MODELING OF REINFORCED MASONRY WALLS WITH BOUNDARY ELEMENTS UNDER BLAST LOADING

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ABSTRACT
Boundary elements (BEs) have been shown to enhance the in-plane performance of reinforced masonry (RM) walls, in terms of both section capacity and ductility. For this reason, in 2014 these elements were introduced in the Canadian standard S304-14 as a seismic force resisting system. When their out-of-plane performance is considered, BEs can significantly increase the load-bearing capacity of RM shear walls when subjected to blast overpressure from live explosives. However, the mechanism by which the wall capacity is affected is still unclear. To shed some light on this problem, a BE-wall was tested statically by the authors to examine the interaction between BEs and the web as well as the change in wall's stiffness beyond its elastic range. In this investigation, two approaches are proposed to model the post-elastic stiffness of the test specimen and their predictive capabilities are discussed on the basis of data from static testing. Furthermore, a single-degree-of-freedom model is used to simulate the maximum out-of-plane displacement experienced by the same wall when subjected to blast overpressure. The numerical results are compared to data from field testing of nominally identical BE-walls, to verify the adequacy of the adopted model. The current study contributes to the growing understanding of BEs' influence on the deformation of the wall central panel.

KEYWORDS: *reinforced masonry, boundary elements, out-of-plane response, blast load*

INTRODUCTION
In the 2014 edition of the Canadian standard S304 [1], boundary elements (BEs) were included as a method for increasing the ductility of earthquake resisting systems. Previous studies [2,3] have

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shown up to 109% increase in the in-plane ductility of BE-walls compared to regular masonry walls. This phenomenon was attributed to the additional reinforcement accommodated inside the BEs and absent in standard masonry walls. As shown Figure 1, the presence of two layers of reinforcement facilitates the arrangement of hoops at the edges of the wall section, thereby instigating a confining effect that augments the ultimate compressive strain of masonry and increases the cross-sectional ductility.

