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SEISMIC RESPONSE PARAMETERS OF DUCTILE REINFORCED CONCRETE MASONRY SHEAR WALLS WITH BOUNDARY ELEMENTS

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ABSTRACT

The ductile type of Reinforced Concrete Masonry (RCM) shear walls was added in the 2015 edition of the National Building Code of Canada (NBCC-15) and was assigned a ductility-related response modification (R_d) factor of 3.0. Recent experimental studies demonstrated the capability of ductile RCM shear walls with masonry boundary elements in attaining displacement ductility capacity higher than their rectangular counterparts. The objective of this study is to quantify the essential force and displacement-based design parameters of RCM shear walls with masonry boundary elements based on all reported experimental test results. The considered experimental studies included quasi-static cyclic testing of flexural dominant walls that varied in the shear span-to-depth ratios, the vertical reinforcement ratios, the confinement of end zones, and the axial load ratios. Based on an analysis of the experimental results, a ductility-related modification (R_d) factor and a stiffness reduction factor are proposed. The proposed factors are compared with the values of North American masonry design standards. It is noted that RCM shear walls with boundary elements can be assigned higher R_d values than the current value specified in the Canadian masonry design standard (i.e., CSA S304-14). Besides, the stiffness reduction factor provided by CSA S304-14 was found to provide reasonable estimates of the cracked stiffness. However, it slightly overestimated the cracked stiffness for the walls with high aspect ratios. Nevertheless, such crucial design parameters cannot be solely derived based on an analysis of the component-level response. As such, the study will be extended to quantify the seismic response parameters based on the overall (system-level) characteristics. It will account for the different system-level aspects, such as the slab coupling, the contribution of orthogonal (out-of-plane) walls, and the level of ductility demand in individual walls.

KEYWORDS: *RCM walls, boundary elements, ductility, effective stiffness, stiffness degradation*

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INTRODUCTION

Significant research efforts were taken to enhance the performance of multi-storey Reinforced Concrete Masonry (RCM) buildings. The most common Seismic Force Resisting System (SFRS) for masonry buildings is RCM shear walls. Previous research established that the integration of enlarged masonry boundary elements to the ends of the rectangular walls enhances the seismic performance of RCM shear walls [1–7]. The findings of the previous studies were supported by experimental testing and numerical simulations. These studies resulted in the addition of the ductile type of RCM shear walls in the 2015 edition of the National Building Code of Canada (NBCC-15). The ductile RCM shear walls were assigned a ductility-related response modification factor of 3.0.

Shedid et al. [8] quantified the impact of axial load and vertical reinforcement ratio on the seismic response parameters of RCM shear walls. It was concluded that the ductility-related response modification factor (R_d) is less affected by the axial load level compared to the vertical reinforcement ratio. Nevertheless, the increase in either the vertical reinforcement ratio or the axial load level lowers the values of Rd. Furthermore, the increase in axial load level increases the initial stiffness and results in higher rate of stiffness degradation. Similarly, Shedid et al. [9] quantified and compared the seismic response modification factors of rectangular, flanged, and end-confined RCM shear walls. The values of R_d were calculated from the results of the quasi-static cyclic tests of seven walls and adopting the equal displacement approach. It was demonstrated that flanged walls and walls with boundary elements had higher ductility-related response modification factors by 50% and 100%, compared to that of the rectangular walls. Besides, there was a 58% reduction in the required vertical reinforcement to achieve a similar lateral resistance.

Based on the available literature, there are no recent studies that performed an extensive analysis of all the previously tested RCM shear walls with boundary elements. As such, this paper summarizes the previously tested RCM walls with boundary elements. Furthermore, it evaluates the effects of the different design parameters on the seismic response factors. It also proposes values for the ductility-related response modification factor and stiffness reduction factor. Finally, it highlights the need for further research to enhance the accuracy of these crucial design parameters by accounting for the system-level effects. Several experimental and numerical studies, such as [10,11], highlighted the substantial influence of the system-level aspects on the seismic response of RCM shear walls. The seismic response modification parameters are intended for the design of building systems. Therefore, it is crucial to consider the effects of the system-level on the proposed seismic response modification parameters.

