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BOUNDARY ELEMENTS CONFIGURATION INFLUENCE ON REINFORCED MASONRY SHEAR WALLS BLAST RESISTANCE

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ABSTRACT

Reinforced masonry walls *(RMW)* are commonly designed to resist gravity loads and in plane seismic force. Recently, several studies have focused on the out of plane performance of different types of masonry walls when subjected to blast load. Studies showed that adding boundary elements *(BEs)* on the edges of the walls enhances their blast resistance. The aim of this study is to investigate the influence of alternative *(RMW)* configurations using *(BEs)* on the out of plane resistance of walls under far-field blast loads. Four *(RMW)* with different *(BEs)* configurations are selected and detailed according to ASCE 59-11. Aspect ratios, reinforcement ratios, axial loads and materials are kept constant for all walls. In this respect, finite element models of the walls are developed using multi-layer shell elements. First, static push over analysis is conducted on the models to determine the influence of the different configurations on the flexure capacities. Afterwards, dynamic analysis under two different far-field blast loads is carried out to assess the response of the walls and level of damage according to ASCE 59-11. The parameters studied in this research are the boundary conditions and blast waves of different scaled distances. The current study facilitates a better understanding of the influence of *(BEs)* configuration on *(RMW)* in an effort to optimize *(RMW)* design and enhance their resistance to blast loads.

KEYWORDS: *blast loading, boundary elements, dynamic response, out of plane performance, reinforced masonry walls*

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INTRODUCTION

RMWs (Reinforced Masonry Walls) are commonly designed to resist gravity loads and in plane seismic force. Although loss of shear walls due to hazardous out of plane loading (e.g. blast loading) may lead to a progressive collapse of structures, limited number of studies addressed the performance of shear walls under out of plane blast loading in the last decades. Nourzadeh [1] studied the global responses of a building to in plane and out of plane dynamic loading, it is concluded that the blast loads could force the structure to deform laterally with magnitudes of deformations that are similar to or higher than those under seismic action. So, it would be necessary for the designers to check the lateral deformations and the global response of the buildings under blast loads, in the same fashion as for earthquake forces. Other researches studied the effect of different parameters on the out of plane performance of *RMWs*. Axial load's effect – for example – was studied on *RMW* under blast loading [2], [3], [4], and [5].

Several studies have focused on the enhanced ductility performance that reinforced RMW with *BEs* (boundary elements) provide to seismic force resisting systems [6] and [7]. Latest studies took into considerations the effect of adding these *BEs* at the edges of *RMWs* on their out of plane behaviour under blast loading [5] and [8]. Simonds [8] observed from the cracking patterns of tested walls and load transfer by the horizontal reinforcement, that the central panel of walls between *BEs* (i.e. web) responded in a two-way bending manner, and the two side boundary elements partially supported the vertical edges. Consequently, the deflections recorded at the mid height of the boundary element were between 20 and 50% less than the deflections recorded at the centre of the web when loaded with the same blast wave. The goal of this study is to investigate the influence of different design parameters on the performance of alternative *RMW*s with *BEs* configurations subjected to out of plane far-field blast loads. The design parameters include the boundary conditions of *RMW* and scaled distances of different blast waves.

TEST MATRIX

In this study, four full-scaled walls were selected with length and height of 3.2 m as shown in Figure 1. Walls' dimensions are assumed to be similar to average walls' dimensions in normal building (from 3 m to 4 m), and 3.2 m is chosen specifically to be simulated with a real number of blocks. Each wall had different configuration to study the influence of *BEs* on the wall performance using standard masonry concrete blocks (190 mm thickness x 190 mm height x 390 mm length). The BEs sizes are assumed to be equivalent to 2 blocks in thickness and one block in length (390 mm thickness and 390 mm length). *Wall (R)* represented the conventional configuration with no *BEs*. The effect of adding *BEs* at edges or at 0.40 m from edges is studied through *Wall (2B-E)* and *Wall (2B)* respectively. Finally, *Wall (3B)* had *BEs* at the centre of the walls and at the edges. Since all walls were detailed according to North American Standards [9 and 10], the walls had bar of area of 265 mm^2 in each cell as vertical reinforcement and bar of area 110 mm^2 every course for the horizontal reinforcement (i.e. reinforcement ratios were 0.62% and 0.25% for vertical and horizontal reinforcement, respectively). Meanwhile, each BEs had 4 bars each of area 250 mm^2 as vertical reinforcement (i.e. reinforcement ratio was 0.63% for vertical reinforcement).

