Enhancing the Seismic Resilience of Existing Reinforced Masonry Shear Wall Building by Incorporating Boundary Elements

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ABSTRACT

The resilience concept is known as the capacity of the structure to resist and maintain a certain level of functionality during and after an unexpected events such as earthquake. In this research work, a framework for the seismic collapse assessment of existing Reinforced Masonry (RM) Shear wall building was developed using numerical modelling approach. In the current study, a five story RM shear wall building, located in Los Angeles and designed based on the American Masonry code which was proposed by FEMA-451, is considered to assess the seismic performance of RM shear wall systems. The above-mentioned building was designed using rectangular RM shear walls, while the current study investigates the impact of incorporating boundary elements at the ends of the rectangular shear walls on the seismic performance of these building. A macro-model numerical approach was used to simulate the dynamic response of the RM shear wall buildings. The numerical model was first validated against the available experimental results to ensure the capability of the proposed model in capturing the hysteretic response of the RM Shear Walls. Afterwards, Incremental Dynamic Analysis is conducted on the building before and after incorporation of the Boundary Elements. The fragility curves were derived subsequently and were used to evaluate the performance function of the structures. In conclusion, the results show a significant level of enhancement in the seismic performance and resilience of the buildings with boundary elements.

Keywords: Fragility Assessment, Incremental Dynamic Analysis, Macro-model Numerical Approach, Reinforced Masonry Shear Wall, Seismic Performance, and Seismic Resilience.

INTRODUCTION

There have been many advancements in understanding the inelastic behaviour of Reinforced Masonry Shear Walls (RMSW) in recent decades. This understanding is a pledge for performance-based seismic design of the structures. The performance-based seismic design incorporates a specific performance level corresponding to the level of damage occurred in the structure (FEMA 445) [1]. The methodology correlates the damage state to a specific functionality level and losses of the whole system when the structure is prone to the seismic events. These definitions form the framework of the seismic resilience of a structure, which declares the level of functionality of a structure in the aftermath of unwanted seismic event. The concept of resilience also shows the capability of a system to resist and maintain its functionality during and after an unwanted event (i.e. flood, earthquake, fire, etc.) [2]. To assess the resilience of a structure against seismic events fragility functions need to be precisely derived after performing collapse assessment (FEMA P-58) [3]. Fragility functions has been used in the past for different applications (ATC-13) [4] where basically they correlate an engineering demand parameter (*EDP*) to the probability of collapse at a specified damage level (Hwang and Jaw [5]). These functions are necessary in predicting the level of damages and losses to evaluate the seismic resilience. Deriving fragility functions is possible through performing collapse assessment which can be done by following the available guidelines in the literature (FEMA P695, P-58, and ATC-13 [3,4,6]). However, all of these methods need Numerical and/or Experimental test matrices to predict the structural response against lateral forces. There have been a few numerical studies addressing the seismic behaviour of RMSW walls with Boundary Elements (BE), where incorporating BEs helps the RMSW to possess greater value of displacement and curvature ductility when imposed to high level of seismic loads [7]. Among the most recent studies, Shedid et al. [8] tested seven half-scale RM shear walls with different end configuration to assess the impact of confinement and shape configuration on the inelastic response of RMSWs. They have concluded that by using end-confined BEs the ductility level was enhanced significantly whereas a maximum saving of around 40% was observed in vertical longitudinal reinforcement in those type of RMSWs. More recently, Banting and El-Dakhakhni [9] tested five half-scale fully grouted RM shear walls with confined boundary elements. They considered different seismic design parameters such as aspect ratios, reinforcement ratio, and gravity load profile to assess the effect of adding BEs on each of them. It has been concluded that by using BEs, the buckling of the longitudinal reinforcement was postponed, therefore the post-peak strength of the walls was enhanced relative to the walls without BEs. In terms of numerical studies, Ezzeldin et al. [7] performed a collapse assessment analysis following FEMA P-695 methodology on the RMSWs before and after having BEs at the component level. They concluded that by using BEs the system was able to satisfy the proposed criteria of the methodology successfully with a great safety margin.