DATABASE OF RCM SHEAR WALLS WITH BOUNDARY ELEMENTS

There is a total of 21 RCM shear walls with boundary elements available in the literature tested by [1,2,6,7,12,13]. These walls, summarized in Table 1, were tested using a quasi-static lateral cyclic loading protocol.

Table 1: Summary of Database of RCM Shear Walls with Boundary Elements

Wall ID	Wall No. in Literature	Reference	l_w (mm)	h_w (mm)	*AR*	$\rho_{v\text{-}BE}$ (%)	$\rho_{v\text{-}total}$ (%)	ρ_h (%)	S/d_b	P/f'_mA_g (%)
W1	W3	[1]	1802	3990	2.21	1.17	0.55	0.3	9.5	5.4
W2	W6	[1]	1802	2660	1.48	1.17	0.55	0.6	9.5	5.4
W3	W7	[1]	1802	2660	1.48	1.17	0.55	0.6	9.5	5.4
W4	W1	[12]	1803	3990	2.21	1.17	0.56	0.3	9.5	3.3
W5	W2	[12]	1803	3990	2.21	1.17	0.56	0.3	9.5	3.3
W6	W3	[12]	1803	3990	2.21	1.17	0.56	0.3	9.5	3.3
W7	W4	[12]	1803	3990	2.21	1.17	0.56	0.3	9.5	9.8
W8	Wall 1	[2]	2660	3990	1.50	1.17	0.51	0.3	9.5	6.0
W9	Wall 2	[2]	1235	3990	3.23	1.17	0.69	0.3	9.5	6.0
W10	Wall 3	[2]	1235	2660	2.15	1.17	0.69	0.6	9.5	6.0
W11	Wall 4	[2]	1235	2660	2.15	1.17	1.17	0.6	9.5	6.0
W12	Wall 5	[2]	1235	1900	1.54	1.17	0.69	0.6	9.5	6.0
W13	W4	[13]	1715	12167	7.09	1.57	0.74	0.2	6.0	10.0
W14	W5	[13]	1725	12167	7.05	1.03	0.67	0.2	6.0	9.0
W15	W6	[13]	1725	12167	7.05	0.77	0.53	0.2	6.0	9.0
W16	W7	[7]	1715	12167	7.09	0.79	0.44	0.2	6.0	14.9
W17	W8	[7]	1715	12167	7.09	1.57	0.74	0.2	6.0	14.9
W18	W9	[7]	1725	12167	7.05	1.03	0.67	0.2	6.0	13.6
W19	W10	[6]	1715	6100	3.56	0.79	0.44	0.2	6.0	12.5
W20	W11	[6]	1715	12167	7.09	0.83	0.45	0.2	6.0	16.4
W21	W12	[6]	1715	12167	7.09	0.79	0.44	0.2	6.0	12.5

The studied parameters were the Aspect Ratio (AR), the vertical reinforcement ratio ($\rho_{v\text{-}BE}$ and $\rho_{v\text{-}total}$), the confinement of end zone (S/d_b), and the axial load ratios (P/f'_mA_g). All the walls had aspect ratios higher than 1 and were designed to fail in flexure. Eleven of the walls had RCM boundary elements built using stretcher masonry units (Figure 1(a)), one wall had boundary elements constructed from pilaster units, and nine walls utilized C-shaped masonry units in the boundary elements (Figure 1(b)). The type of masonry units in the boundary elements controls the flexibility in sizing the boundary elements, spacing the transverse reinforcement, and arranging the vertical rebars. The use of the C-shaped concrete masonry units provides the most flexibility for the design of the end zones.

