TESTING OF A RESILIENT MASONRY STRUCTURAL WALL SYSTEM UNDER BLAST LOADS

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ABSTRACT

As part of an on-going research program at McMaster University, six walls constructed utilizing 1/3 scale concrete masonry units were tested to observe their response due to out-of-plane explosive loading. Three of these walls were constructed with a unique feature; built-in masonry boundary elements producing a shear wall with end confinement. The response of these three walls is compared to three similarly reinforced walls without boundary elements subjected to the same blast loads in order to document, both quantitatively and qualitatively, the effect of the boundary elements. To conduct this comparison, the maximum deflection at the wall's mid-height and the overall crack pattern in each trail was compared to a conventionally designed rectangular wall. It was found that the walls with masonry boundary elements behaved more like reinforced concrete slabs supported on four sides, thus responding in two-way bending, instead of the one-way bending seen in the walls with rectangular cross section. The maximum crack width sustained by the rectangular walls was always larger than those observed on the walls with boundary elements. In addition, the level of deflection was significantly less in the walls with boundary element. The maximum out-of-plane deflection at the mid-height of the wall was reduced by approximately 20 and 25% under 5 and 10 kg equivalent TNT shots, respectively.

KEYWORDS: blast loading, boundary element, experimental testing, shear walls

INTRODUCTION

In North America, reinforced concrete design codes have been specifying the use of special detailing to create confined boundaries in shear walls to increase the overall performance for the wall during seismic events. It has been known for some time that confining the vertical reinforcement near the ends of the reinforced concrete walls with lateral steel ties delays the onset of buckling in the vertical reinforcement [1] [2]. Delaying the onset of the buckling of this vertical steel increases the in-plane ductility of the concrete wall. Until recently, utilizing this method of providing lateral ties to delay buckling of the flexural reinforcement in reinforced masonry shear walls was impractical since there is only space for a single row of this vertical steel. To overcome this issue of having only one row of vertical reinforcement, new features have been considered to be added to the ends of conventionally constructed (i.e. rectangular) masonry walls. Creating masonry column-like features at both ends of a shear wall, the designer allows for lateral ties to be incorporated around at least four vertical steel reinforcement rods, thus creating confining boundary elements similar to those utilized in reinforced concrete design. In a separate research program, walls with this new feature have been tested under simulated seismic loads and it has been observed that there is indeed a decrease in lateral buckling of the vertical steel, leading to increased capacity and ductility [3].

Shear walls are not typically designed with consideration of high out-of-plane capacity since the main concern is their response due to lateral in-plane loading caused by seismic or wind loading. In most cases the amounts of vertical (flexural) and horizontal (shear) reinforcement in shear walls are determined by the requirement due to such in-plane lateral loading. Because shear walls are designed in this manner they are susceptible to a large amount of damage if loaded to bend in the out-of-plane direction due to blast loads. Loading due to explosions, either accidental or deliberate, can easily cause a significant damage to a loadbearing wall building system by destroying shear walls which have not been designed to resist these large, energetic loads. It has been hypothesized that the same masonry confined boundary elements, which have been shown to improve the capacity and ductility of shear walls under in-plane (seismic) loading, would also increase the performance of the wall under out-of-plane (blast) loading. To investigate the out-of-plane response of masonry shear walls with boundary elements, the experimental program reported in this paper was conducted. The maximum out-of-plane deflection and the overall crack pattern of these walls are compared to conventionally designed rectangular shear walls with similar reinforcement to demonstrate the effectiveness of the proposed design.

TEST MATRIX

The six shear walls investigated during this experimental program were tested utilizing three explosive charges. To ensure the companion walls were being subjected to as close to the same pressure wave as possible the two walls, one with and one without boundary elements, were tested using the same explosive shot. Table 1 outlines the test matrix for this section of the experimental program. The three different charge weights were chosen to allow the observation of increasing level of damage as described by the blast standard CSA S850-12 [4]. It is common practice when dealing with explosives to deal with the charge weight as an equivalent weight of TNT to make comparison easier. The Pentex Booster used as the explosive in this experiment has a TNT equivalence of 1.2 [5]. It should be noted that to make discussion easier the rectangular shear walls will be designated as R1, R2, and R3; while the shear walls with boundary elements will be referred to as B1, B2, and B3.