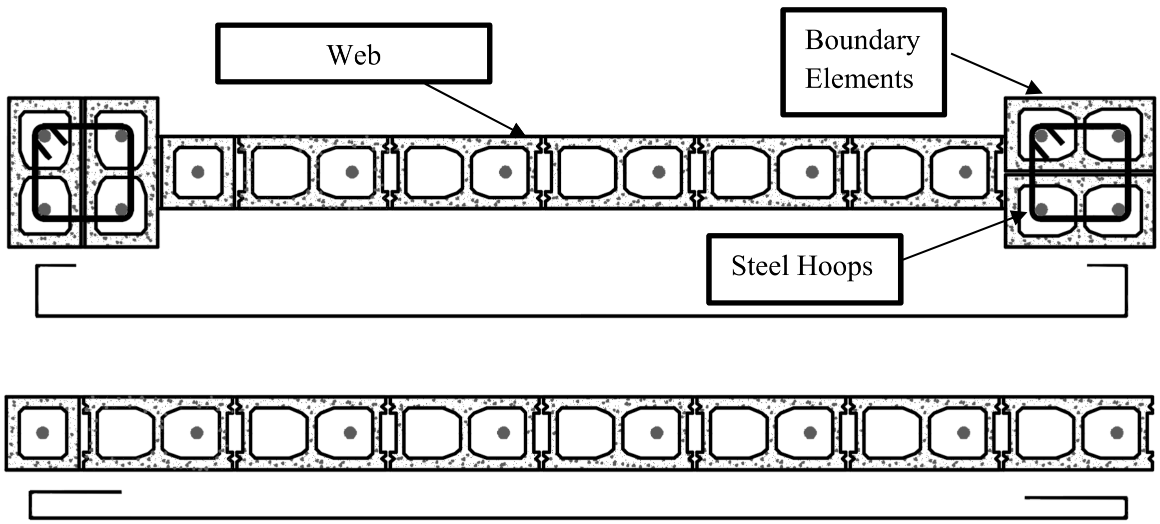

Figure 1: Reinforcement detailing in BE-walls vs. regular walls

Most studies on BE-walls have been performed to investigate their performance in the in-plane direction, which is key in a system designed to resist seismic action. On the other hand, their performance under out-of-plane bending, induced by either wind or blast loads, is yet to be fully investigated. Blast loading, in particular, may have severe effects on specific structural components, whose failure may initiate progressive collapse and cause disproportionate, catastrophic losses in a community at a time of crisis. To better understand the blast resistance of masonry, an experimental investigation involving live ammunition was carried out on BE-walls [4]. The deformed shape of the walls showed a two-way bending mechanism developing through the wall's web—the central panel between boundary elements. A nominally identical wall was tested by the authors under static loading, to investigate the interaction between web and BEs. Static test data are used in this paper to establish a load-deflection relationship, which is assumed as input in a single-degree-of-freedom (SDOF) model. Its predictions are compared with the data gathered from arena testing with explosive charges, to discuss the applicability of the adopted model and advance the current understanding of BE-wall mechanics.

BE-WALL EXPERIMENTAL INVESTIGATION

In 2014, dynamic tests were performed on BE-walls as a part of a study [4] that used live explosives to determine the behavior of reinforced concrete block masonry under blast waves. Afterwards, static testing was carried out in a laboratory setting on a nominally identical wall to determine its mechanical behavior. The results of both testing stages are discussed in this work to develop a greater understanding of BE-walls performance.

Geometric and material properties

Three fully grouted RM walls were built as third-scale models of full-scale 3.0 × 3.0 m walls. The overall width of the wall and the width of each BE were 1.00 m and 126 mm, respectively; the thickness of the web and that of the BEs were 63 mm and 126 mm, respectively. For vertical reinforcement, D4 bars were used, with yield stress of 477 MPa and tensile strength of 515 MPa. Six bars were distributed in the web, at every other cell, while 4 bars were placed in each BE. The horizontal reinforcement consisted of W1.7 wires (yield stress = 268 MPa, tensile strength = 362 MPa) mounted at every other course in the form of one hooked bar (web reinforcement) and two hoops (BE reinforcement). Standard prisms were assembled and their average compressive strength was found to be 19.4 MPa. The selected boundary conditions involved fixed supports at both ends; in an attempt to achieve this goal, C-channels were mounted on the restrained sides and welded to two lateral (vertical) steel plates spanning top to bottom, as shown in Figure 2. These two plates restrained the C- channels' rotation, thereby providing a sufficient degree of fixation. In addition, the vertical reinforcement was also welded to the foregoing channels, in order to simulate the necessary development length beyond the supports.

Figure 2: Wall C-section steel support configuration.

Dynamic Testing

Two of the walls characterized earlier were tested in the field using Pentex D explosive (Pentolite), which has an equivalent TNT factor approximately equal to 1.2. Charges of two different weights were detonated at a 5.0 m distance from the center of each specimen; the scaled distances associated with these two experiments were Z = 2.18 m/kg$^{1/3}$ and 2.75 m/kg$^{1/3}$. In each test, one wall was placed in a steel bunker that supported the wall's top and bottom edges while providing sufficient clearance for the BEs to deform freely [4]; the latter measure was taken to ensure that no additional support would be provided along the walls' vertical edges. A linear variable differential transformer (LVDT) was positioned behind each wall at the center of the web. The recorded maximum deflection (Δ_{exp}) is reported in Table 1 for walls W-6 and W-12, tested with charge weights equivalent to 6 kg and 12 kg of TNT, respectively; the calculated support rotation (θ_{exp}), which is considered a key parameter in assessing the component damage level by the Canadian standard CAN/CSA S850-12 [5], is reported as well. Based on the support rotations, both walls were categorized as moderately damaged according to both Canadian [5] and American [6] Standards.

Table 1: Test results of BE-walls subjected to blast load

Wall ID	**Z (m/kg$^{1/3}$)**	**Δ_{exp} (mm)**	**θ_{exp} (deg.)**
W-6	6	27.8	3.2
W-12	12	48.0	5.5

Static Testing

The load-deflection function (or resistance function) of the wall is a key property that needs to be characterized for inelastic dynamic analysis. In most cases, a simple elasto-plastic relation is a standard assumption for intermediate reinforced masonry walls; however, due to the presence of BEs, the applicability of any pre-established approach is called into question. For the purpose of the current analysis, static testing was performed to determine the resistance function, in order to use it in numerical simulations of the wall blast response and compare the output displacement history with test data. Different approaches have been attempted to match the test records with predictions, and their accuracy is discussed in the following sections.