In the current study, the impact of using BEs on seismic response of a full 3D RMSW building is studied before and after adoption of BEs. In this regard, a macro-modeling numerical approach is used and a numerical model is developed in *OpenSees* platform [10]. The validation of the modeling approach was conducted against available experimental test results to ensure the capability of the modeling technique in prediction of the nonlinear behavior of the RMSW buildings. Subsequently, the above-mentioned modelling technique was utilized in modeling a five-story RMSW building located in Los Angeles, California. The building was initially designed and proposed by FEMA 451 [11]. Afterwards, the building was redesigned to incorporate end-confined BEs in the shear walls. Furthermore, Incremental Dynamic Analysis (IDA) was performed to diagnose the collapse mechanism of the building prior and after adoption of BEs. A suite of 44 far-field ground motion was used to perform IDA analysis in accordance to the FEMA-P695 recommendation. Fragility functions are derived for structural component based on the IDA results for different performance level considering both analytical and EDP-based failure criteria. In addition, the inter-story drift level and story shear response of the building is compared before and after using BEs to assess the damage level and probable losses due to the damages.

NUMERICAL MODELING AND ANALYSIS METHODOLOGY

A new modified macro-modeling approach is utilized to capture the nonlinear response of the RM shear walls using *OpenSees* platform. Four Displacement-Based (DB) beam-column element with fine discretization was used to model the shear walls' segment of one story level along with elastic shear links to resemble the shear flexibility of the shear walls and tentative failure due to sliding shear. Fiber-based approach found to be most suitable technique to model the inelastic response of wall components. In this regard, two different material model, namely Masonry and Steel, were assigned to the fibers to resemble the behaviour of each constituent part which will be elaborated on the subsequent section. Five Gaussian integration points were considered in DB Beam-Column elements to precisely capture the inelastic deformation of shear wall elements. Zero-length elements were used to model the shear deformation of the walls. A linear uniaxial Force-Deformation Elastic Material model relationship, originally introduced by Beyer et al. [12], was defined and assigned to the translational Degree of Freedom (*DOF*) respective to in-plane and out-of-plane direction of the wall and rest of the active *DOF*s were constrained to follow the previous nodal deformation using *EqualDOF* command incorporated in *OpenSees*. A fully restrained constraint was modeled and soil-structure interaction was ignored as per as recommendation of NIST (2010) [13]. a zero-length element section was modeled at the base level of the wall to capture the effect of strain penetration of longitudinal steel reinforcement using Bond_SP01 material available in the material library of *OpenSees* [14]. The schematic configuration of the wall segment nodes and elements are shown in Figure 1. Finally, *rigidDiaphragm* constraint was used to build a rigid diaphragm for the building and to assign the effective seismic masses to that center of mass node.