Table 1: Test Matrix

Shot Number	Wall	Stand-off Distance (m)	Pentex Charge Weight (Kg)	Equivalent TNT Charge Weight (Kg)
1	R1	5	5	6
	B1	5	5	6
2	R2	5	10	12
	B2	5	10	12
3	R3	5	25	30
	B3	5	25	30

The primary motivation for the selection of the charge sizes in this experiment was to simulate a car-bomb, charge weight ranging from 100 to 1,000 kg, being detonated at 15 m away from the structure containing the shear wall. This scenario was broken down to three charge weights in the range mentioned above, to produce three different levels of damage and when scaled down to 1/3 scale becomes the three tests outlined in the text matrix, Table 1. All shots were created by explosives located 0.3 m above the surface of the ground, simulating the 1/3 scale of a vehicle.

MATERIAL PROPERTIES

All walls tested in this project was constructed using Type S mortar with an average flow of 129% (c.o.v. = 3.2%) [6]. The mortar was a mixed with the ratio by weight of Portland cement : sieved masonry sand : lime : water of 1.0 : 3.53 : 0.2 : 0.85. The average strength of the mortar cubes cast during construction was 29.6 MPa (c.o.v. = 10.11%). A grout mixed with the ratio by weight of Portland cement : fine sieved masonry sand : lime : water of 1.0 : 3.9 : 0.04 : 0.85 was utilized to fill all cells of each wall. The average cylinder strength of this grout was 22.4 MPa (c.o.v. = 14.2%). Four course high, running bond prisms were constructed and tested to obtain an average masonry compressive strength of 19.36 MPa (c.o.v. = 15.88%) [7]. The vertical reinforcement in all walls, boundary element and rectangular, was D4 deformed wires, cross sectional area of 25.4 mm^2, with average yield strength of 477.6 MPa (c.o.v. = 0.99%) and a Young's Modulus of 232.2 GPa (c.o.v. = 18.5%). W1.7 smooth wires, cross sectional area of 11 mm^2, were chosen as ties in the boundary elements and horizontal reinforcement in the walls. The W1.7 wires had an average yield strength of 268.1 MPa (c.o.v. = 2.38%) and Young's Modulus of 258.2 GPa (c.o.v. = 24.0%). It should be noted that while selecting the above wall constituent materials, proper scaling requirements were considered [8].

WALL DETAILS AND CONSTRUCTION

All walls tested in this experimental program were of the same design and were constructed using the same method by the same experienced mason. A 1/3 scale concrete masonry unit, previously tested and correlated to full-scale blocks at McMaster University [9], was utilized in the construction of these walls. The 1/3 scale blocks have dimensions of 130 mm x 63.3 mm x 63.3 mm, which corresponds to the common North American 20 cm full-scale concrete masonry unit. The walls were designed to have an aspect ratio of 1.0, resulting from having a wall height and length of 1.0 m; 15 courses tall by 7.5 units long. For ease of discussion, the section of the wall between the masonry boundary elements will be referred to as the *central panel* throughout the rest of this paper. This section was 5.5 units long, 740 mm, and had vertical D4 reinforcement bar in every other cell beginning in the first cell of this section. The masonry boundary elements, located at either end of the central panel, were constructed using two blocks laid side-by-side creating a square, 130 mm^2, which was centred on the central panel. Looking at a wall cross section, as in Figure 1, this construction method creates a wall that looks like a "barbell". All four cells making up the boundary element had vertical D4 bars as reinforcement as well as W1.7 wires as lateral ties in every course. The details of the boundary elements can be seen clearly in Figure 2. The horizontal reinforcement, W1.7 wires, were placed in every other course and extended into both boundary elements.

