain corresponding to the confined masonry peak stress, and S is a parameter guiding the degradation slope.

Computing f_{mc-max} , ϵ_{mc-max} , and S requires four RMBE's properties, namely: (1) the compressive strength of the corresponding unreinforced unconfined masonry prism, f_{prism} ; (2) the aspect ratio of the RMBE (height to thickness), AR ; (3) the vertical reinforcement ratio, ρ_v ; and (4) the volumetric ratio of transverse reinforcement (hoops), ρ_t . Data fit

software is employed to generate the equation [18]. It should be noted that f_{prism} can be estimated experimentally or by using available analytical models (e.g. [10]). These models are capable of predicting f_{prism} from the characteristics of masonry prism components (i.e. block, grout, mortar, prism pattern, and mortar bedding). Based on the model calibration, empirical best-fit equations have been generated for f_{mc-max} , ϵ_{mc-max} , and S , where two sets of empirical equations are proposed for each parameter. As such, the first equation is high order polynomial equation with a higher R-squared (coefficient of determination) value. On the other hand, the second equation is a simple linear regression relationship with R-squared value lower than their counterparts.

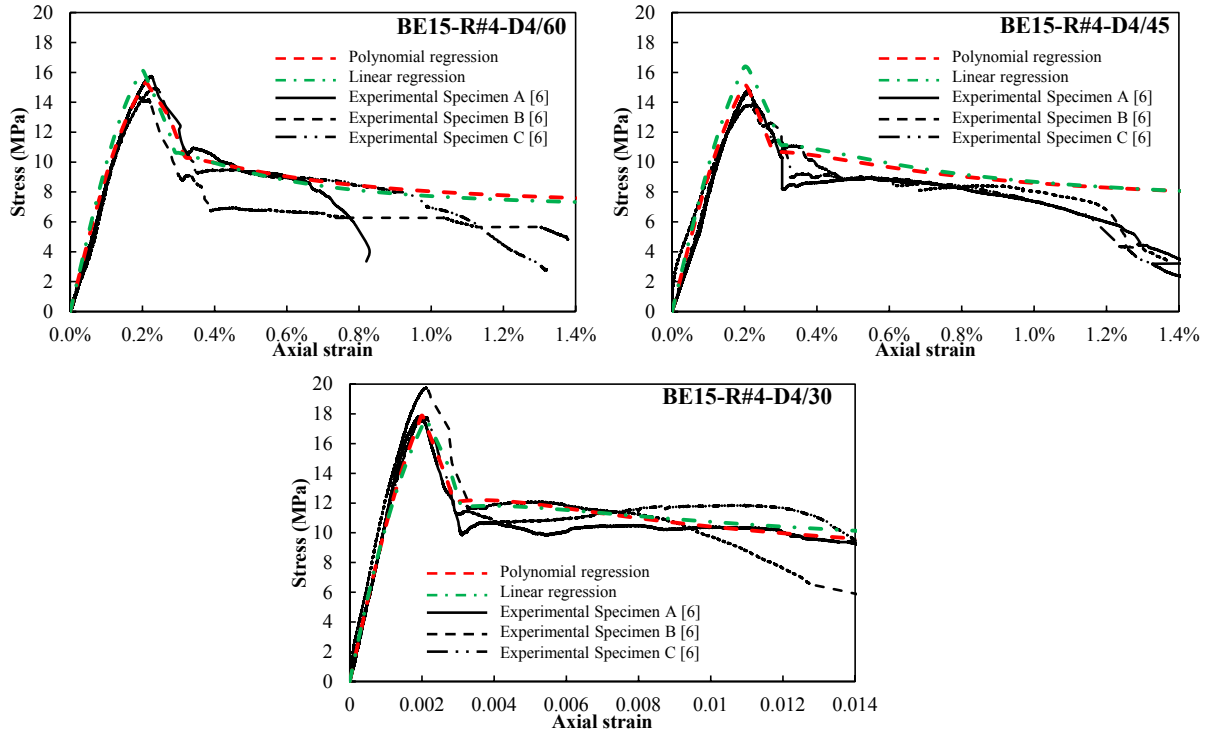


Fig. 10. Model predictions versus the experimental results for RMBE built using #4 vertical bars.