One wall matching the geometric and material properties of the specimens tested in the field was subjected to out-of-plane static loading under controlled laboratory conditions. The load was applied using a pneumatic airbag mounted between the wall and a rigid self-reacting support , as shown in Figure 3. During testing, the applied load was measured by load cells positioned between wall and self-reacting frame, while the displacement of the web and BEs at the mid-span were measured by LVDTs. The records show that up to 25.8 kN (40% of the failure load) both web and BEs experienced almost the same mid-span displacement, as the difference in terms of secant elastic moduli between web and BEs is less than 5%. For greater loads, the web exhibited a significant decrease in stiffness while the BEs maintained their initial stiffness up to 33.4 kN (51%

of the failure load), as shown in Figure 4. The wall attained a failure load of 65.3 kN, at which point the web developed vertical and horizontal cracks followed by crushing of the concrete face shells in the web, which ultimately led to wall failure.

At the point of incipient failure, when the load attained its peak value, the web exhibited higher displacement than the BEs, by about 230%, and revealed the crack pattern shown in Figure 5. Upon careful visual inspection, some ruptured horizontal bars were also noticed through the cracks. In addition, the masonry damage observed at the wall's lower and upper courses confirms that at least some degree of fixation was effectively applied to the walls' edges, albeit not necessarily full fixation. Based on these finding it is clear that the wall experienced two-way flexure. Meanwhile, the BEs experienced significant cracking on the tension side but did not suffer any compression failure at midspan, which may be attributed to the confining effect of the hoops. These observations suggest that the BEs do not follow the behavior noted for the web, yet they affect the web deformation and the overall wall performance to a significant degree.