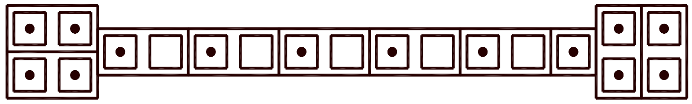

Figure 1: Plan view of test walls, showing vertical reinforcement

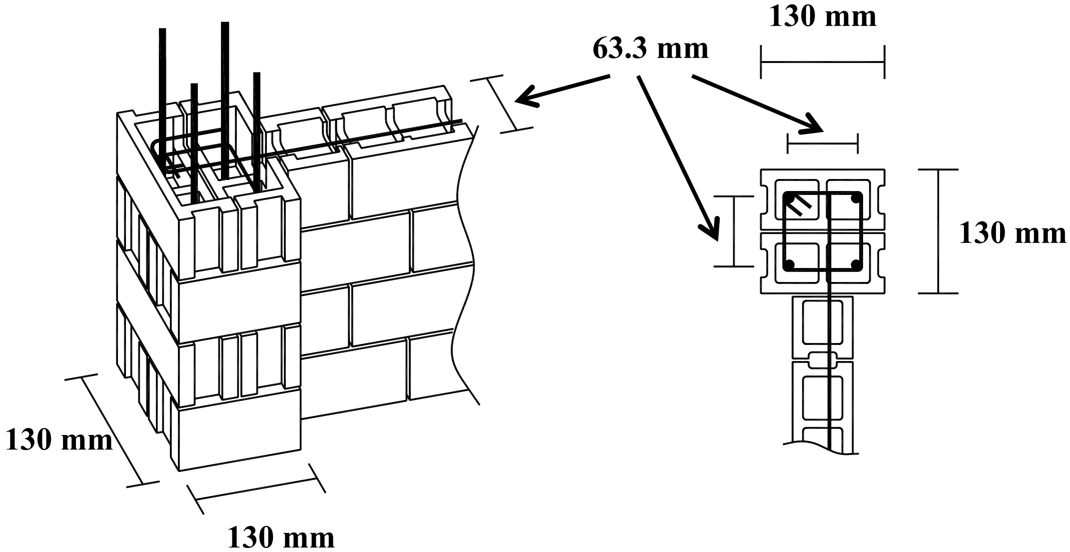

Figure 2: Boundary element detailing: a) vertical reinforcement; b) horizontal reinforcement and lateral ties

The three walls with rectangular cross sections, which will be used as the basis for comparison with the walls with boundary elements, were constructed in the same method and utilizing the same materials by the same mason, and within the same time frame, as the ones outlined above. These walls with rectangular cross sections were also 1 m by 1 m, contained the same horizontal and vertical reinforcement as the central panel and were designed to have the same boundary conditions at the top and bottom of the wall. As such each of Wall B1, Wall B2, and Wall B3 (all with boundary elements), will be directly compared to their counterparts with rectangular cross sections, where each pair of walls were subjected to 5, 10 and 25 kg charge, respectively.

TEST SET-UP AND INSTRUMENTATION

To enforce a fixed-fixed boundary conditions on the wall (simulating wall out-of plane bending between two floor slab with the reinforcement going through), the vertical reinforcement bars were passed through and welded to two 8 inch steel C-channels; one at the base and one at the top of the wall. The wall was then constructed around the vertically welded steel reinforcement bars. The final step in the construction was to weld a vertical steel plate spanning the gaps between the C-channels on both sides of the wall. By creating this steel frame around the specimen, the top and bottom of each wall would be held in place and prevented from any appreciable rotation during the explosive loading, thus creating the desired fixed-fixed boundary conditions.