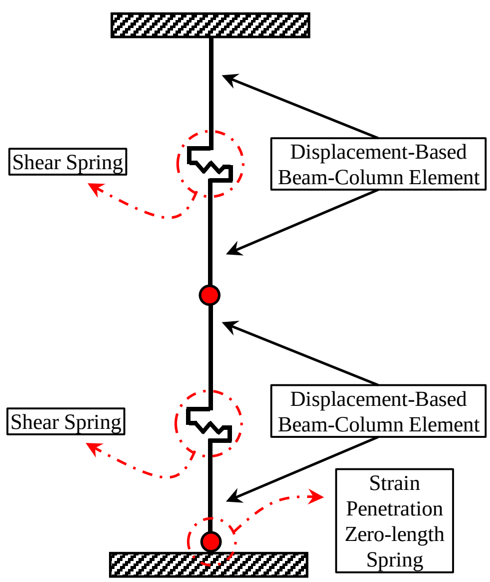

Figure 1. Schematic element assembly of the shear wall segment

Material properties

Fiber sections were assigned to DB Beam-Column elements to simulate the behaviour of masonry and steel reinforcement independently. Chang and Mander's [15] uniaxial material model (*Concrete07* in *OpenSees*) was assigned to the masonry fibers and were carefully calibrated based on available experimental data which is discussed in detail in validation part. The benefit of using this uniaxial material model is the capability of *Concrete07* to capture the post-peak behavior due to cracking and/or crushing of the masonry elements with a remarkable accuracy, which differentiate it from all other available constitutive material models available for concrete and masonry. The vertical reinforcement steel rebars were modeled using Menegotto-Pinto [16] Uniaxial constitutive material model for steel (i.e. *Steel02* in *OpenSees*) which is a common material model to capture the main characteristics of steel rebars including the yield strength, initial stiffness, isotropic strain hardening, pinching and strength degradation. The value of material properties parameters are consistent with the ones reported by the authors and researchers published the work and can be found on the original studies. The effect of buckling/rupture of the reinforcement could not be captured directly by *Steel02* Material, however, *MinMax* material model was used to mimic the aforementioned effect by restraining the ultimate strain of steel material. The value of 0.06 was considered based on the available experimental data to clarify the onset of rupture/buckling of the rebars. It is worth noting that, the failure criteria of the RMSW are considered in accordance to the recommendation of the original study of GCR 10-917-8 proposed by NIST (2010). The effect of confinement for the masonry material of Boundary Elements was considered following the recommendation of Chang and Mander [15].

Validation of modeling approach

The model verification was performed to ensure the robustness of the proposed modelling method in predicting the hysteretic response of RMSW structures. To achieve this goal, three half scale fully-grouted RM shear walls with different end configuration originally tested by Shedid et al (2010) was numerically modeled incorporating the above-mentioned methodology and was analyzed against reverse quasi-static cyclic loading scheme using the identical loading protocol performed in the structural lab. As can be seen in Figure 2 the proposed modeling approach was able to successfully capture the principal characteristics of hysteretic response of the RMSW subjected to cyclic analysis. In general, the model was able to predict the main response characteristics of RMSW including the initial stiffness of the walls, peak strength, post-peak degradation, hysteretic shape, and pinching of the element with great level of accuracy. A maximum difference of 7% and 13% was observed in capturing the maximum peak strength and hysteresis energy dissipation, respectively which is considered acceptable.

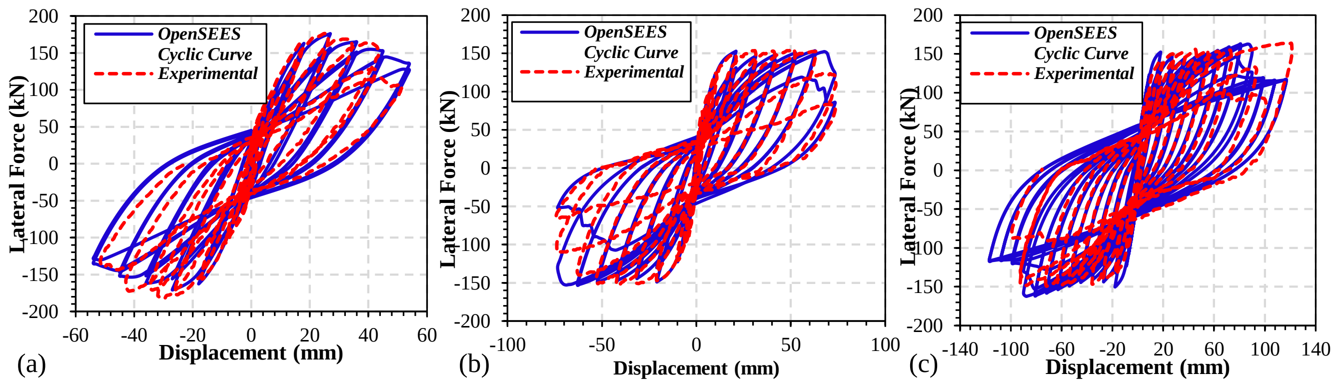

Figure 2. Comparison of Numerical versus Experimental Hysteretic loops: (a) W1; (b) W2; and (c) W3 (Experimental data from Shedid et al. 2010)

MODELLING AND SPECIFICATION OF STUDIED ARCHETYPE

In this paper, a five story residential RMSW building designed by FEMA 451 was considered to assess the seismic performance of such buildings prior and after adding boundary elements at the walls' ends. The building is located in Los Angeles, California and has structural walls of 8-in. thick reinforced masonry units. The roof was made of 8-in. thick hollow core precast pre-stressed concrete slabs. The building was built on site class D soil type and the Seismic Design Category of D was considered for it. The full detail of the building besides the configuration and design procedures of the buildings is fully discussed in FEMA 451[11]. The building was once again designed incorporating the identical seismic design parameters (i.e. Response modification factor and deflection amplification factor) while having boundary elements at its ends to investigate the impact of using boundary elements on its response. The reinforcement detail and configuration of the RM shear walls with boundary elements are summarized in Table 1.