Each wall configuration was macro modeled and analyzed using *Opensees Software* (Open System for Earthquake Engineering Simulation) [11] as will be discussed in the next section. Using these models, a parametric study was conducted to determine the influence of different design parameters on the out of plane performance. The parameters included the wall boundary conditions (fixed and hinged) and the effect of different scaled distances (1.3 and 1.8 $\text{m/kg}^{1/3}$) on different *RMWs* configurations with *BEs*.

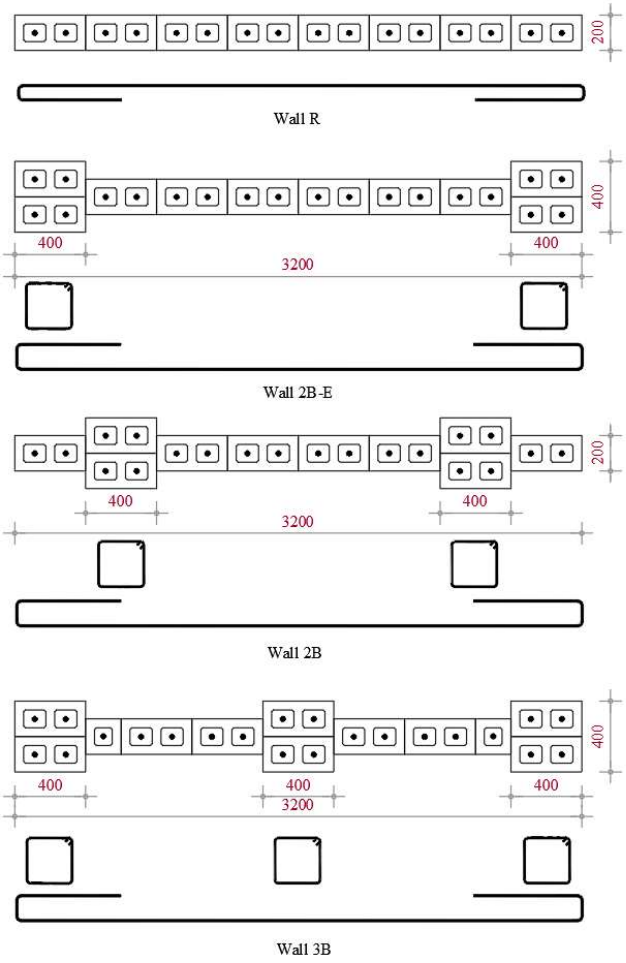


Figure 1: *RMWs* Configurations

Both concrete and reinforcing steel bars were assigned the same material properties in [3], the average masonry compressive strength for unconfined concrete was 21.2 MPa, and the reinforcement bars used in the walls have an average yield strength of 515 MPa. Since the BEs are confined with stirrups, the confined concrete strength was estimated to be 30 MPa using [12]. The ultimate compressive strain for confined concrete was assumed to be 0.007 as per experimental results in [5].

For the four basic models, the walls' aspect ratio is taken equals to 1, as both the height and the width are 3.2 m. For the boundary conditions, the walls are assumed as hinged from top and bottom edges, simulating an ideal hinged connection between wall and slab. The studied walls are restrained in vertical direction so no axial load transferred to them (non-load bearing walls).

