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Evaluation and Quantification of Seismic Performance of Reinforced Masonry Core Walls with Boundary Elements

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ABSTRACT

Reinforced masonry (RM) structures have recently gained popularity as they are considered a cost-effective and fast construction technique. However, the seismic design of mid- to high-rise RM structures is still a challenge because it requires a reliable seismic force-resisting system (SFRS) capable of providing the required ductility and capacity. Reinforced concrete (RC) core walls are commonly used as the primary lateral force-resisting system in modern building construction as it accommodates the elevators and staircases. Therefore, this study examines the adequacy of using reinforced masonry core walls with boundary elements (RMCW+BEs) as a potential SFRS alternative to rectangular reinforced masonry shear walls (RMSWs) with and without boundary elements, given their enhanced structural and architectural characteristics in typical RM buildings. Furthermore, this study introduces a new modeling technique utilizing the applied element method (AEM) implemented in the Extreme Loading for Structures software (ELS), that can capture the seismic performance of RMSWs having different cross-sectional configurations and design parameters. Moreover, the developed models are used to evaluate the seismic performance of RM buildings located in North American moderate seismic zones that employ the RMCW+BEs as the main SFRS. The performance of the proposed system is evaluated using nonlinear time history analysis (NLTHA) utilizing typical ground motion records for North America. The system ductility and overstrength are quantified using nonlinear pseudo-static pushover following the FEMA P695 procedure. The results showed that utilizing the RMCW+BEs as the main SFRS can adequately control the seismic demand results from typical North American ground motions. Nonetheless, the system provides the required ductility, overstrength and deformation capacity for a ductile SFRS for typical mid- and high-rise buildings. The findings of this study contribute toward implementing the RMCW+BEs as an effective SFRS for typical RM buildings in the next generation of North American design standards for masonry structures.

KEYWORDS

Core walls; Boundary elements; Nonlinear analysis; FEMA P695; Applied element method; Seismic response.

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INTRODUCTION

Recent improvements in performance-based seismic design tools allow nonlinear collapse simulation to evaluate building system performance. This assessment can be done using collapse simulation in a probabilistic framework. According to the FEMA P695 [1] approach, seismic performance characteristics such as response modification coefficient (R), system overstrength factor (Ω_o), and deflection amplification factor (C_d) directly impact building system performance. This method uses experimental data on structural components to assess structural configuration and ground motion changes. FEMA P695 fragility curves are critical for assessing seismic risk and quantifying structure resilience. These curves show the likelihood that a structure or its elements would suffer or exceed a specific degree of damage at a ground motion intensity metric, such as basic period spectral acceleration. Damage depends on the building's functioning capabilities and repair cost. Pre-earthquake planning and post-design verification require fragility curves [2,3]. They also help prioritize retrofitting and quantify losses after an earthquake, speeding up recovery assessment [4].

Reinforced Masonry (RM) shear walls with boundary elements have been tested for seismic performance in several experiments and numerical studies. Research shows that adding limited masonry boundary elements to wall end zones improves lateral capacity and displacement ductility [5,6]. In residential masonry buildings, North American standards include reinforced masonry shear walls with boundary elements (RMSW+BEs) as an efficient seismic force-resisting system (SFRS). Mahrous et al. [7] performed a numerical analysis to assess the sufficiency of CSA S304-14 [8] design provisions for hybrid reinforced masonry structures with reinforced masonry core walls with boundary elements (RMCW+BEs) as the primary seismic force-resisting system. RMCW+BEs performed well in design-level earthquakes. The NBCC 2015 [9] height constraints for ductile RMSW buildings necessitate a new shear demand amplification factor for RMSWs, according to the study.