Table 1. Dimensions and Reinforcement Configuration of RMSW building with Boundary Elements

Wall ID	Height (mm)	Length (mm)	Vertical Reinforcement ratio (%)	Horizontal Reinforcement ratio (%)	Aspect ratio
Wall A	13818	10972.8	0.4	0.13	1.26
Wall B	13818	10363.2	0.44	0.13	1.33
Wall C	13818	9956.8	0.50	0.15	1.39
Wall D	13818	9956.8	0.50	0.15	1.39

Both RMSW buildings were analyzed against a 44 far-field ground motion proposed by FEMA P-695 to assess the seismic collapse of the structure. Based on the adopted methodology, Incremental Dynamic Analysis (*IDA*) [17] was performed to track down the collapse initiation of the RMSW buildings. The analysis involves subjecting the structure to Nonlinear Time History Analysis by various ground motion suites and increase the intensity such that the ground motion record cause structure to fail or collapse at a certain degree in accordance to the predefined failure modes. The spectral acceleration of 5% damping was considered as intensity measure and maximum inter-story drift ratio was monitored as the demand parameter of interest. A five percent damping ratio was considered in the model analysis based on the Rayleigh damping formulation built in command of *OpenSees* which is a common value of damping ratio in Reinforced Masonry building practice.

Selection and scaling of ground motion records

Based on the recommendation of FEMA P-695, 44 far-field ground motions proposed by the methodology were used to perform IDA analysis. It's worth nothing that, using as many as possible record will help reducing the uncertainties arising from record-to-record variability. However, large computational effort is the main drawback of using such a large database of strong ground motions. The individual response spectrum of the unscaled records together with the median of the spectrums and upper and lower bound of seismic response spectrum of the specified site location is depicted in Figure 3.

The scaling method was followed as per as recommendation of FEMA P-695. First, the records were normalized to their peak ground acceleration and then the median of the spectrum were scaled such that it matches the Target response spectrum of Maximum Credible Earthquake (MCE) level at the fundamental period of the structure, *T*.

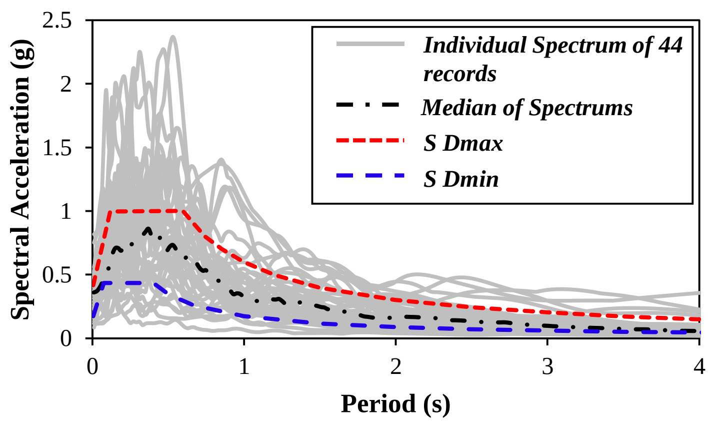

Figure 3 Response Spectrum of 44 unscaled Ground motions along median spectrum; Upper bound (S Dmax); and Lower bound (S Dmin)

SEISMIC ASSESSMENT AND PERFORMANCE ANALYSIS

After performing the analysis, the IDA curves were derived and are shown in Figure 4 for the RMSW building before and after adding boundary elements. As can be seen, by adding the boundary elements the collapse capacity of the system has been increased significantly. This result can be related to the fact that the boundary elements increased the wall's curvature ductility at the ultimate stage. The IDA curves also show that the dispersion of the response data of each archetype were lowered for different ground motion's frequency content in terms of inter-story drift ratio.