FINITE ELEMENT MODEL

Although blast design standards in the United States allow the use of equivalent single-degree-of-freedom models to simulate structural components subjected to blast, there are some limitations associated with such models that may result in inaccurate predictions, as discussed by El-Dakhakhni et al. [13]. Alternatively, *FE* (finite elements) models can be used to more accurately describe a component's geometrical details, boundary conditions, and material properties. Subsequently, in the current study, a layered FE model (LFEM) was utilized to simulate the out-of-plane response of *RMW*s using *OpenSees.* This parametric study includes studying the effect of different configurations of BEs on the out-of-plane performance of RMW under both quasistatic loading and dynamic blast loading based on previously verified models [14]. The four quasistatic verified models in El-Hashimy et al. [13], showed an average deviation in wall resistnace (i.e. out-of-plane load copacity) of 16% and 6.6% relative to experimantal results of walls without and with BEs, respectively. While the seventeen dynamic models [14], showed an average deviation of 12.9% and 11.3% relative to experimental results for displacements of walls without and with BEs, respectively. The following sections describe the model geometry, material models adopted, and both quasistatic and dynamic analysis and results.

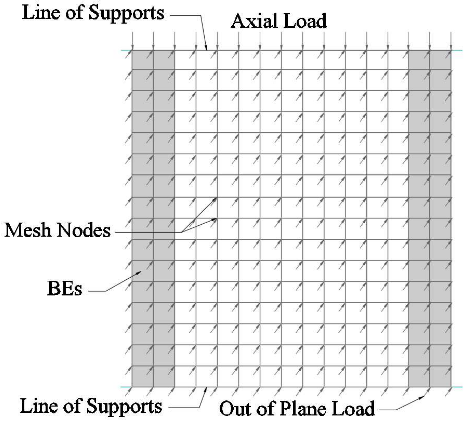
Model Geometry

For macro finite element model, the *RMWs* were simulated as multi-layer shell element following the concrete model developed by [15]. The use of multi-layer shell element represented in *OpenSees* with element ShellMITC4 resulted in good agreement with the results from experimental testing [15] and [5]. A sketch for the model geometry is shown in Figure 2, illustrating the meshes distribution and load directions. The ShellMITC4 is composed of multi-layers representing the concrete masonry and vertical and horizontal reinforcement. The vertical reinforcement is represented by one middle layer along the webs of the wall with its equivalent thickness corresponding to the walls' thicknesses and by two layers in BEs. While the horizontal reinforcement is represented by two layers surrounding the vertical layers. The mesh size is chosen equals to the masonry block height h_b according to [5] to optimize the model behaviour and the upper and lower lines of nodes are restrained according to the boundary conditions in each case.

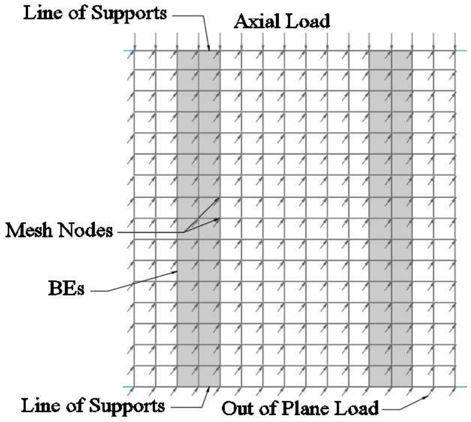
Material Model

Two material models are used in this study, one for concrete masonry and the other for the reinforcement. Two types of concrete are defined using Plate from Plane Stress Material definition in *OpenSees* [14 and 15], with average compressive strength, f_m', as mentioned before, young's modulus, E_m, equals 900 f_m' and shear modulus, *G*, equals 0.4 E_m according to [9]. Unconfined concrete was used for the webs of the wall, and confined concrete for the concrete confined by ties in the *BEs* zone.