A steel reaction frame (bunker) with wing-walls was created to hold the individual walls during each shot in the experimental program. The reaction frame was constructed utilizing six hollow rectangular steel sections (HSS 152.4mm x 101.6mm x 95mm) welded to create a vertically standing square frame with two diagonal supports. The reaction frame was then welded to a base plate, so that the entire bunker would be movable as one piece. Other members made of hollow square steel sections (HSS 101.6mm x 101.6mm x 95mm) were erected at the rear of the base plate, for use as mounting surfaces for the instrumentation. Steel plates were then welded to the frame ensuring that the covered the gaps on the two sides and the back of the reaction frame. Finally, an additional plate was attached by hinges to cover the top opening of the steel frame, creating a closed bunker with a “lid” that could be opened or access to the equipment kept inside during testing. When a blast wave hits a surface it will reflect causing an increase in the pressure the surface must resist [10]. As the wave passes the surface it wraps around the edges creating a drop in the reflected pressure at the edges of the structure [10]. This blast wave clearing phenomenon would have had a significant effect on the walls tested in this experimental program because of their relatively small dimensions. To negate this effect and ensure each wall was loaded with an even pressure distribution wing-walls were added to the test frame. The wing-walls were also made of steel plate and were attached to the front of the reaction frame, one extending to each side of the frame and one extending vertically above it. The completed test frame can be seen in Figure 3.

Figure 3: Test frame: a) The reaction frame without wing-walls, b) Wing-walls attached and wall loaded

Four displacement potentiometers were attached to the three walls to record the out-of-plane displacement of the walls with masonry boundary elements. Three of these were spring-returned linear rod potentiometers, with 300 mm stroke, and one was a string potentiometer, with 360 mm stroke rated for high accelerations. The string pot was attached to the centre of the wall, while the others were attached to the mid-height of one of the boundary elements, the ¾ height of the same boundary element, and at the ¾ height of the central panel directly above the string pot.
The walls utilized for comparison in this paper were simultaneously loaded within their respective test frame and the data was recorded using consistent types of instrumentation.

POST BLAST OBSERVATIONS

The crack patterns for Walls R1 and B1 can be seen in Figures 4 and 5 respectively. The loading during this trial was produced from a 5 kg Pentex shot. The damage done by this explosive charge was very small on both walls. The maximum out-of-plane deflection for each of these test walls was recorded at the wall's centre, as 11.5 mm for Wall B1 and 14.0 mm for Wall R1.

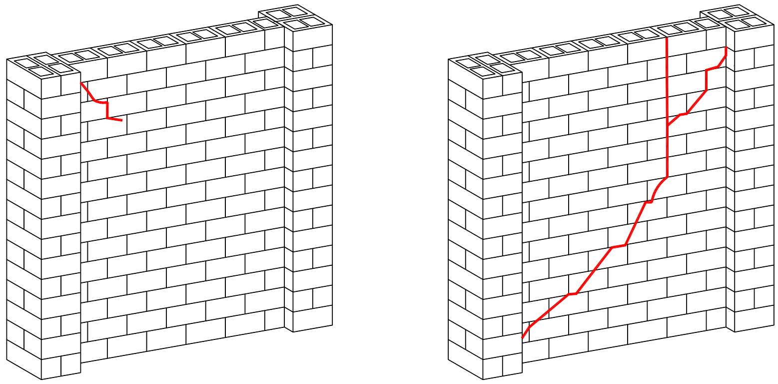

Figure 4: Post Blast Crack Pattern of Wall B1: a) Compression Face; b) Tension Face