Quantification of performance parameters

The median collapse capacity of the structure, S_{CT}, was defined as per as the guideline methodology [6] as the intensity level which half of the records cause failure of the structure. The other term defined by the methodology is the Collapse Margin Ratio (*CMR*). This parameter is used to characterize the safety of the structure against collapse and can be calculated as the ratio of median collapse capacity (S_{CT}) to the spectral acceleration capacity of the structure at its fundamental period (S_{MT}). The calculated *CMR* value of the building before and after adding boundary element is presented in Table 2. As can be seen, the *CMR* value has been increased by adding the boundary element. This is due to the fact that the boundary elements has increased the confinement at the outermost fibers of the walls and postponed the buckling of longitudinal reinforcement, hence, leading to higher curvature and overall displacement ductility.

Collapse Fragility Assessment

The probability of the collapse versus the Intensity Measure (IM) can be derived by adopting a Cumulative Distribution Function (CDF) forming the Fragility functions. Fragility function parameters can be calculated as the logarithms value of each records *IM* value associated with onset of collapse with calculating the mean and standard deviation. The lognormal *CDF* can be defined as follows:

$$P(C \mid IM) = \Phi\left(\frac{\ln(\frac{x}{\theta})}{\beta}\right) \tag{1}$$

Where *P(C|IM)* shows the probability of collapse corresponding to specific *IM*; Φ is the *CDF*, and θ ,β are the mean and standard deviation of the data, respectively. A sample curve fitting dataset is shown in Figure 5 using the aforementioned method.

Table 2. Summary of CMR value of the building

Building ID	Configuration	$S_{MT}[T]$(g)	$S_{CT}[T]$(g)	CMR
5 Story Building Los- Angeles	Without Boundary Element	1.0	1.4	1.4
	With Boundary Element	1.0	2.1	2.1

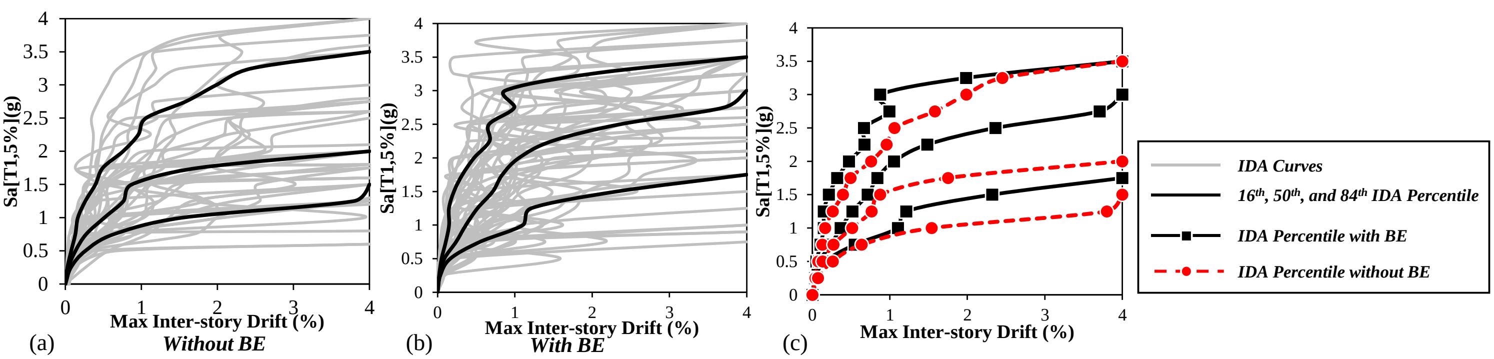

Figure 4. IDA Curves and 16th, 50th, and 84th percentile: (a) RMSW Building without Boundary Element; (b) RMSW Building with Boundary Element; (c) Comparison of the results.