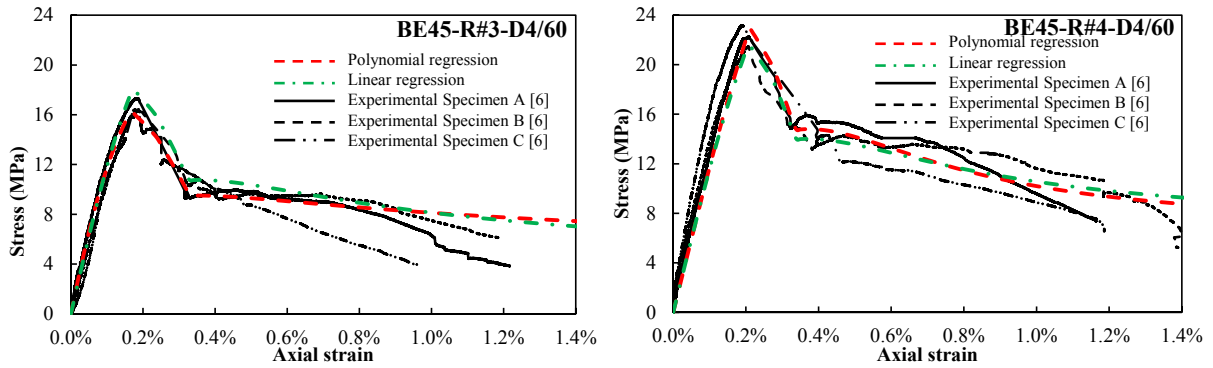


Fig. 11. Model predictions versus the experimental results for RMBE built using 45 MPa grout.

Therefore, f_{mc-max} is calculated using Eqs. (4) and (7), ε_{mc-max} is calculated using Eqs. (5) and (8), and S is calculated using Eqs. (6) and (9), for polynomial regression and linear regression, respectively.

4.3.1. Polynomial regression

$$f_{mc-max} = a + bx_1 + c/x_2 + dx_1^2 + e/x_2^2 + fx_1/x_2 + gx_1^3 + h/x_2^3 + ix_1/x_2^2 + jx_1^2/x_2 \quad (4)$$

$$R^2 = 94.3\%$$

$$a = 619.011, \quad b = -328.425, \quad c = -2727.636, \quad d = -16.984, \\ e = 1477.570, \quad f = 1797.299, \quad g = 1.386, \quad h = 1679.370, \\ i = -1827.581, \quad j = -0.1055.$$

$$x_1 = f_{prism}/AR, \quad x_2 = \rho_l/\rho_v$$

$$\varepsilon_{mc-max} = (a + bx_1 + cx_1^2 + dx_1^3 + ex_2 + fx_2^2 + gx_2^3 + hx_2^4 + ix_2^5)/10000 \quad (5)$$

$$R^2 = 92.8\%$$

$$a = -3769.319, \quad b = 66.500, \quad c = -15.247, \quad d = 1.185, \\ e = 10003.658, \quad f = -10328.925, \quad g = 5103.408, \quad h = -1204.992,$$

$$\text{and } i = 108.509.$$

$$x_1 = f_{prism}/AR, \quad x_2 = \rho_l/\rho_v$$

$$S = a + bx_1 + cx_2 + dx_1^2 + ex_2^2 + fx_1x_2 + gx_1^3 + hx_2^3 + ix_1x_2^2 + jx_1^2x_2 \quad (6)$$

$$R^2 = 86.3\%$$

$$a = 21.158, \quad b = -18.376, \quad c = 2.175, \quad d = 5.788, \quad e = 0.100, \\ f = -1.952, \quad g = -0.498, \quad h = -0.062, \quad i = 0.189, \quad j = 0.095$$

$$x_1 = f_{prism}/AR, \quad x_2 = \rho_l/\rho_v.$$

4.3.2. Linear regression

$$f_{mc-max} = ax_1 + bx_2 + cx_3 + dx_4 + e \quad (7)$$

$$R^2 = 74.3\%$$

$$a = 1.530, \quad b = -0.640, \quad c = 1.775, \quad d = 0.891, \quad e = -5.329$$

$$x_1 = f_{prism}, \quad x_2 = AR, \quad x_3 = \rho_l, \quad \text{and } x_4 = \rho_v$$