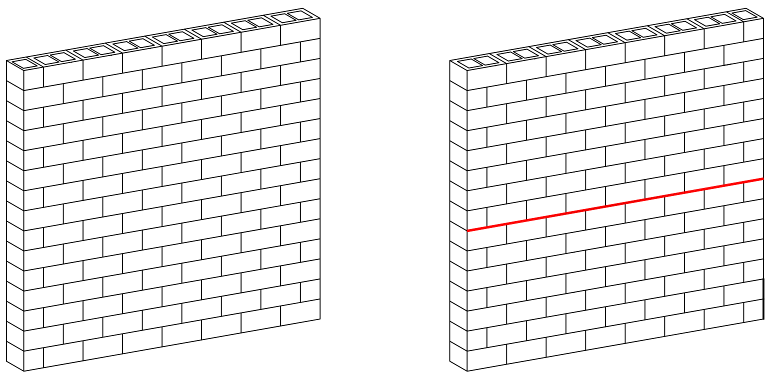

Figure 5: Post Blast Crack Pattern of Wall R1: a) Compression Face; b) Tension Face

Shot 2 was a 10 kg Pentex charge, which produced the crack patterns shown in Figures 6 and 7. As expected, the increase in the amount of explosive utilized during the test led to an increase in the amount of damage observed in the post blast inspection for both types of shear walls. It should be noted, and will be discussed in greater detail later in this section, that Wall B2 contained horizontal, vertical, and diagonal cracks on the tension face of the central panel, while Wall R2 sustained only horizontal cracks. The maximum out-of-plane deflections of Wall B2 and R2 were recorded as 21.6 and 29.0 mm respectively.

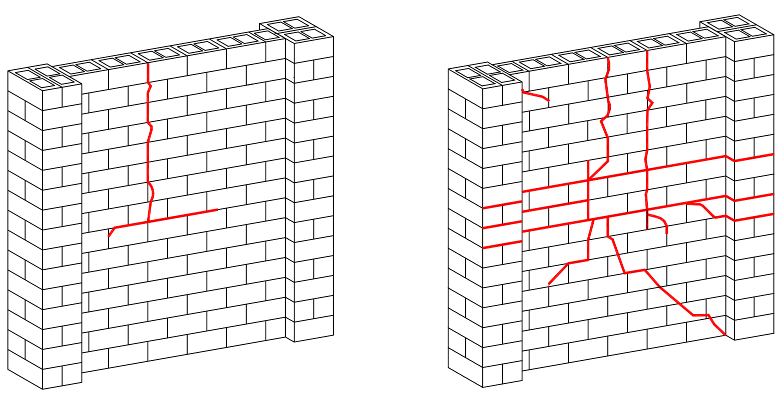

Figure 6: Post Blast Crack Pattern of Wall B2: a) Compression Face; b) Tension Face

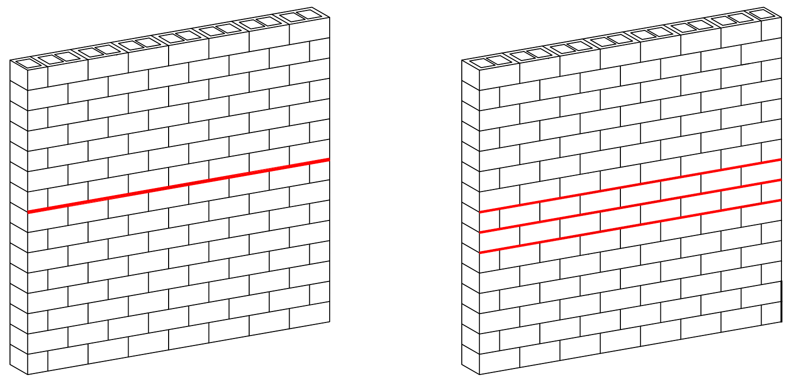

Figure 7: Post Blast Crack Pattern of Wall R2: a) Compression Face; b) Tension Face