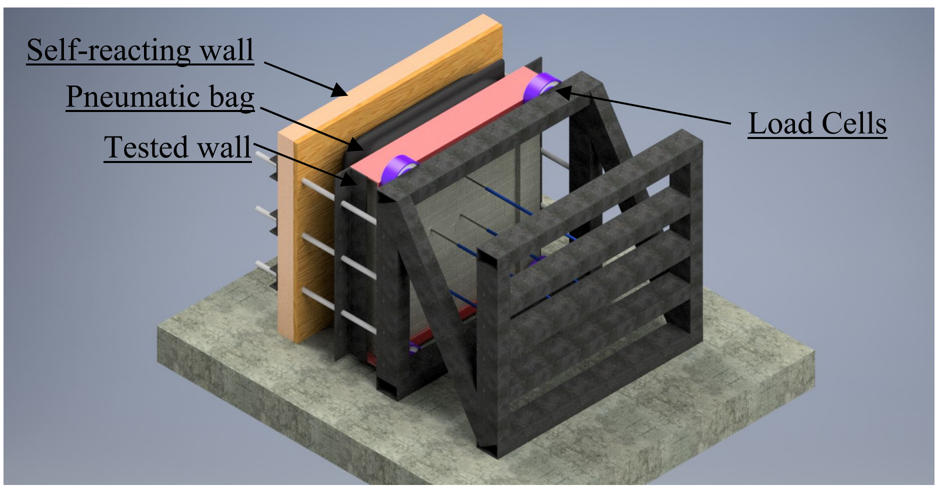

Figure 3: Schematic of the static test setup

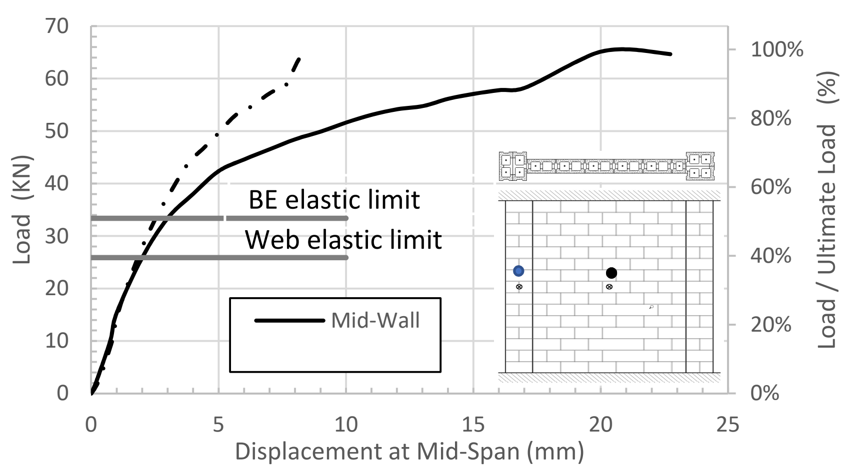

Figure 4: Mid-span load-displacement curves recorded during static testing

Figure 5: Failure crack pattern under static loading

MODELLING OF BE-WALLS

Both the CSA [5] and ASCE [6] standards suggest different methods for determining the dynamic response and failure mode of a structural system. Finite element methods are extremely valuable in this respect; however, they generally require specialized modeling expertise. Conversely, single-degree-of-freedom (SDOF) techniques are much simpler to implement, albeit limited to represent single structural components [5]. A well-established software based on SDOF analysis is the so-called SDOF-Blast-Effect-Design-Spreadsheets (SBEDS) [7], which is developed by the U.S. Army Corps of Engineering and is used in this study to simulate the wall behaviour. In SBEDS, the structural system is represented by a lumped mass –the wall mass– connected to a horizontal spring that represents the wall flexural stiffness. The dynamic response, in terms of displacement history and dynamic reactions, is found by explicit time integration of the equation of motion. Damping properties are neglected [8] in the calculations, as they are generally insignificant given the small duration of a blast wave compared to the structure's fundamental period of vibration. The load is applied directly to the mass, and the wavefront parameters defining it are obtained on the basis of the scaled distance. Afterwards, the reflected pressure history is determined by recourse to a Friedlander formulation [7]. As a first approximation, the wall is assumed to deflect following a one-way mechanism. Accordingly, the transformation factor K_{LM} is adopted from the UFC manual 3-340-02 [9] on the basis of one-way bending. Since signs of damage were observed at the lower and upper courses of the test wall, the analysis was repeated twice, each time with different boundary conditions, either fixed-fixed (FF) or simply supported (SS).

Since structural components impacted by blast loads typically experience large deformations that may well exceed the elastic limit, the ASCE standard [6] recommends carrying out inelastic dynamic analysis that accounts for the change in stiffness. Since the influence of BEs on the wall is not well understood, different approaches are attempted to characterize the resistance function. The first approach, named "Web Only," neglects the contribution of the BEs and considers only the web contribution to the cross-sectional capacity: under this assumption, SBEDS predicts either a tri-linear or bi-linear resistance function, depending on the boundary conditions and the cross-sectional capacity at the supports and at the mid-span. Strain rate effects are also taken into account by including dynamic increase factors (DIFs) associated with the masonry and reinforcing steel properties. The second approach, named "Web+BEs," follows the same methodology [8] used in SBEDS to determine the flexural capacity, but a section that includes the geometric properties of the BEs is assumed instead. It should be noted that both approaches assume a plastic plateau past the deflection value associated with the ultimate load-bearing capacity.

RESULTS AND DISCUSSION

The resistance functions obtained from the "Web Only" and "Web+BEs" approaches for both FF and SS boundary conditions are shown in Figure 6. For the sake of comparison with test data from static loading, the plotted curves are calculated after setting DIF = 1 in SBEDS, for both concrete masonry and steel. As the figure shows, the "Web+BEs-FF" approach results in a cross-sectional capacity overestimated by 86%. Conversely, the "Web Only-FF" approach produces a resistance function that has ultimate capacity 27% lower than that measured. Moreover, the elastic stiffness predicted by both approaches under FF boundary conditions was grossly overestimated, which resulted in under-estimated deformations. This observation strongly suggests that full fixation of the specimen's edges was not achieved.

On the other hand, the SS simulation produced elastic stiffness values similar to those inferred from the experimental results. Although the "Web Only-SS" approach showed a grossly under-estimated resistance capacity, the "Web + BEs-SS" approach was able to predict the load-bearing capacity within a 9% error. This comparison also suggests that the wall acted mostly in simply supported manner. Hence, although two-way bending mechanism is likely to contribute significantly to the wall deflection, one-way analysis is found to be able to predict the resistance function with reasonable accuracy.

The maximum dynamic displacements predicted by SBEDS on the basis of both approaches are reported in Table 2. The "Web+BEs-FF" approach results in grossly and consistently underpredicted displacements when compared to the test results. On the other hand, the "Web Only-FF" approach provides an accurate prediction of W-12 deflection, yet underestimates the deflection in W-6 by almost 40%, which is unsafe and unacceptable for design purposes. Meanwhile, the "Web+BEs-SS" analysis showed good results for W-6 while overestimated W-12 deflection by 34%, which is a conservative prediction. This error may be attributed to the use of one-way K_{LM} factors in the current simplified analysis.