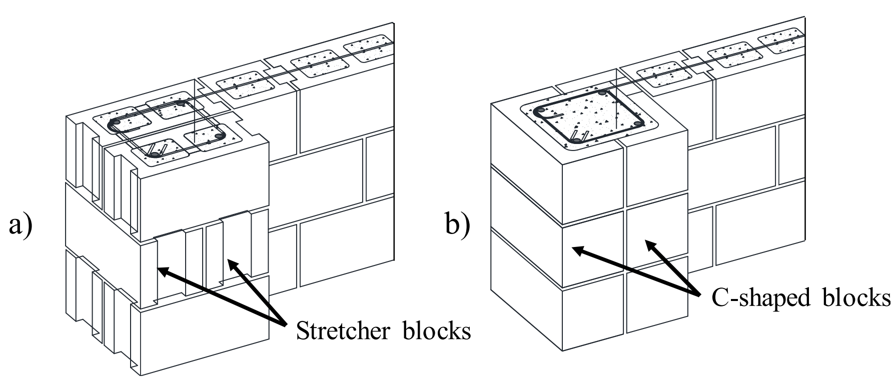


Figure 1: RCM Shear Walls with Boundary Elements Built using: (a) Stretcher Blocks; (b) C-Shaped Blocks

Idealization of Response
The experimental load-displacement envelope was obtained for each of the walls by connecting the peaks of the first hysteresis loops. Different techniques exist for the idealization of the load-displacement response with no consensus among researchers. Subsequently, in this study, the load-displacement response was idealized using the conservative method proposed by Priestley et al. (2007) into a bi-linear load displacement curve. The idealized yield displacement was calculated as the intersection between a line from the origin having the slope of the initial yield stiffness with a line tangent to the lateral capacity.

Ductility-Related Response Modification Factor
The response of the tested walls was used to calculate the ductility-related response modification factor (R_d) for RCM shear walls with boundary elements. The values of R_d were calculated based on the equal displacement and equal energy assumptions. It is worth highlighting that the equal displacement is mostly applicable when the natural period of the structural system (T_n) exceeds 0.5sec, while the equal energy method applies for structural systems with short periods of vibration (i.e., $T_n < 0.5$sec) [15]. Figure 2 compares the values of R_d with the value of the Canadian masonry design standard (i.e., CSA S304-14 [16]). Besides, it shows the variation of the ductility-related modification factor with respect to the natural period (T_n) of the shear wall. The R_d values calculated based on the equal displacement approach were evaluated at the ultimate displacement, which corresponds to the lateral load at 20% strength degradation.

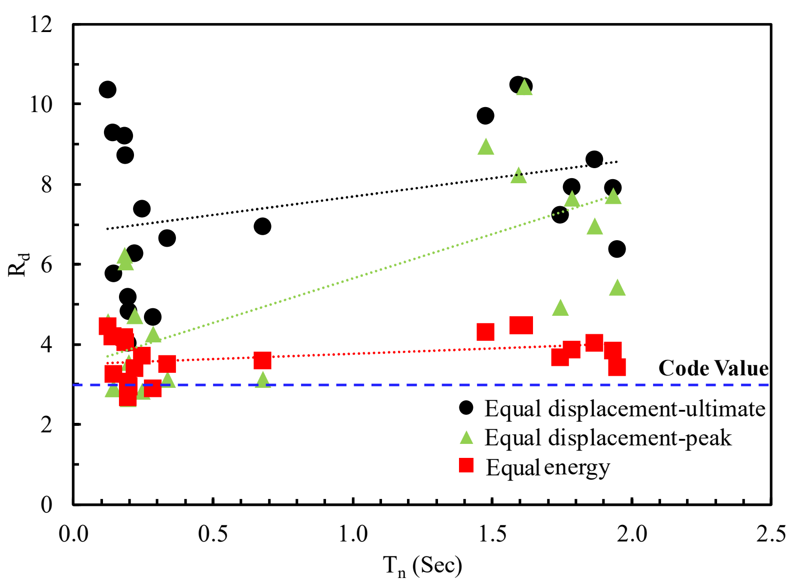


Figure 2: Variation of ductility-related response modification factor with natural period of vibration