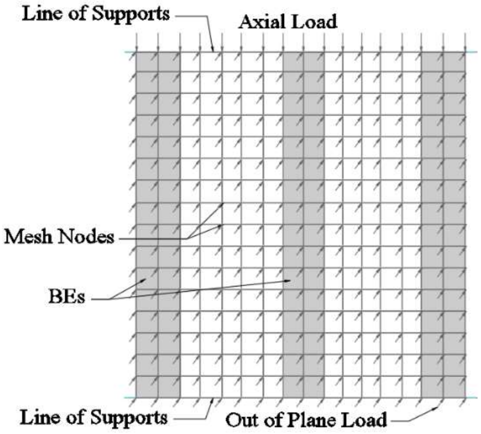
Both the vertical and horizontal reinforcement details/ratios were modeled as an equivalent thickness of steel layers, thus the PlateRebar material model (available in *OpenSees*) was used. The yield strength, f_y, for each type of reinforcement, was defined based on experimental tension tests [9], and the strain hardening ratio (ratio between post-yield and initial elastic tangents of 1% was assumed, while the steel Young's modulus, E_s, was taken as 200 GPa.



a) Wall 2B-E



b) Wall 2B



c) Wall 3B

Figure 2: Sketch for Model Geometry for Different Walls' Configurations

Quasistatic and dynamic load Models

In order to assess the resistance function (i.e. load-displacement relation) of the selected walls under quasistatic loading. The *RMWs* models were analyzed by applying load at each node in the out of plane direction displacement controlled using the node at the centre of the web. The boundary conditions were assumed to be fully hinged for the basic four configurations, while no axial loads are transferred to walls.

On the other hand, for the dynamic models, since blast loads is characterized by very high loading rates, DIFs (Dynamic Increase Factors) were applied for the material properties to account for high strain rate effects, subsequently DIF is taken equal to 1.2 for both concrete and reinforcing steel material according to [16]. The damping effects were also considered through Rayleigh damping formulation, with damping ratio of 5% as suggested by [17].

Since scaled distance, Z, is an important parameter for classification of blast load scenarios and it was used in this study to represent the blast wave which is a function of the equivalent charge weight of the explosive material, W, and the standoff distance from the detonation source, R.

$$Z = R/W^{1/3} \tag{1}$$

Based on Z, blast loads can be categorized into near-field and far-field detonations. Under a far-field detonation, the reflected blast pressure is applied to the target structure as a uniformly distributed loading. However, the shape of distributed blast loading tends to be more concentrated around explosion effective area with decreasing the scaled distance for near-field detonations. According to ASCE 59-11, blast loads with Z less than 1.2 $\mathrm{m/Kg}^{1/3}$ are identified as near-field detonations. Blast load is changed in this study based on Z values to study its effect on RMW. So, two different far-field scaled distances are used in this research which are 1.3 $\mathrm{m/kg}^{1/3}$ and 1.8 $\mathrm{m/kg}^{1/3}$.Thus to apply such blast wave to the model, a time series pressure time history was generated based on the selected scaled distance and was assigned to the load acting on each node.

PARAMETRIC STUDY RESULTS

Quasistatic loading results

Static pushover analysis was conducted on the models to determine the influence of different BEs configurations on the flexure capacities and ductility performance. Out of plane displacement-controlled pressure is uniformly distributed on the modelled walls. Consequently, the walls' resistance functions are shown in Figure 3.