This study evaluates seismic performance parameters system overstrength (R_o) and period-based ductility (μ_T) for RMCW+BEs as SFRS in RM buildings. In this context, a three-dimensional numerical model for the proposed structural system is developed using Extreme Loading for Structures software (ELS) [10] for two RM buildings of 10, 15 stories. The two structures have the structural system, using RMCW+BEs as SRFS and RM partially grouted walls as load-bearing gravity system. The numerical model was calibrated and validated using RMSW+BEs experimental data [5] from the literature.

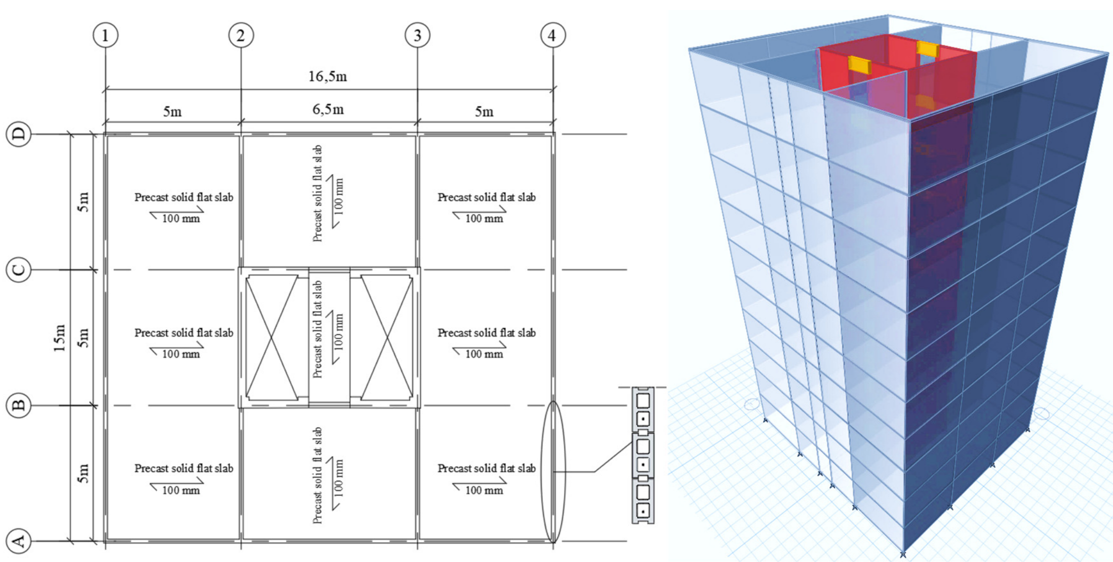
STRUCTURAL SYSTEM AND PROTOTYPE BUILDINGS

Two prototype structures with different heights are chosen to examine the seismic behaviour of tall masonry buildings that adopt RMCW+BEs as the primary SFRS. Moreover, to identify the seismic design forces, the buildings are presumed to be located in Montréal (Site Class C), Québec, which falls under the moderate seismic zone category. The suggested building layout fits RM structures with external and interior walls, partitions, and C-shaped core walls for elevator shafts and staircases. The 10 and 15-story buildings are 30 and 45 meters tall, with an average story height of 3 meters. Table 1 shows the two structures' height, plan, RMCW+BEs dimensions, and plastic hinge (PH) vertical and horizontal reinforcement ratios. Precast prestressed slabs utilized in RM constructions are used for the flooring. Fig. 1 shows the structural layout of the buildings and 3D view for the 10-story building.

The design and detailing of the studied buildings conform to guidelines specified in CSA S304-14 [8] and NBCC 2020 [11] for ductile shear walls. The loads considered in the design are dead, live, and snow loads, in addition to the predominant lateral forces associated with seismic or wind loads. The seismic loads governed the lateral load design of both buildings (10-, and 15-Story). The vertical and horizontal reinforcements utilized in the design of the walls were of grade 400 in accordance with CSA S304-14 [8] design provisions for ductile shear walls. Fig. 2 and Table 2 summarize the dimensions and reinforcement details for the RMCW+BEs as well as gravity walls for the studied buildings. Along the height of the core wall, the design was optimized for the web thickness, as well as vertical and horizontal reinforcements.