The significant variation in the values of R_d, at similar natural periods of vibration, shown in Figure 2, is due to the changes in the different design parameters (i.e., aspect ratio, vertical reinforcement ratio, confinement, and axial load level) in each of the walls. It can be seen that all walls from the database had ductility-related response factors, evaluated assuming equal displacement at peak load and ultimate displacement, higher than the code values of 3.0. The average R_d was 7.5, 5.2, and 3.7 for the equal displacement at peak load, ultimate displacement, and equal energy approaches, respectively. The Figure also suggests that there might be a correlation between the ductility-related modification factor and the natural period of the shear wall. There is an increase in the values of R_d with the natural period, whether calculated assuming equal displacements or equal energy. The natural periods were calculated by idealizing the wall as a single degree of freedom system. The mass was taken as the applied axial load and the stiffness was the idealized yield stiffness ($K_{y\text{-}id}$).

The database of RCM shear walls with boundary element were divided into groups to allow investigating the influence of the different design parameters on the values of R_d. Figure 3 shows the effect of axial load level ($P/A_g f'_m$), aspect ratio (AR), vertical reinforcement ratio in each boundary elements ($\rho_{v\text{-}BE}$), and the total vertical reinforcement ($\rho_{v\text{-}total}$) on the ductility-related response modification factor. The values shown in Figure 3 were calculated at the ultimate displacement assuming the equal displacement approach applies. As illustrated in Figure 3(a), an increase in the axial load ratio ($P/A_g f'_m$) clearly reduced the ductility-related response modification factor. For the walls with the higher aspect ratio (i.e., AR = 7.1), the reduction in R_d values due to the increase in axial load ratio was smaller compared with the shorter walls. This is due to the increased flexural contribution in the taller walls and because these walls had masonry boundary elements built using C-shaped masonry blocks, which allowed providing sufficient confinement in the end zones. As a result, these walls showed a better ability to mitigate the impact of the axial load on the ductility. No clear trend was observed for the influence of aspect ratio, Figure 3(b), on the ductility-related response modification factor. There is a slight increase in the ductility-related response modification factor with the increase in aspect ratios. Figure 3(c) shows that the increase in the vertical reinforcement of the boundary elements results in reducing the values of R_d. This is less evident for the walls subjected to the high axial stress of 2.25 MPa. Figure 3(d) shows the relation between the ductility-related response modification factors and the total vertical reinforcement. A trend cannot be concluded as there was only two data points. Unlike previous studies, such as [8], the increase in axial load was effective in reducing the ductility-related response modification factor.