The increase in charge size from 10 kg to 25 kg Pentex Booster resulted in a significant increase in the amount of damage sustained by both walls tested in shot 3. The crack patterns shown in Figures 8 clearly show that there was an increase in the number of cracks on Wall B3. As seen in the post blast crack pattern of Wall B2, Wall B3 exhibits vertical, horizontal and diagonal cracks in the central panel, along with horizontal cracks in the boundary elements on the tension face. This larger blast load resulted in face shell spalling on the compression face, shown as red areas in Figure 8a). The face shell spalling along the top and bottom of the wall was likely due to high shear forces developing between the masonry and the steel C-channel boundaries. On both the compressive and tensile faces of Wall B3 it was observed that there were vertical cracks along the central panel-boundary element joints. These were also attributed to the development of high shear forces at these locations. The maximum out-of-plane deflection was recorded to be 71.3 mm. Figure 9 clearly shows the blowout of Wall R3 resulting from the 25 kg shot. This wall was broken completely in half, including shearing of all flexural reinforcement. Upon closer inspection it was seen that Wall R3 actually broke along two horizontal planes, one at the approximate mid-height and the other along the joint between the top masonry course and the upper steel C-channel. Because the wall was completely blown into the steel reaction bunker the maximum out-of-plane deflection could not be recorded.

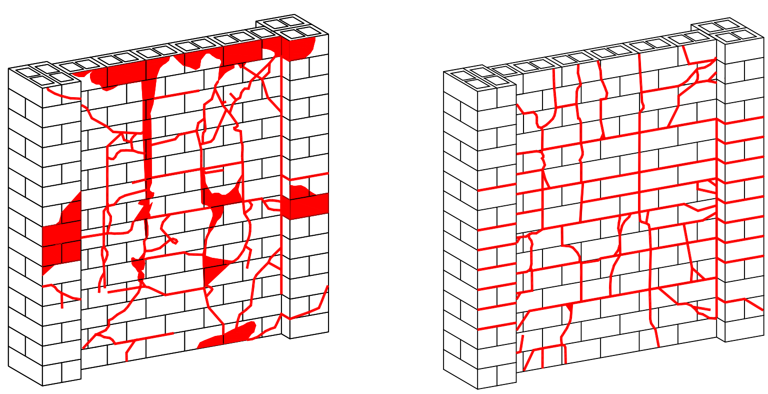

Figure 8: Post Blast Crack Pattern of Wall B3: a) Compression Face; b) Tension Face

Figure 9: Damage Sustained by Wall R3

DISCUSSION

The observed crack patterns of the rectangular walls were all horizontal centred on the approximate mid-height. This alone indicates that these conventionally designed rectangular shear walls were responding with one-way bending when subjected to the out-of-plane loading from the explosive charge. The post blast crack patterns of the central panel of the walls detailed with the masonry boundary elements suggests that this panel is actually bending along two axes, vertical and horizontal. The evidence for two-way bending of the central panel can be seen by the evidence of horizontal, vertical and diagonal cracks, at similar locations as would be seen if the central panel was treated as a uniformly loaded slab supported along all edges. Further evidence of the two-way bending can be seen in Table 2, where the recorded out-of-plane deflection results are provided for the walls with boundary elements. This table has been broken into two sections, corresponding to bending along the horizontal and vertical axes. During the first and third test there were two LVDTs that did not record the deflection data properly and therefore "N/A" has been entered at those locations in Table 2.

Table 2: Maximum Deflection during Blast Loading

	Maximum Out-of-Plane Deflection (mm)			
Specimen	LVDT Location Showing Bending Around the Horizontal Axes		LVDT Location Showing Bending Around the Vertical Axis	
	¾ Height of Wall	Centre of Wall	Mid-height of Boundary Element	Centre of Wall
B1	7.26	11.5	1.0	11.5
B2	10.3	21.6	N/A	21.6
B3	N/A	71.3	41.9	71.3

In combination with the horizontal cracks observed in the post blast observations the fact that the deflection at the ¾ height of the wall's mid-span is less than that recorded at the centre strongly suggests, as expected, that there is bending around the horizontal axis of the shear walls. In a similar manner the observed vertical cracking along with the deflection data collected by the LVTDs located at the mid-height of the boundary element and the centre of the wall suggest that the shear walls were also bending about the vertical axis. The deflections recorded at the mid-height of the boundary elements mean that the central panel of these shear walls was being fully supported along all four edges, but was instead fully supported along the top and base of the wall and only partially supported along the sides. Since the masonry boundary element is deforming while the top and base of the wall is held fixed, asymmetric two-way bending is occurring in the central panel during the explosive loading.