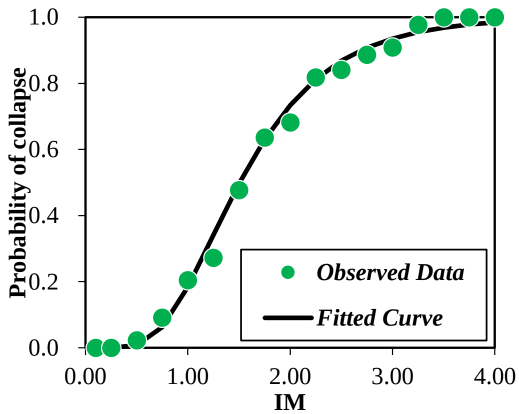

Figure 5. Sample Fragility Function Curve Fitting

The collapse fragility curve of the building before and after adding Boundary Elements were extracted for different performance level proposed by ASCE 41-17 [18] and presented in Figure 6. The results indicate that by using the boundary elements the collapse capacity of the building was increased for all performance level. The results highlight the impact of using boundary elements on delaying the collapse of the RMSW building at different level of inter-story drift ratio.

Inter-story Drift and Response Shear Variation

The variation of response story shear and the inter-story drift ratio of all records are shown in Figure 7 and Figure 8, respectively. The results show that by adding boundary elements the base shear of the building has increased, however, the initial stiffness of the building was considered to be identical for the building with and without boundary elements. It can be inferred that, due to higher level of ductility that RMSW with boundary elements has; the building could incorporate higher story shear at the upper level of the building (i.e. the story shear diagram shifted rightwards in the upper stories). Having higher story shear capacity within the identical initial stiffness will help controlling the losses and damages caused to the overall structure and helps increasing the seismic resilience of the building.

The inter-story drift ratio also was carefully monitored and it can be concluded that, having boundary elements helped the building to experience lower level of inter-story drift ratio which in turns means lower level of structural and non-structural damage of the components. Hence, higher seismic resilience can be estimated for such buildings.

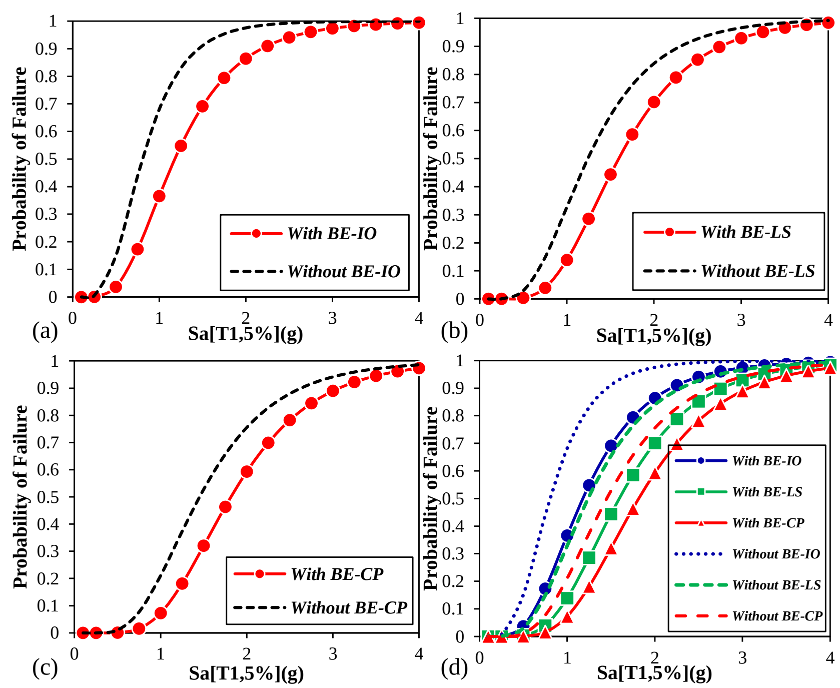

Figure 6. Fragility Curves of different Performance Levels: (a) IO; (b) LS;(c) CP; (d) Comparison of different performance levels