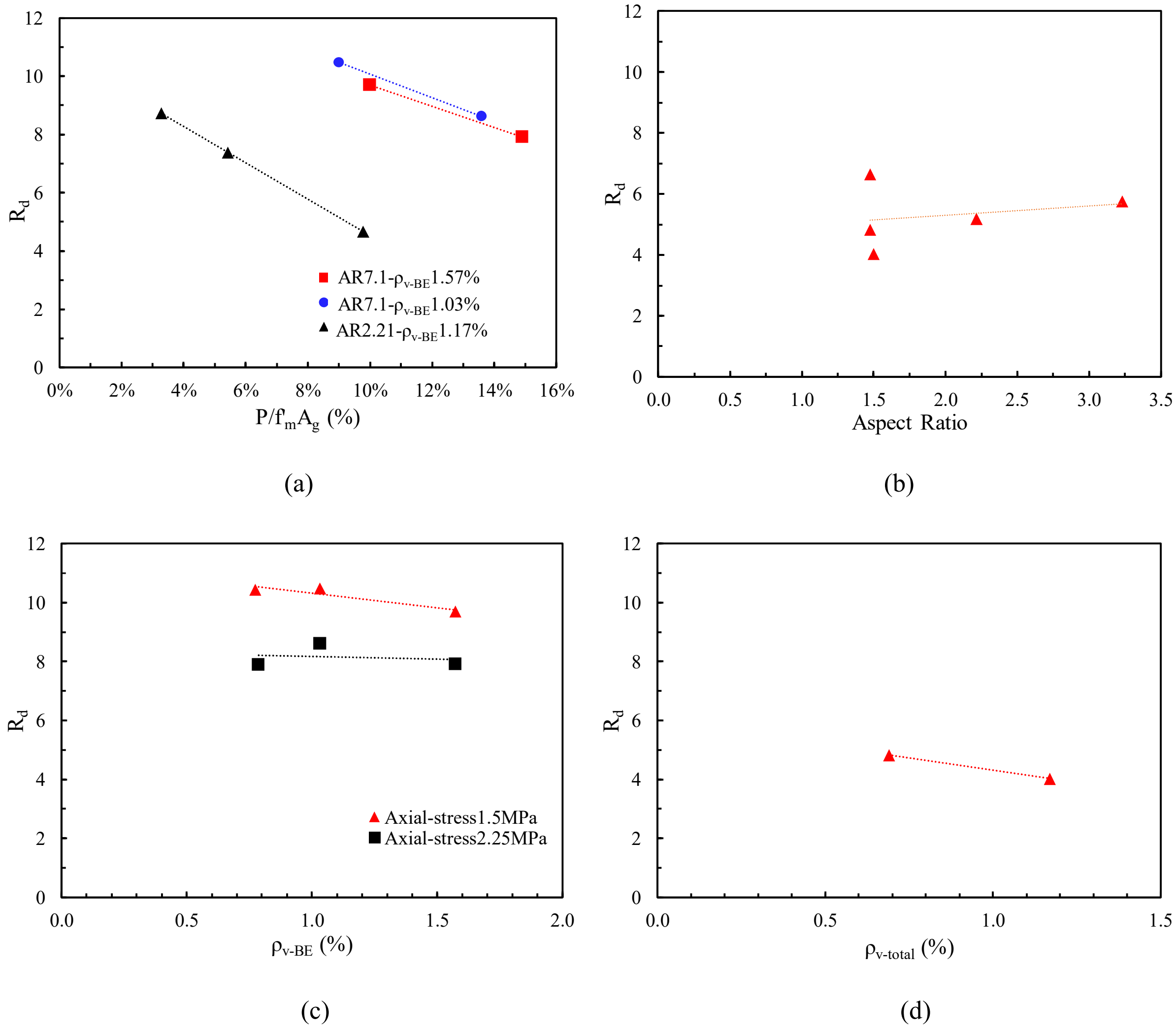


Figure 3: Influence of design parameters on the ductility-related response factors

Stiffness Degradation

Analysis of the database of RCM shear walls with boundary elements, summarized in Table 1, confirmed that the idealized yield stiffness is directly proportional to the axial load level, the vertical reinforcement of the boundary elements, and the total vertical reinforcement. However, it is inversely related to the aspect ratio of the wall. As such, the stiffness degradation should ideally account for these parameters. The variation of the stiffness degradation ratio, which is calculated as the ratio of idealized yield stiffness ($K_{y\text{-}id}$) to gross stiffness (K_g) is depicted in Figure 4. It can be seen that, in line with previous research such as [8], the stiffness degradation is clearly increasing with the increase in the axial load ratio. The degradation in lateral stiffness is also directly proportional to the aspect ratio and the vertical reinforcement of the boundary elements. The total vertical reinforcement seems to be the least effective on the lateral stiffness degradation, possibly due to the limited data points available in the current database.