Table 1: Main characteristics of the studied buildings

Characteristic	10-story	15-story
Typical floor height (m)	3	3
Total height of the building (m)	30	45
Plan dimensions (m)	15 × 16.5	15 × 16.5
Core wall dimensions (m)	5.2 × 2.6	5.2 × 2.6
Vertical reinforcement ratio in the PH zone (%)	0.15	0.15
Horizontal reinforcement ratio in the PH zone (%)	0.34	0.34



(a) **(b)**

Figure 1: Structural layout: Plan; and 3D view for the 10-story.

NON-LINEAR NUMERICAL MODELING

Numerous researchers have conducted extensive numerical simulations to capture the nonlinear behavior of reinforced masonry shear walls (RMSWs). These simulation methods can be broadly categorized into micro-modeling and macro-modeling approaches. Micro-modeling involves capturing the behavior of individual components of RMSWs, including blocks, mortar, grout, and reinforcement, along with the connecting interfaces, with a high level of detail. In contrast, the macro-modeling approach employs equivalent materials to represent the properties of the entire wall assembly, including blocks, grout, and mortar, to capture the overall behavior of RMSWs [12].

Micro-modeling, due to its detailed approach and the discretization of the wall into small elements, is computationally intensive. Conversely, macro-modeling uses larger elements to represent average material properties, resulting in less complex models and reasonable computational requirements compared to micro-modeling. The efficiency of macro-modeling in simulating the seismic behavior of RMSWs has been demonstrated by various studies [7,13–16]. However, modeling entire reinforced masonry buildings necessitates a high level of detail and poses significant computational challenges. Therefore, there is a need to develop simple numerical models capable of predicting seismic behavior under various loading conditions.

The applied element method (AEM) [17–19] is utilized to model the studied reinforced masonry (RM) buildings, representing a pioneering modeling technique that employs the discrete cracking concept. This method discretizes the elements and employs connecting springs to represent their corresponding material properties, as illustrated in Fig. 3. The stiffness matrix for each element is established by applying unit displacement in six degrees of freedom, and element forces are determined by integrating the developed stresses along the spring surface. Element separation occurs when the connecting springs reach the failure criteria assigned to the material, with the Mohr-Coulomb failure envelope controlling the failure of brittle materials.