$$\varepsilon_{mc-max} = (ax_1 + bx_2 + cx_3 + dx_4 + e)/10000 \quad (8)$$

$$R^2 = 91.5\%$$

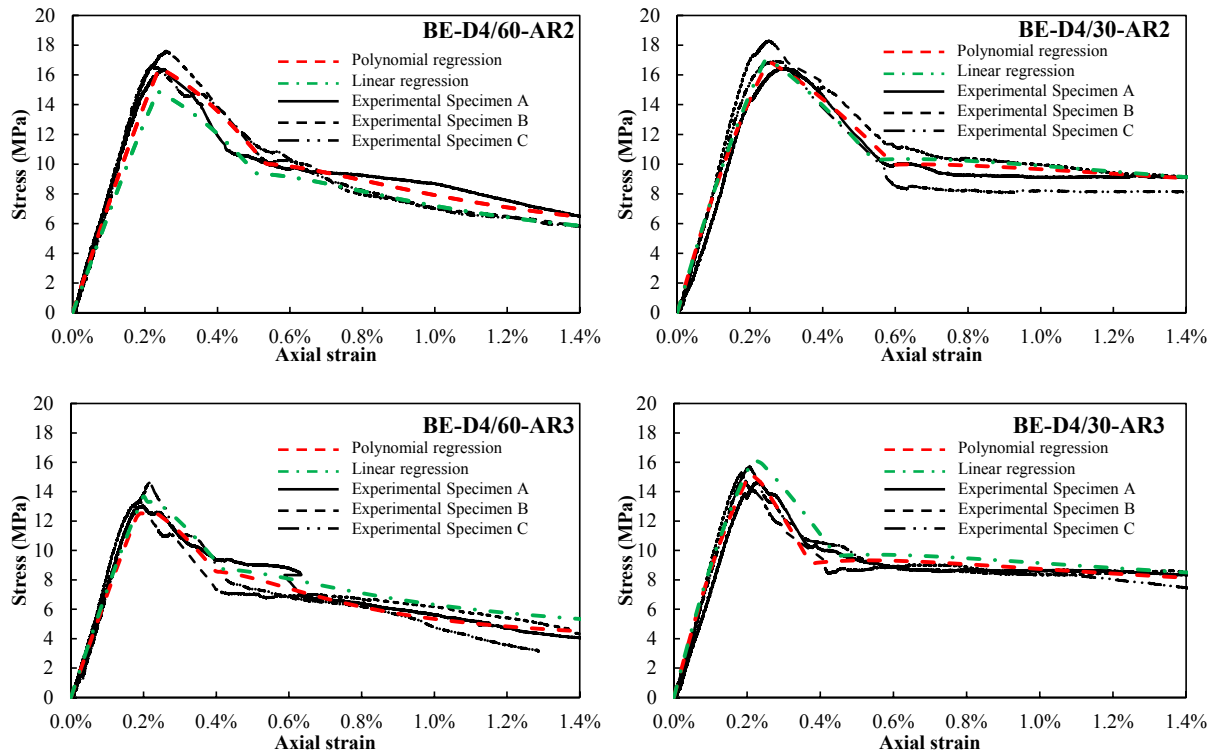


Fig. 12. Model predictions versus the experimental results for RMBE built using different aspect ratios.

Table 5

Percentage of difference between the proposed model and the experimental results.