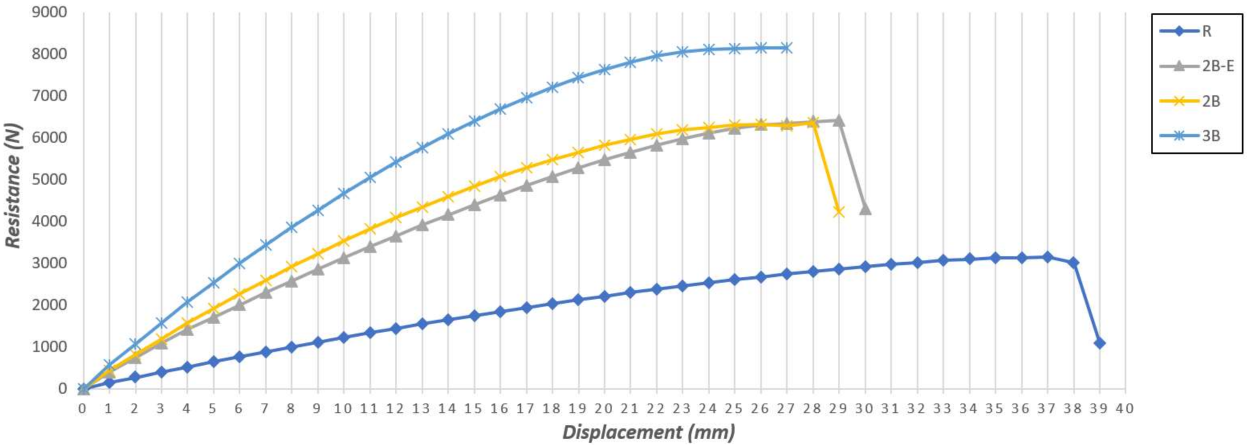


Figure 3: Walls' Resistance Functions

From Figure 2, it is observed that *Wall (R)* had the lowest resistance and maximum deformation. This was expected due to the absence of the dual layer of reinforcement provided by the *BEs*. As for *Walls (2B-E) (2B)* and *(3B)*, the resistance function showed enhanced performance, with the former two, having resistance almost double that of *Wall (R)* and *Wall (3B)* approximately has a resistance which is 2.5 times that of *Wall (R)*. While considering the maximum displacements of walls, *Walls (2B-E) (2B)* and *(2B)* have lower displacements than *Wall (R)* by around 30%. This reflects the enhancements a conventional RMW may gain by using BEs. It is also clear the influence of adding such BEs on increasing the initial stiffness of the RMWs and decreasing the maximum displacements.

DYNAMIC RESULTS

BEs Configurations

One of the main goals of this study is to determine the effect of BEs and their locations on the out of plane behaviour of RMW under blast load. The four basic models shown in Figure 1 are studied under blast loading with the scaled distance taken as 1.3 $\mathrm{m/kg^{1/3}}$ [(W) = 12 kg, and (R) = 3 m]. As shown in Table 1, the deflections and support rotations are used to understand the effect of different BEs' configurations on the out of plane behaviour of RMW. It is observed for *Wall (2B-E)* that the deformations decreased at centre by 31.3%, while decreased by 61.1% at edges. This is because the BEs at edges forced the wall web into a two-way mechanism rather than one-way in the conventional *RMWs* as mentioned before [8]. Moreover, for *Wall (2B)*, the deformations at midspan and edges decreased by 41% and 51% respectively than that of *Wall (R)*. This further reduction in mid-span deformation is attributed to the reduced spacing between BEs in *Wall (2B)*. By adding third BEs in *Wall (3B)* deformations and support rotations at middle and edges was further reduced. In this case, the deformations at centre decreased by 49.7% than that of *Wall (R)*, while at edges decreased by 63.2%.

Table 1: Summary of Results of Basic Models

Points of Comparison	R	2B-E	2B	3B
Max Deformation at Mid Span (mm)	40.63	27.91	24.03	20.44
Max Deformation at Edges (mm)	40.47	15.73	19.96	15.30
Support Rotation at Mid Span (degrees)	1.45°	1.00°	0.86°	0.73°
Support Rotation at Edges (degrees)	1.45°	0.56°	0.71°	0.55°

Regarding the support rotations, it is observed that adding BEs with various configurations can improve the behaviour of *RMW*s to get lower support rotations with approximately the same percentages of decrease in deformations. In the studied case, all configurations with and without BEs did not exceed the hazardous level of damage according to [10], as they resulted support rotations less than 2°.

From all the previous results, it is concluded that the existence of BEs greatly decreases the deformations and support rotations especially at their locations. As for the different studied configurations, the maximum deformations and support rotations decreased by average of 55% when adding BEs. It is also concluded that the best location for BEs – with respect to the deformations and support rotations – is at edges, and if it is capable to add one more BE at middle it will be much better for deformations at midspan.