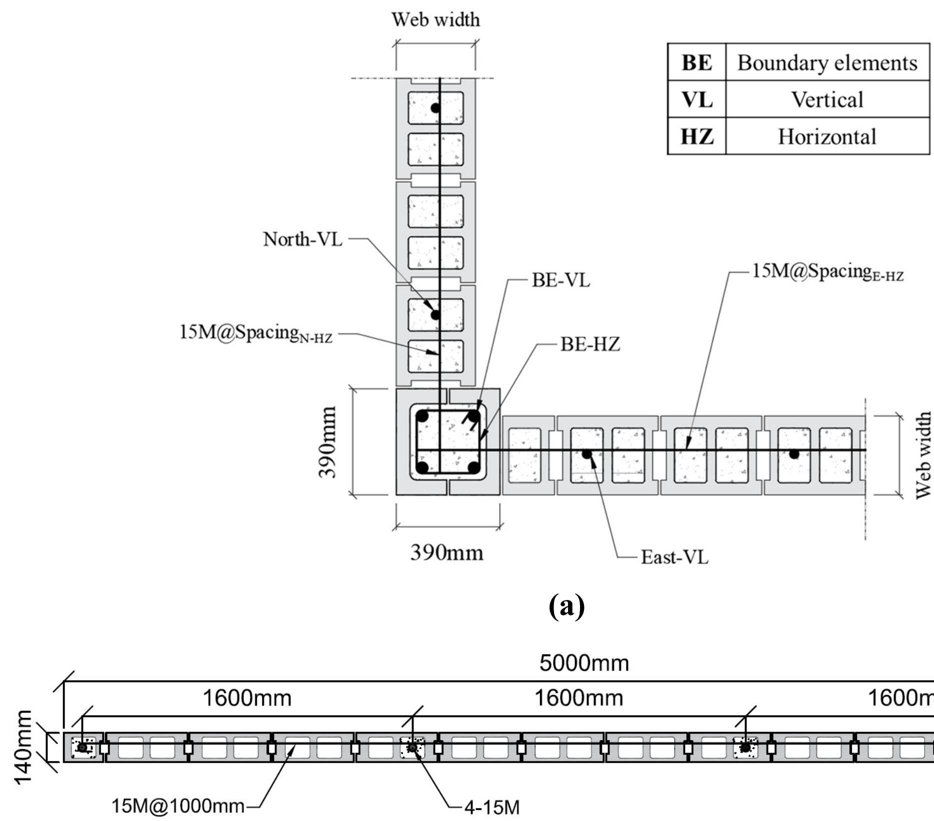
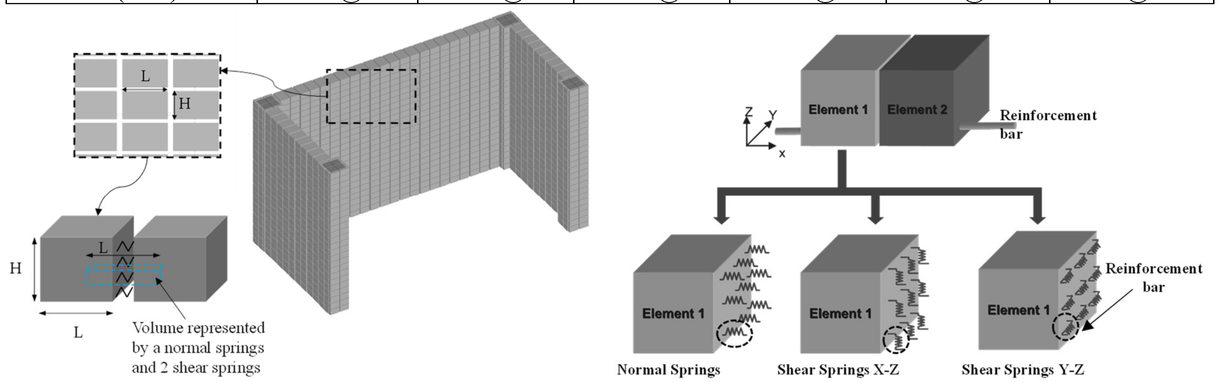


Figure 2: Typical Reinforcement details of: (a) RMCW+BEs; and (b) Partially grouted walls.

Table 2: Summary of reinforcement details for buildings

Reinforcement	10-Story			15-Story		
	Story 1&2	Story 1-3	Story 1-3	Story 1-3	Story 4-7	Story 8-15
Web width (mm)	290	290	290	290	290	190
North-VL	3-15M	3-15 M	3-15 M	3-15 M	2-15M	2-15M
East-VL	6-15M	6-15 M	6-15 M	6-15 M	4-15M	4-15M
Spacing$_{N\text{-}HZ}$ (mm)	600	600	600	600	1000	1200
Spacing$_{E\text{-}HZ}$ (mm)	200	200	200	200	1000	1200
BE-VL	4-20M	4-20 M	4-20 M	4-20 M	4-15M	4-15M
BE-HZ (mm)	15M@80	15 M@80	15 M@80	15 M@80	10M@250	10M@250



(a) **(b)**

Figure 3: AEM Modeling technique: (a) Element generation; and (b) Connectivity matrix springs.