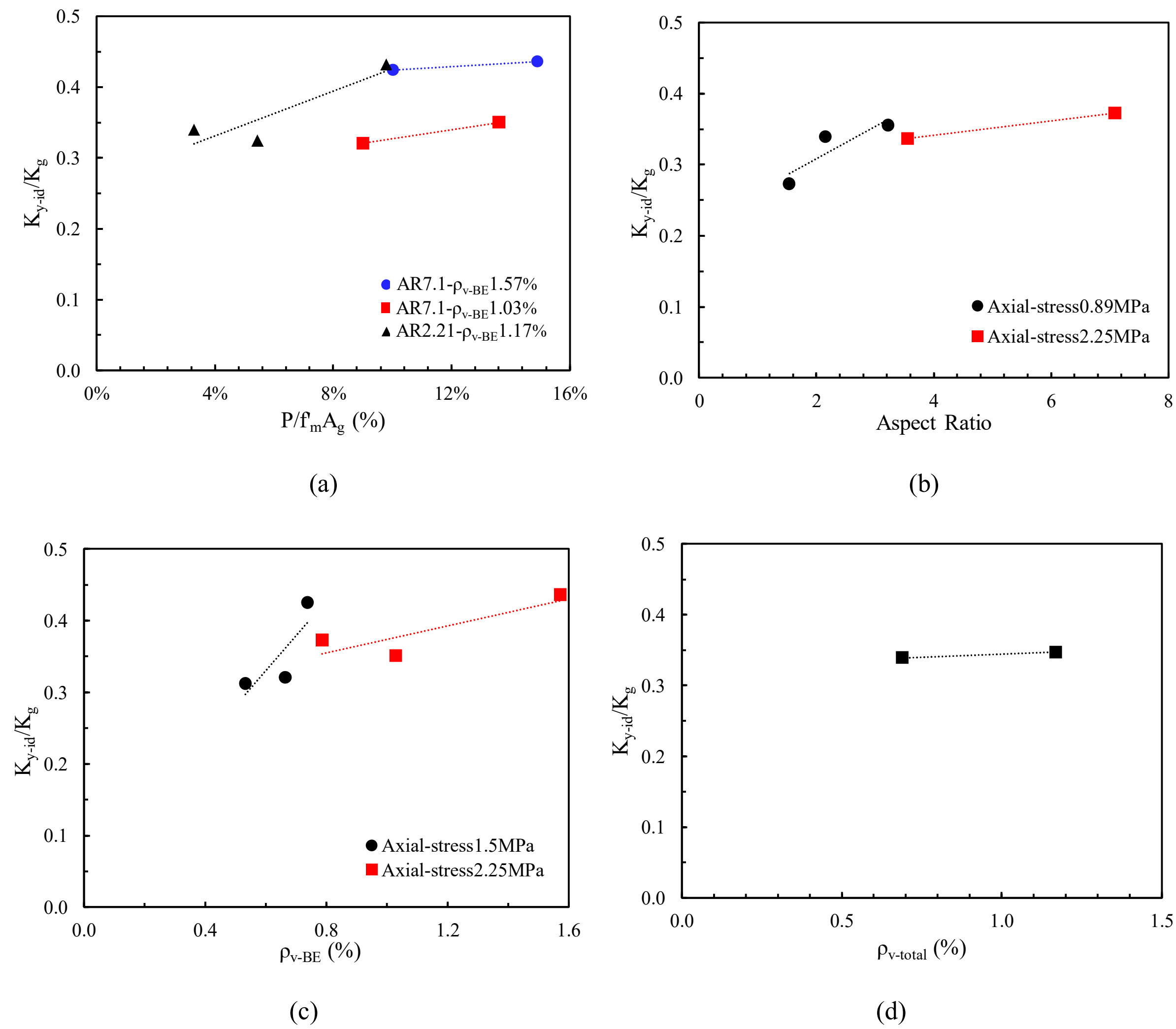


Figure 4: Influence of design parameters on the stiffness degradation

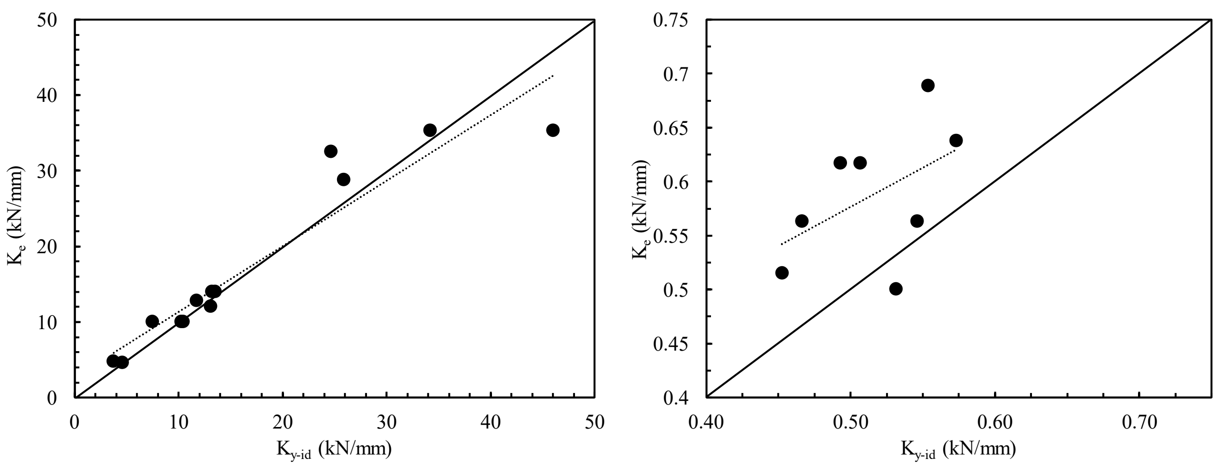
Stiffness Reduction Factor

Table 2 summarizes the stiffness reduction coefficients proposed in the different design standards. In this paper, the coefficient given in the Canadian masonry design standard was used to evaluate its capability of estimating the effective stiffness of RCM shear walls with boundary elements. The other coefficients were calculated for the walls but generally resulted in higher effective stiffness values. The average stiffness reduction factors were 0.39, 0.5, 0.68, and 0.5 for CSA S304-14 [16], TMS 402/602-16 [17], CSA A23.3-04, and CSA A23.3-14 [18], respectively. The calculated standard deviation was 0.04 for CSA S304-14 [16], 0 for TMS 402/602-16 [17] as it is a fixed reduction factor, 0.04 for CSA A23.3-04, and 0 for CSA A23.3-14 [18] as it was dependent on R_d and R_o, which did not vary among the walls.

The relation between the effective stiffness (K_e), calculated using $\alpha_{CSA\ S301-14}$, and the idealized yield stiffness (K_{y-id}) is presented in Figure 5. Figure 5(a) shows that the use of the coefficient of CSA S304-14 resulted in a reasonable approximation of the idealized yield stiffness. However, the effective stiffness was overestimated for the walls with high aspect ratio as shown in Figure 5(b). It should be noted that for the walls with high aspect ratios the displacements reported in the literature were measured at the top of the plastic hinge and not the full specimen [6,7,13]. As such, the experimental stiffness values were calculated by estimating the lateral idealized displacement at the top of the full wall.