Boundary Conditions

In order to assess the boundary condition effect on the selected *RMWs*, the results of hinged supports at top and bottom sides (H) are compared to their counterparts with fixed supports (F) as shown in Figure 3. *Wall (R-F)* displacement at middle and edges decreased by around 55% than that of *Wall (R-H)*, while the deformation of *Wall (2B-E-F)* decreased at mid span by 40% and at edges by 65% than *Wall (2B-E-H)*. This trend was similarly observed for *Walls (2B-F)* and *(2B-H)* as well. For *Wall (3B-F)*, it is observed that the deformation at mid span and edges decreased by 52% and 63% respectively than *Wall (3B-H)*. Noting that, it is shown from Figure 4 that wall (2B-E-F) gives lower deformation at edges than *Wall (3B-F)*, this is only because these curves are conducted at time of maximum displacement for the whole wall. This means that for *Wall (2B-E-F),* at time of maximum displacement at middle – which is wall's maximum deformation – the displacement at edges doesn't reach its maximum. It can be concluded that when the boundary conditions are changed to fixed connections, the deformations and support rotations decreased by average of 50% than the hinged RMW. However, it is more tedious to conduct fixed connections for walls with slabs.

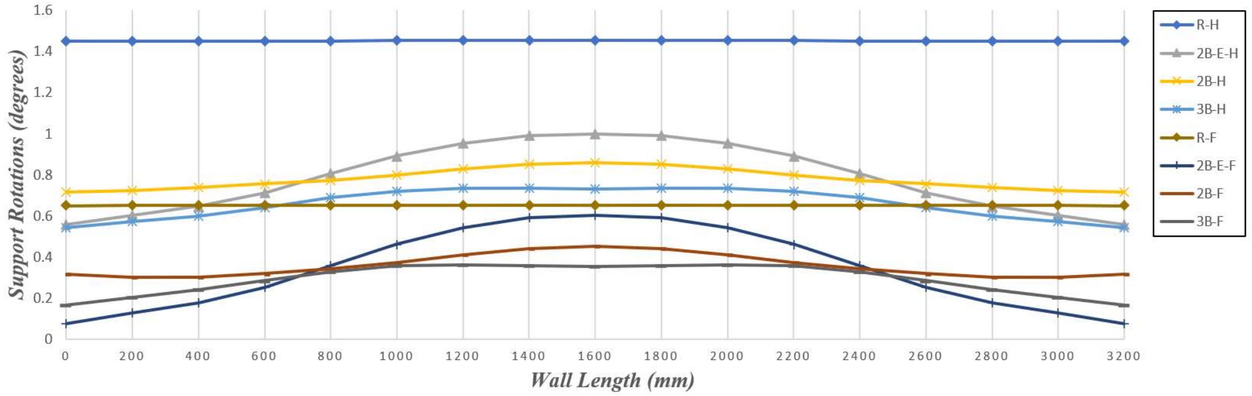


Figure 4: 2D Profiles of RMW with Different Boundary Conditions

Scaled Distance

The performance of *RMWs* under blast load of scaled distance 1.3 $\mathrm{m/kg^{1/3}}$ (ZL) and 1.8 $\mathrm{m/kg^{1/3}}$ (ZH) are compared as shown in Figure 5. According to ASCE 59-11, blast loads with scaled distances less than 1.2 $\mathrm{m/kg^{1/3}}$ are identified as close-in detonations while far-field detonations are only studied in this research. So, wave with scaled distance 1.3 $\mathrm{m/kg^{1/3}}$ is considered –eased by around 38% to get blast wave of scaled distance = 1.8 $\mathrm{m/kg^{1/3}}$ to estimate the effect of different blast loads on the out of plane performance of RMW. Blast wave of scaled distance = 1.3 $\mathrm{m/kg^{1/3}}$ is corresponding to stand-off distance between explosive source and the structure (R) = 3 m and quantity of explosive (W) = 12 Kg. While Blast wave of scaled distance = 1.8 $\mathrm{m/kg^{1/3}}$ is corresponding to stand-off distance between explosive source and the structure (R) = 5 m and quantity of explosive (W) = 12 Kg.