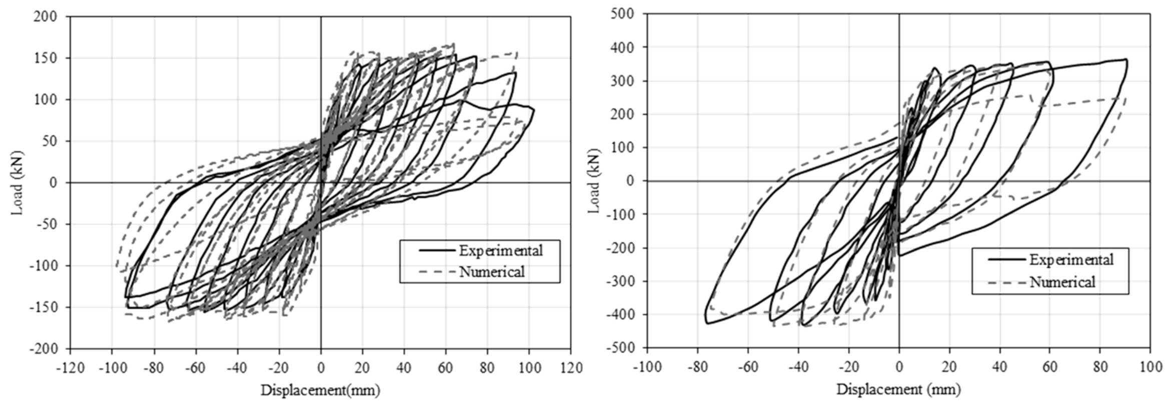
Model Validation

To the authors' knowledge, there is currently no available experimental data in the literature specifically addressing the seismic behavior of reinforced masonry core walls with boundary elements (RMCW+BEs). Consequently, the numerical models developed in this study are validated using experimental data obtained from tests conducted on RMSWs+BEs, as well as on reinforced concrete (RC) core walls. For the validation of the numerical models, experimental data from the study conducted by Shedid et al. [5] is utilized. This experimental program includes test on RMSWs+BEs with boundary elements. Additionally, experimental data from tests conducted on a single C-shaped RC core wall, as reported by Beyer et al. [20], is employed to further validate the robustness and accuracy of the developed numerical models in predicting the seismic performance of core walls.

The results obtained from the developed numerical model for RMSW+BEs are compared against experimental data provided by Shedid et al. [5], as illustrated in Fig. 4 (a). The cyclic behavior of the numerically modeled walls using ELS exhibits good agreement with the reported experimental results across various parameters, including initial stiffness, lateral load capacity, pinching behavior at different drift levels, as well as stiffness and strength degradations.

Similarly, the experimental results of Wall TUB tested by Beyer [20] validate the model's capability to accurately capture the cyclic behavior of core walls. The developed model demonstrates proficiency in capturing the core wall's cyclic response, including its initial stiffness, lateral load capacity, and pinching behavior. Fig. 4 (b) depicts the results of the developed model for the core wall, aligned with the corresponding experimental data of Wall TUB tested by Beyer.

The developed numerical model, along with the calibrated constitutive material models, effectively captures the behavior of the analyzed walls with reasonable accuracy. These walls exhibit different aspect ratios, cross-sectional configurations (e.g., rectangular with boundary elements, C-shaped), axial stresses, and varying vertical and horizontal reinforcement ratios. Therefore, the validated model is well-equipped to accurately predict the seismic response of reinforced masonry core walls with boundary elements utilized as the primary seismic force-resisting system in the current study.