RMBE #	RMBE ID	Polynomial regression Difference %			Linear regression Difference %		
		f_{max}	ε_{max}	ε_{75}	f_{max}	ε_{max}	ε_{75}
1	BE15-R#3-D4/60-A	-2.39	-2.50	-8.33	2.19	-8.24	-10.20
2	BE15-R#3-D4/60-B	-2.99	0.00	4.17	1.56	-5.88	2.04
3	BE15-R#3-D4/60-C	0.90	6.25	-4.17	5.62	0.00	-6.12
4	BE15-R#3-D4/45-A	4.29	0.00	-7.41	-1.20	5.88	0.00
5	BE15-R#3-D4/45-B	11.51	1.11	-3.70	5.64	7.06	4.00
6	BE15-R#3-D4/45-C	8.97	-2.78	-11.11	3.23	2.94	-4.00
7	BE15-R#3-D4/30-A	11.13	8.33	7.41	20.95	8.33	11.54
8	BE15-R#3-D4/30-B	-1.88	5.56	0.00	6.80	5.56	3.85
9	BE15-R#3-D4/30-C	9.00	19.44	3.70	18.64	19.44	7.69
10	BE15-R#4-D4/60-A	-2.29	-4.76	-6.67	-7.14	0.00	1.82
11	BE15-R#4-D4/60-C	2.94	0.00	-13.33	-2.17	5.00	-5.45
12	BE15-R#4-D4/45-A	0.07	7.00	13.21	-7.26	7.00	5.26
13	BE15-R#4-D4/45-B	16.58	0.00	9.43	8.05	0.00	1.75
14	BE15-R#4-D4/45-C	-2.37	5.00	5.66	-9.51	5.00	-1.75
15	BE15-R#4-D4/30-A	10.39	10.00	16.98	12.27	4.76	8.77
16	BE15-R#4-D4/30-B	-0.67	5.00	13.21	1.02	0.00	5.26
17	BE45-R#3-D4/60-A	6.91	6.47	-17.86	-3.78	6.47	-17.86
18	BE45-R#3-D4/60-C	1.30	10.00	3.57	-8.83	10.00	3.57
19	BE45-R#4-D4/60-A	-6.20	0.00	3.23	-0.09	0.00	3.23
20	BE45-R#4-D4/60-B	-2.79	4.76	0.00	3.53	4.76	0.00
21	BE45-R#4-D4/60-C	1.22	0.00	-6.45	7.81	0.00	-6.45
22	BE-D4/60-AR2-A	-0.67	4.17	-13.33	10.74	4.17	-11.36
23	BE-D4/60-AR2-B	6.79	0.00	-6.67	19.05	0.00	-4.55
24	BE-D4/60-AR2-C	0.79	-8.33	0.00	12.36	-8.33	2.27
25	BE-D4/60-AR3-A	4.00	-12.50	2.70	-5.11	5.00	5.56
26	BE-D4/60-AR3-B	6.88	-16.67	-13.51	-2.48	0.00	-11.11
27	BE-D4/60-AR3-C	16.80	-8.33	-8.11	6.57	10.00	-5.56
28	BE-D4/30-AR2-A	-2.08	0.00	-9.28	-3.80	4.00	-2.22
29	BE-D4/30-AR2-B	8.93	-7.69	-17.53	7.02	-4.00	-11.11
30	BE-D4/30-AR2-C	1.07	6.15	-19.59	-0.70	10.40	-13.33
31	BE-D4/30-AR3-A	0.53	4.76	9.38	-5.09	0.00	-5.41
32	BE-D4/30-AR3-B	-3.29	9.52	6.25	-8.70	4.55	-8.11
33	BE-D4/30-AR3-C	3.62	9.52	3.12	-2.17	4.55	-10.81

$$\begin{aligned}
 a &= 2.336, b = -7.139, c = 10.020, d = 1.691, e = 16.488 \\
 x_1 &= f_{prism}, x_2 = AR, x_3 = \rho_l, \text{ and } x_4 = \rho_v \\
 S &= \exp(ax_1 + bx_2 + cx_3 + dx_4 + e)
 \end{aligned} \quad (9)$$

$$\begin{aligned}
 R^2 &= 68.0\% \\
 a &= -0.014, b = -0.088, c = -0.302, d = 0.323, e = 1.575 \\
 x_1 &= f_{prism}, x_2 = AR, x_3 = \rho_l, \text{ and } x_4 = \rho_v
 \end{aligned}$$

The complete compressive stress-strain relationship of the unconfined masonry is computed using Eqs. (10)–(12). The unconfined response of masonry shell was divided in three zones to capture the post peak stress-strain response of the unconfined zone. The stress-strain response up to the peak strain, ε_{mu-max} , is computed using formulation similar to the one proposed by Mander et al. [14] [Eq. (10)]. Then this is followed by a linear stress degradation representing the transition zone between ε_{mu-max} and the spalling strain, ε_{sp} [Eq. (11)]. Finally, Eq. (12) represented that the unconfined zone has no resistance following the spalling (see Fig. 8).

$$f_{mu} = \frac{f_{mc-max} \left(\frac{\varepsilon_{mu}}{\varepsilon_{mc-max}} \right)^S}{S - 1 + \left(\frac{\varepsilon_{mu}}{\varepsilon_{mc-max}} \right)^S} \text{ for } 0 < \varepsilon_{mu} \leq \varepsilon_{mu-max} \quad (10)$$

$$f_{mu} = f_{mu-max} - f_{mu-max} \frac{\varepsilon_{mu} - \varepsilon_{mu-max}}{\varepsilon_{sp} - \varepsilon_{mu-max}} \text{ for } \varepsilon_{mu-max} < \varepsilon_{mu} \leq \varepsilon_{sp} \quad (11)$$

$$f_{mu} = 0 \text{ for } \varepsilon_{mu} > \varepsilon_{sp} \quad (12)$$

where f_{mu} is the unconfined compressive stress corresponding to specific strain ε_{mu} ; ε_{mu-max} is the strain at peak stress of unconfined RMBE; and ε_{sp} is the strain corresponding to the end of face shell spalling.