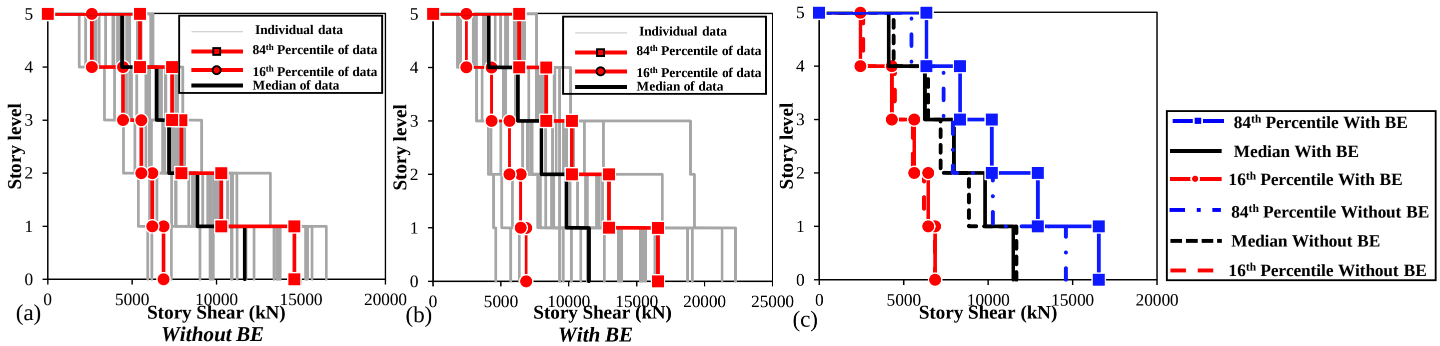

Figure 7. Response Story Shear Variation before and after Boundary Elements: (a) Without Boundary Elements; (b) With Boundary Elements; (c) Comparison prior and after adding Boundary Elements.

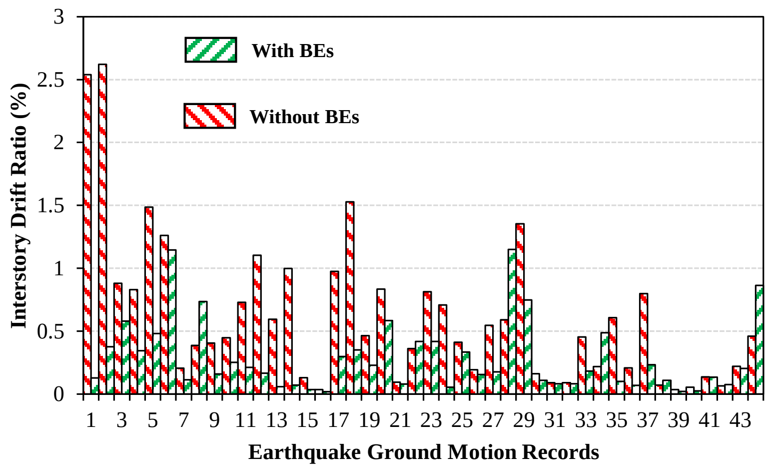

Figure 8. Inter-Story Drift Variation of the RMSW Building before and after having Boundary Elements

CONCLUSIONS

In this study, the impact of adopting boundary elements on the seismic behavior of a five-story fully-grouted RMSW building located in Los Angeles was investigated. A fiber-based macro-modeling approach was utilized to capture the inelastic behavior of RMSW and was validated against the experimental data to validate capability and robustness of the approach. Afterwards, *IDA* analysis was conducted on the numerical model and fragility curves were derived. Also, the variation of the story shear and inter-story drift ratio was studied after utilizing Boundary elements. The following remarks were concluded:

- The proposed modeling approach was able to capture both elastic and inelastic characteristic of the response of RMSW with outstanding level of accuracy. A maximum difference of 7% and 13% was observed in capturing maximum peak strength and hysteresis energy dissipation, respectively.
- The results of IDA curves show higher collapse capacity for the shear walls with Boundary elements, meanwhile, lower dispersion of data was found after utilizing Boundary Elements.
- The CMR ratio of the walls with Boundary Elements found to be higher than the rectangular walls due to the fact that BEs will delay the buckling of the vertical reinforcement besides confining the extreme sides of the Shear Walls which in turn leads to higher ductility and safeguards against collapse. A 50% increase in the *CMR* value was observed after adding Boundary Elements to the RMSW Building.
- The collapse fragility curves of the walls with BEs had up to 65% lower probability of failure for a specific intensity measure at different performance level as a result of possessing higher ductility.
- There was a maximum of 20 % increase in the response story shear after adding BEs and story shear diagram shifted rightwards in the upper stories by having BEs.
- The Inter-Story Drift ratio of the RMSW building with BEs had decreased dramatically for most of the records. Hence, lower level of damages are expected for structural and non-structural components of the building with Boundary Elements.

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