(a) **(b)**

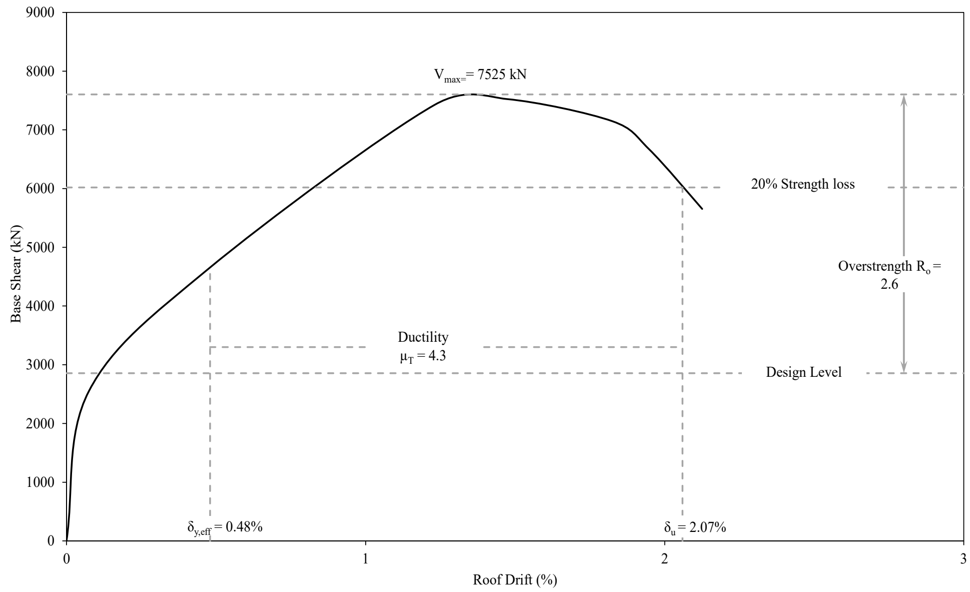
Figure 4. Comparison of results from of numerical model and the experimental data: (a) W1, [5]; (b) RC-Core, [20].

NON-LINEAR PUSHOVER ANALYSIS

Nonlinear static pushover analysis was carried out following the FEMA P695 [1] guidelines for the 10-, 15-story buildings in the east–west (E–W) and north–south (N–S) directions to assess the buildings' lateral load and deformation capacities. The pushover analysis considers the gravity and distributed lateral loads at each floor level following the FEMA P695 specifications. The pushover analysis results are utilized to compute the system overstrength (R_o) and the period-based ductility (μ_T). The system overstrength (R_o) is defined as the ratio between the maximum base shear (V_{max}) obtained from the analysis of the SFRS (i.e., RMCW+BEs) and the design base shear (V_d) calculated based on the CSA S304-14 code provisions. The period-based ductility (μ_T) is defined as the maximum roof drift (δ_u) obtained at 20% degradation in the system's strength, divided by the effective yield drift of the roof ($\delta_{y,eff}$), which is calculated as per equation Eq. [1], where C_o is a factor used to correlate the spectral displacement of an equivalent single-degree-of-freedom system with the roof drift of the multi-degree-of-freedom system, calculated following ASCE 41-06 [21], W represents the weight of the building, g is the gravitational acceleration, T represents the maximum natural period of the building (i.e., $2T_a$) specified by NBCC 2020 [11], and T_1 is the natural period obtained from the modal analysis.

$$(1)\quad \delta_{y,\mathrm{eff}} = C_o \frac{V_{max}}{W} \frac{g}{4\pi^2} \max\left(T, T_1\right)^2$$

The pushover curves are obtained for the SFRSs of the three buildings in the E–W and N–S directions, as shown in Fig. 5 and Fig.6. The RMCW+BEs showed an overstrength (R_o) of 2.6 and 3.3 for the 10-, 15-story buildings, respectively, for the E–W direction, while for the N–S direction, the system showed an overstrength of 3.4 and 3.6 for the 10-, 15-story buildings, respectively. The proposed SFRS (RMCW+BEs) exhibited an appropriate overstrength with the lowest value of 2.6 compared to the NBCC's specified design limit of 1.5 for ductile masonry shear walls. Furthermore, the pushover analysis results for the three archetype buildings showed a ductile response with a calculated μ_T of 4.3 and 5.4 for the E–W direction and 2.19 and 2.53 for the N–S direction for the 10-, and 15-story respectively. Table 3 summarizes the results of the performed nonlinear static pushover analysis for the 10-, 15-story buildings, with the RMCW+BEs as the main SFRS. Finally, assessing the system response using the nonlinear pushover analysis procedure following FEMA P695 emphasized the enhanced performance of using RMCW+BEs as a main SFRS in RM structures.