Similar to the confined model, two regression techniques were utilized; polynomial regression and linear regression. The f_{mc-max} , ε_{mc-max} , and S are calculated as discussed above. ε_{mu-max} is calculated by Eqs. (13) and (15) and ε_{sp} is calculated by Eqs. (14) and (16), for polynomial regression and linear regression, respectively.

4.3.3. Polynomial regression

$$\varepsilon_{mu-max} = (a + b/x_1 + c/x_1^2 + d/x_1^3 + e/x_2 + f/x_2^2 + g/x_2^3 + h/x_2^4 + i/x_2^5) / 10000 \quad (13)$$

$$\begin{aligned}
 R^2 &= 77.3\% \\
 a &= 1108.230, \quad b = -14.055, \quad c = -229.929, \quad d = 415.095, \\
 e &= -11954.400, \quad f = 50626.963, \quad g = -102380.018, \\
 h &= 98965.561, \quad i = -36608.490. \\
 x_1 &= f_{prism}/AR, \quad x_2 = \rho_l/\rho_v
 \end{aligned}$$

$$\varepsilon_{sp} = (a + bx_1 + cx_2 + dx_1^2 + ex_2^2 + fx_1x_2 + gx_1^3 + hx_2^3 + ix_1x_2^2 + jx_1^2x_2) / 10000 \quad (14)$$

$$\begin{aligned}
 R^2 &= 95.1\% \\
 a &= 119.108, b = -36.576, c = -81.598, d = 9.136, e = 33.409, \\
 f &= 5.676, g = -0.894, h = -3.752, i = -2.257, j = 0.908. \\
 x_1 &= f_{prism}/AR, \quad x_2 = \rho_l/\rho_v
 \end{aligned}$$

4.3.4. Linear regression

$$\varepsilon_{mu-max} = \exp(ax_1 + bx_2 + cx_3 + dx_4 + e) / 10000 \quad (15)$$

$$\begin{aligned}
 R^2 &= 65.5\% \\
 a &= 0.0052, b = -0.102, c = 0.0401, d = 0.298, e = 2.976 \\
 x_1 &= f_{prism}, x_2 = AR, x_3 = \rho_l, \text{ and } x_4 = \rho_v
 \end{aligned}$$

$$\varepsilon_{sp} = \exp(ax_1 + bx_2 + cx_3 + dx_4 + e) / 10000 \quad (16)$$

$$\begin{aligned}
 R^2 &= 85.8\% \\
 a &= 0.026, b = -0.178, c = 0.041, d = 0.052, e = 3.848 \\
 x_1 &= f_{prism}, x_2 = AR, x_3 = \rho_l, \text{ and } x_4 = \rho_v
 \end{aligned}$$

4.4. Model results

Figs. 9–12 show the comparison of the proposed empirical model with the experimental results. The model provides overall good results for both the ascending and descending branches of the compressive stress-strain curves. The model was able to simulate the most relevant characteristics of the RMBE stress-strain response, including the initial stiffness, peak load, strain corresponding to peak, stiffness and stress degradation at different strain levels. Table 5 shows the percentage of the difference between the proposed model and the experimental data at f_{max} , ε_{max} , and ε_{75} using the two regression approaches. A difference range between the model predictions using polynomial regression and the experimental results of (−6 to +17%), (−8 to +19%), and (−20 to +9%), was computed for f_{max} , ε_{max} , and ε_{75} , respectively. Similarly, a difference range of (−10 to +21%), (−8 to +19%), and (−18 to +12%) was observed when using linear regression. Although this model fits the analyzed experimental data well, further calibration against larger set of experimental data, when available, is recommended to generalize the model.