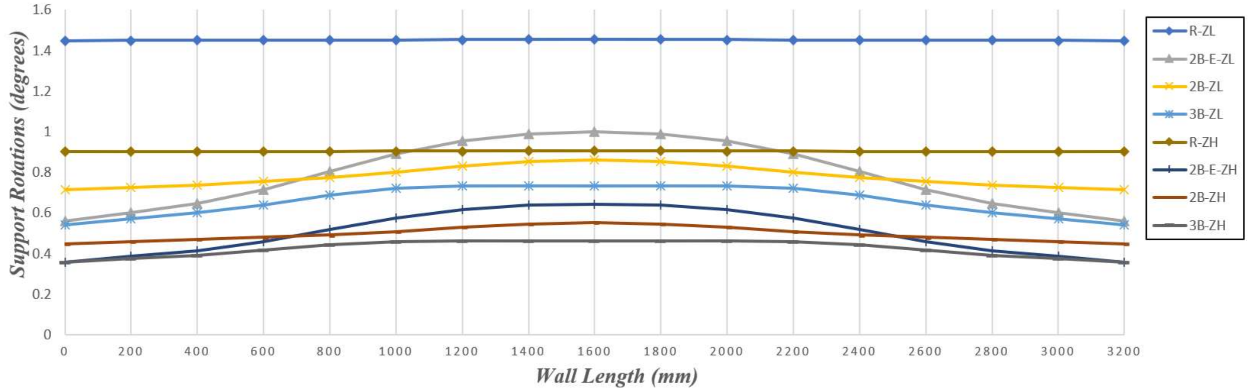


Figure 5: 2D Profiles of RMW Under Different Blast Waves

As shown in Figure 5, it is observed that the displacements of *Wall (R-ZH)* are lower than those of *Wall (R-ZL)* by around 38%. While the deformations and support rotations of *Wall (2B-E-ZL)* decreased at middle by 36% and at edges by 35% than those of *Wall (2B-E-ZH)*. Concerning *Wall (2B-ZL)*, its deformations decreased at middle by 36% and at edges by 37% than *Wall (R)*. It is also observed that the deformation at mid span and at edges for *Wall (3B-ZL)* decreased by 37% and 34% respectively than that of *Wall (3B-ZH)*.

To summarize all these results as the deformations for all configurations almost decreased by approximately 36% increasing the scaled distance with 38%. Comparing the results of different configurations under the higher scaled distance *(ZH)*, it is concluded that they all have the same trend as the configurations under *(ZL)* mentioned before.

CONCLUSIONS

Latest studies investigated the out of plane response of reinforced masonry shear walls *RMW* with boundary elements *BEs*. These results showed that adding BEs on the edges of the walls enhances their blast resistance. Therefore, the influence of alternative configurations of the out of plane performance *RMWs* with *BEs* was investigated under quasistatic and far-field blast loads. The influence of different design parameters on the wall out of plane behaviour was highlighted. These parameters were studied under four different configurations *RMWs* with *BEs*. Boundary conditions and scaled distances are the parameters considered in the dynamic analysis of this study.

It is concluded that the *BEs* enhance the walls' performance under blast loading resulting in reduced support rotations and higher resistance. Considering the levels of damage according to ASCE 59-11, adding BEs with various configurations can improve the behaviour of *RMW*s to get a lower level of damage through lower support rotations.

Concerning the different parameters studied, it is concluded that fixed boundary conditions at top and bottom sides increases the stiffnesses of *RMW*s effectively. So, it is worth to construct RMW with fixed connections with slabs if applicable by the designer. And finally, it is concluded that different configurations of *RMWs* with *BEs* have the same trend under different blast loads. Further investigation is required for different blast scenarios to investigate these walls under more severe blast waves.

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