Table 2: Lateral stiffness reduction coefficients

Design standard	Stiffness reduction coefficient
CSA S304-14	$\alpha_{CSA\ S301\text{-}14} = 0.3 + P/A_g f'_m$
TMS 402/602-16	$\alpha_{TMS} = 0.5$
CSA A23.3-04	$\alpha_{CSA\ A23.3\text{-}04} = 0.6 + P/A_g f'_m$
CSA A23.3-14	$\alpha_{CSA\ A23.3\text{-}14} = 1.0 - 0.35\ (R_d R_o/\gamma_w - 1)$



(a) (b)

Figure 5: Correlation between effective stiffness (K_e) as calculated by CSA S304-14 and idealized yield stiffness ($K_{y\text{-}id}$)

Comparison between the values of $\alpha_{CSA\ S301\text{-}14}$ and the stiffness degradation ratio is shown in Figure 6. It can be seen that in general the code stiffness reduction coefficients are overestimating the stiffness degradation. This might result in a conservative estimate of the seismic design forces in the force-based design context. However, it would result in an overestimation of the lateral stiffness and unconservative evaluation of the lateral displacements due to seismic loading. The average stiffness reduction factor as calculated by CSA S304-14 [16] was 0.39 and the average ratio of stiffness degradation ($K_{y\text{-}id} / K_g$) was 0.36.

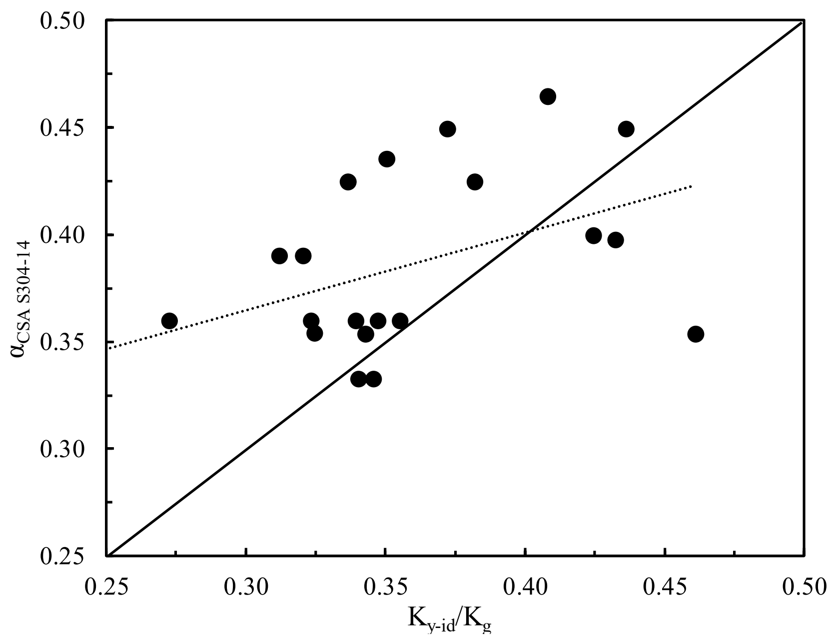


Figure 6: Comparison between $\alpha_{CSA\ S301\text{-}14}$ and ($K_{y\text{-}id}$ / K_g)

CONCLUSIONS AND FUTURE WORK

This paper summarizes the response of all previously tested RCM shear walls with masonry boundary elements to quantify crucial seismic design parameters. The summarized database was used to evaluate the influence of the different design parameters on the ductility-related modification factors, idealized yield stiffness, and the stiffness degradation. Based on the analysis of the reported results, RCM shear walls with boundary elements can be a ductile alternative structural system. The R_d value assigned by CSA S304-14 is conservative and RCM shear walls with boundary elements could be assigned higher values. For instance, it could be assigned a value of 3.5, similar to that of ductile reinforced concrete shear walls. However, these results being evaluated from the response at the structural component-level and from quasi-static testing are not sufficient. Further work is still required to consider the loading rate effects and the effects from the system-level aspects as the seismic design parameters are meant for structural systems and not components. The stiffness reduction factor given in CSA S304-14 was capable of providing reasonable estimates of the cracked stiffness and could be applied to RCM shear walls with boundary elements. The presented results are preliminary and will be extended to provide reliable seismic response modification parameters for RCM shear walls with boundary elements. It will account for the different system-level aspects, such as the slab coupling, the contribution of orthogonal (out-of-plane) walls, and the level of ductility demand in individual walls.

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