4.5. Model limitations

This study presents an empirical stress-strain model for RMBEs. The proposed model considers the change in: grout strength, aspect ratio, vertical reinforcement ratio and the volumetric ratio of transversal reinforcement. Moreover, the model can predict the stress-strain response of RMBEs having different vertical reinforcement ratios and different confined core dimensions. Therefore, this model presents an effective tool that can be utilized in various analytical/numerical analysis packages. However, this model, similar to any empirical model, has limitations and still open for further enhancements. Considering the limited available experimental data, this model is calibrated with limited data of RMBEs. The considered experimental data consisted of half-scale RMBEs built using C-shaped concrete blocks. It should be noted that two regression techniques were implemented in this model. The polynomial regression is well suited for samples having similar properties to the calibrated RMBEs. However, due to the high order of polynomial equations it could result in out of range predictions for other RMBEs, so it should be used with care. On the other hand, the linear regression equations are applicable for a wider range of RMBEs, however, with a lower coefficient of determination. This model presents an essential tool to engineers need to predict the compressive stress-strain response of confined and unconfined masonry zones, essential for predicting RM shear walls with boundary elements seismic response.

5. Conclusions

This study presents the second phase of a research project conducted at Concordia University aiming at investigating the axial stress-strain response of reinforced masonry boundary elements (RMBEs). The first phase investigated, experimentally, the effect of changing grout strength, vertical and horizontal reinforcement ratio on the stress-strain response of thirty RMBEs and unreinforced masonry boundary elements (BEs) (Obaidat et al. [13]). Moreover, the first phase tested the capability of existing stress-strain models in predicting the stress-strain response of RMBEs where none of the examined models was capable of capturing the overall response of the RMBEs. On the other hand, the second phase of this project, which is the focus of the current study, investigated the effect of changing the RMBE's height to thickness ratio (i.e. aspect ratio) on the stress-strain behavior considering different confinement ratios by testing seventeen RMBEs and unreinforced BEs. Finally, this study was concluded by presenting a stress-strain empirical model calibrated using the experimental data of the two phases.

The current study investigated the effect of three different aspect (AR) ratios and two confinement ratios of transverse reinforcement (i.e. by changing the hoop spacing) on the compression stress-strain

behavior of RMBE. The results showed that increasing the confinement ratio of transverse reinforcement and decreasing the AR enhanced the RMBE peak stress. On average, as the AR decreased from 5 to 2, the peak stress increased by 20%, 28%, and 2% for unreinforced BEs, RMBEs having 60 and 30 mm hoops spacing, respectively. On the other hand, as the confinement ratio of transverse reinforcement increased from 0.022 (i.e. 60 mm hoops spacing) to 0.062 (i.e. 30 mm hoops spacing), the peak stress increased by 2%, 12%, and 29% for RMBEs with AR of 2, 3 and 5, respectively. It was also observed that decreasing the aspect ratio did not affect the RMBE peak stress in specimens having highest confinement ratio of transverse reinforcement (i.e. 30 mm hoops spacing).

In general, decreasing the hoop spacing and/or the AR exhibited an increase in the corresponding RMBE post-peak strain. The strain ductility, $\mu_{50\%}$, increased as the aspect ratio decreased from 5 to 2 by 46%, and 69% for unreinforced BEs and RMBEs having 30 mm hoops spacing, respectively. Moreover, the strain ductility, $\mu_{50\%}$, increased by 130%, 131%, and 19%, as the confinement ratio of transverse reinforcement increased from 0.022 to 0.062, for RMBEs with aspect ratio of 2, 3 and 5, respectively.

An empirical stress-strain model was proposed for half-scale C-shape RMBE simulating the end zones of reinforced masonry shear walls with BEs. The proposed model considered different parameters, namely, aspect ratio, the volumetric ratio of transverse reinforcement, the vertical reinforcement ratio, and the grout strength. This model was calibrated with the experimental data of thirty-three RMBEs. Two regression approaches were implemented to calibrate this model; polynomial and simple linear regression. The model results fitted well with the experimental stress-strain relationships. The proposed model was capable of capturing the descending part of the compressive stress-strain curve including the sudden stress drop after the peak stress due to the face shell spalling. A maximum difference varies from -20 to $+21\%$ was observed when comparing the model predictions with the experimental results at RMBE peak stress ($f_{\max}$), strain at the peak stress ($\epsilon_{\max}$) and strain at 75% of the peak stress (ϵ_{75}). Although this model is still open for more enhancement considering more experimental results, it presents a simple and effective tool that can be used in different analytical/numerical analyses.

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