If one simply looks at the number of cracks appearing on the two types of shear walls studied in this project then it would seem like the walls with masonry boundary elements sustained greater damage. However, this method of assessing damage is not a valid technique. Since most design codes stipulate a maximum deflection when designing a wall for out-of-plane loading a better comparison of the damage would come from the maximum deflections of the two types of walls. Table 4 contains the maximum out-of-plane deflection recorded at the middle of each shear wall during the blast load duration as well as the percentage reduction in the response.

Table 4: Comparison of Maximum Deflection

	Maximum Deflection (mm)		
Shot Number	**Rectangular Wall**	**Wall with Boundary Elements**	**Percent Reduction in Deflection**
1	**14.0**	**11.5**	**17.9 %**
2	**29.0**	**21.6**	**25.5 %**
3	**Complete Blowout**	**71.3**	**N/A**

As can be seen in the above table the addition of masonry boundary elements to the shear wall significantly decreased the maximum deflection recorded at the wall's centre. When the charge size was 5 kg the boundary elements reduced the deflection by approximately 18%. When the charge was increased to 10 kg the percentage reduction in the mid-point deflection was even greater, slightly over 25%. In the case of the third shot, the 25 kg Pentex charge, a percentage reduction could not be given since the rectangular wall was blown completely into two pieces. This test is extremely important because the high velocity debris coming off the structure is what actually causes injury and death to the occupants during an explosive loading. Because the shear wall designed and constructed with masonry boundary elements did not fracture, the potential for danger to occupants would be much less than the hazard caused by the rectangular shear wall fracturing.

CONCLUSIONS

The purpose of this paper was to investigate the response of 1/3 scale masonry shear walls with boundary elements when subjected to out-of-plane blast loads. The effectiveness of the boundary elements was clear with the crack patterns and maximum deflection in these walls was compared with conventionally designed rectangular walls subjected to the same blast loads. The crack patterns observed in the central panel of the shear walls with masonry boundary elements were much more like those seen in rectangular reinforced concrete slab supported on all four sides, having horizontal, vertical and diagonal cracks. This crack pattern indicated that the boundary elements are acting to restrain the central panel along its height, similar to the steel C-channels at the top and bottom of the wall which simulated the storey slabs, forcing two-way bending to develop. The crushing observed at the mid-height of the boundary elements in the tests with larger shots shows that the masonry columns, comprising the boundary elements, also bent with the central panel. This means that the boundary elements do not behave entirely as rigid supports for the central panel along its height. This partial restraint is also evidenced by the fact that the horizontal cracks in the central panels were always wider than the vertical cracks. In contrast, the rectangular walls developed no vertical or diagonal cracks, because there was no vertical support along the height of the wall. The lack of vertical support in the latter case forces the wall to behave as a one-way slab, bending only about a single axis. Even though a greater number of cracks were seen in the walls with boundary elements, the significance of those cracks was much less in the boundary element walls. The second, and possibly more definitive, comparison is the maximum out-of-plane deflection at the mid-height of the test walls. In the first shot, 5 kg equivalent TNT, the peak deflection of the wall with boundary elements was reduced by almost 20%, while an even greater reduction, 25%, was seen with the larger shot, 10 kg TNT equivalence. The final test, 25 kg equivalent TNT, the wall with boundary elements sustained a large deflection but maintained its structural integrity and remained standing, while the rectangular wall was separated in two parts. This test demonstrated how effective the addition of masonry boundary elements could be to ensuring life safety, limiting structural damage, and reducing the possibility of a progressive collapse scenario.

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