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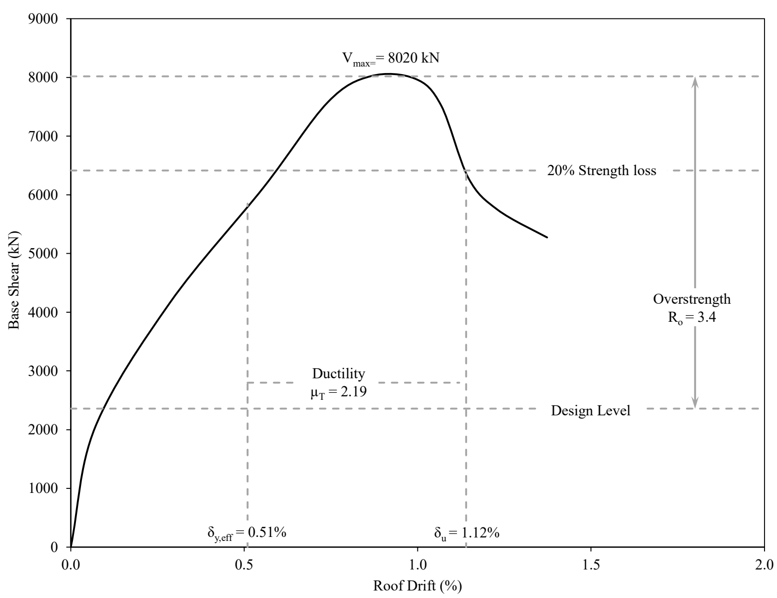
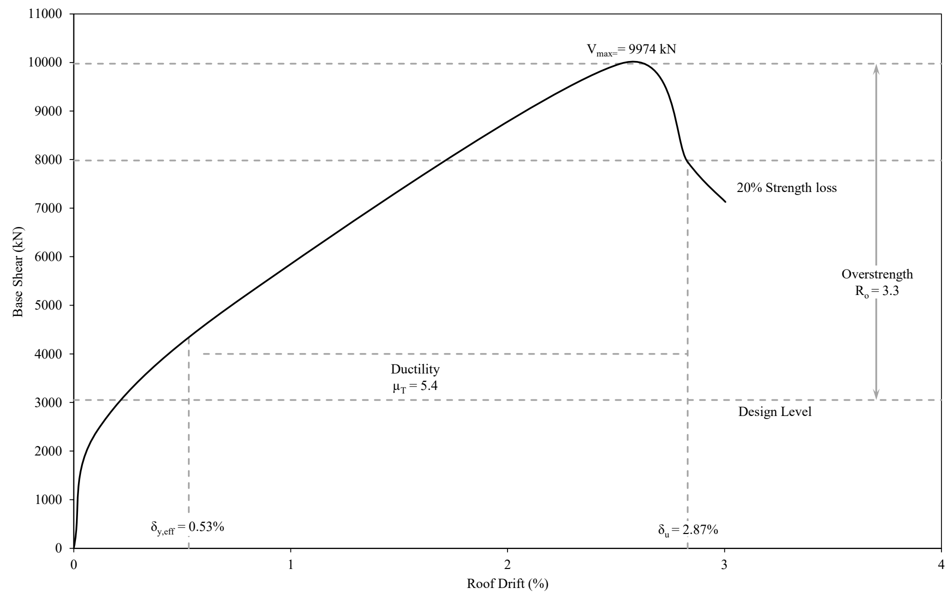


(b)

Figure 5: Nonlinear static pushover analysis results of the SFRS for the: (a) 10-story E–W; and (b) 10-story N–S.