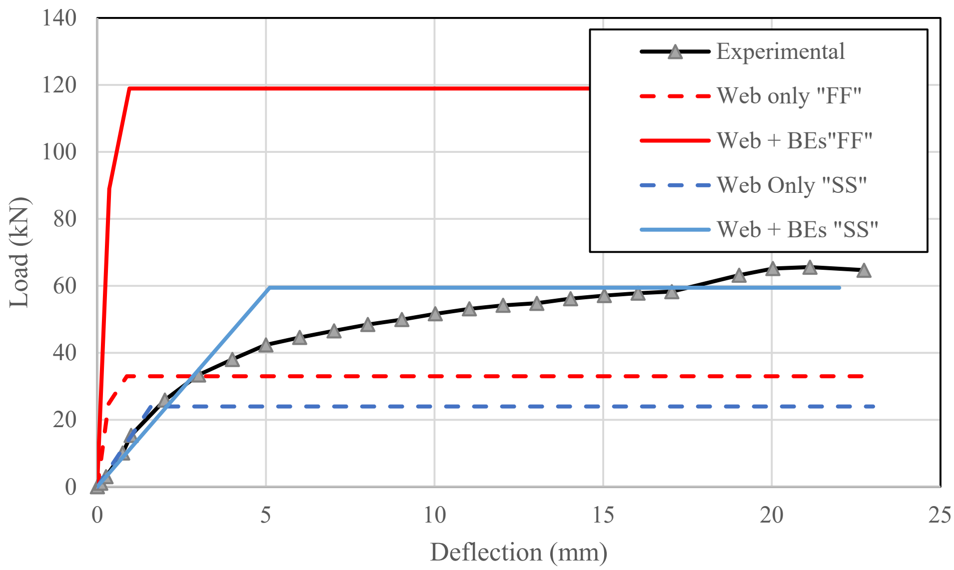

Figure 6: Comparison of predicted resistance functions (DIF = 1) with data from static testing

Table 2: Maximum displacement of RM walls with BEs

Wall	**Δ_{exp} (θ_{exp})**	**Maximum Displacement Δ (support rotation θ) mm (degrees)**			
		Web Only (FF)	**Web+BEs (FF)**	**Web Only (SS)**	**Web+BEs (SS)**
W-6	27.8 (3.2°)	16.0 (1.83°)	4.5 (0.52°)	62 (7.1°)	23.9 (2.74°)
W-12	48.0 (5.5°)	47.6 (5.43°)	15.9 (1.82°)	178 (19.5°)	64.5 (7.67°)

In terms of support rotation and component damage, only the “Web+BEs-SS” approach was able to predict levels of damage similar to those observed in field-tested walls. The latter approach was able to predict the ultimate capacity of the test specimens but failed to predict the dynamic response of wall W-12. BEs influence on the web in terms of dynamic displacement clearly needs further investigation.

CONCLUSIONS

A reinforced masonry wall with boundary elements was tested to determine its performance under static loading. The wall was nominally identical to two walls previously tested under blast loading. The static test exposed a two-way bending mechanism instigated by the boundary elements; the latter maintained their initial stiffness up to 51 % of the ultimate wall capacity; the web, however, began losing its stiffness after exceeding 40% of the peak load. By the end of the test, the BEs did not experience failure at mid-span, while the web showed crushed concrete and some ruptured bars. It may be concluded that the BEs do not affect the entire web but only part of it; further investigation is required to assess their contribution to the wall capacity.

To predict the maximum dynamic displacement, the specialized software SBEDS was used with two different resistance functions, which were obtained from simplified engineering approaches designed to bound the solution. It was found that the approach that accounts for both web and BEs contributions adequately predicts the wall resistance function when simply supported conditions are assumed; however, this approach, when used in dynamic analysis, overpredicts, by a large margin, the maximum wall deflection and is therefore not recommended. Conversely, a complete dismissal of the influence of the boundary elements leads to underestimating the ultimate failure load. Clearly, future work is required to determine the influence of the BEs on the web, in order to more accurately characterize the displacement response of BE-walls.

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