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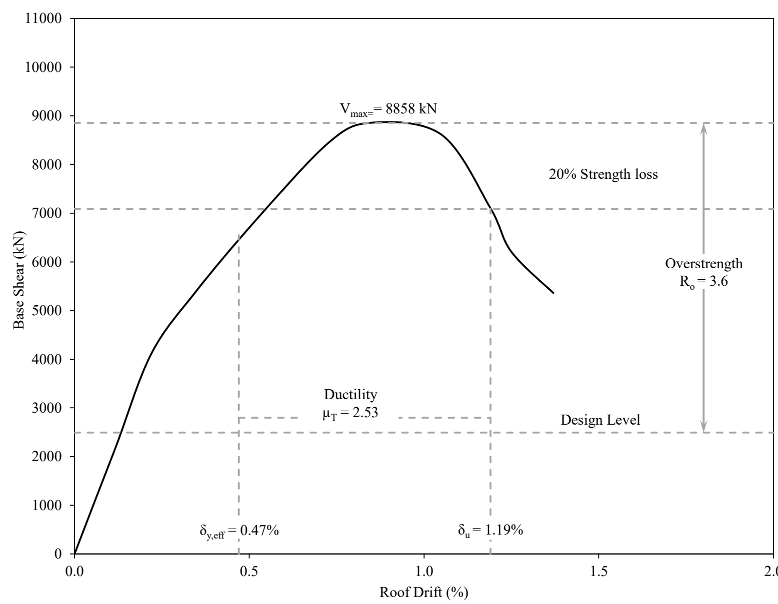

(b)

Figure 6: Nonlinear static pushover analysis results of the SFRS for the: (a) 15-story E–W; and (b) 15-story N–S.

Table 3: Summary of the results for the nonlinear static pushover analysis.

Building ID	Static R_o	$\delta_{y,eff}$ (%)	δ_u (%)	V_{max}	V_{max}/W (%)	μ_T
East–west direction						
10-story	2.6	0.48	2.07	7525	4.68	4.30
15-story	3.3	0.53	2.87	9974	4.16	5.40
North–south direction						
10-story	3.40	0.51	1.12	8020	4.99	2.19
15-story	3.60	0.47	1.19	8858	3.69	2.53

CONCLUSION

This study presents a seismic assessment of RM buildings with reinforced masonry core walls with boundary elements (RMCW+BEs) as the main SFRS. To achieve the aims of this study, three RM archetype buildings (10- and 15-story) were evaluated following the FEMA P695 [1] methodology using a three-dimensional (3D) numerical model developed using the extreme loading for structures software (ELS). The utilized numerical model was calibrated and validated against available experimental data in the literature, where it shows an excellent capability in capturing the walls' response in terms of the wall's initial stiffness, unloading stiffness at different drift levels, capacity, postpeak behaviour and inelastic deformation under cyclic loading. The validated numerical model was then used to perform a nonlinear pushover analysis for the three reference buildings to quantify the system overstrength (R_o) and the period-based ductility (μ_T) of the proposed structural system. The system overstrength (R_o) shall be determined according to FEMA P695 by incorporating broader range of buildings with different configuration and design parameters.

The nonlinear pushover analyses of the studied buildings demonstrated an enhanced response for RM structures with RMCW+BEs as the main SFRS compared to other RM counterparts (i.e., based on NBCC's specified parameters). In addition, it revealed reasonable strength and deformation capacities, while pushover curves have highlighted a notably improved ductile response, particularly as the height of the building's increases.

This study evaluates the seismic performance of RMCW+BEs as a new potential SFRS in RM structures. In addition, it quantifies the main seismic performance parameters of this newly proposed system. In addition, it enriches the numerical simulation database and modelling of RMSWs and RM buildings subjected to different seismic actions.

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