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TORNADO & HIGH WIND SHELTERING WITH MASONRY

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ABSTRACT

Urbanization, increases in population, and climate change have placed increasing numbers of the populace in areas subjected to high winds across the globe. In response to this, the 2015 edition of the International Building Code (IBC) requires that most schools and emergency facilities located in a significant portion of the Central US contain tornado shelters. These shelters must be designed to resist wind speeds up to 250 mph, be tornado debris impact resistant, accommodate all the building occupants and, must meet other requirements described in the ICC 500, *Standard for the Design and Construction of Storm Shelters*. For areas that use the 2015 IBC, this new requirement will impact the majority of new school and emergency facility construction spanning as far north as central Minnesota, as far south as southern Mississippi, and stretching to western Pennsylvania in the east and western Texas to the west. Masonry can provide safe, practical and cost effective solutions for sheltering from tornados and high wind events. For years however, the only masonry solutions that were tested and passed the tornado debris impact testing were solidly grouted masonry walls. This paper will summarize the results of recent tornado missile debris impact tests conducted on partially grouted brick and block cavity wall systems. Also summarized in this paper is an investigation of the use of exterior masonry wall systems in typical school configurations to provide these mandated tornado shelters with minimum increase in costs and changes in design. Both solidly grouted single wythe walls and cavity walls are addressed.

KEYWORDS: *masonry walls, high wind loads, tornado shelters, debris impact testing*

INTRODUCTION

Urbanization, increases in population and climate change have created conditions that have shown a significant rise in damage due to severe weather events [1]. Much of this damage is related to increasing numbers of the global population being subjected to increasing numbers of high wind

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events, and this is especially true in the US. The building damage that often results from these high wind events (as shown in Figure 1) places significant numbers of people at risk.

Figure 1: Tornado Wind Damage of a School in Joplin MO

In response to this increasing risk, the 2015 edition of the International Building Code (IBC) [2] requires that most schools and emergency facilities located in a significant portion of the Central US have tornado shelters. This area is shown in Figure 2 and is where tornadoes with wind speeds of at least 402 km/hr (250 MPH) are expected. These shelters must be sized to hold all the building occupants and must meet the requirements of the ICC 500, *Standard for the Design and Construction of Storm Shelters* [3]. Based on the dark area shown in Figure 2, this impacts new construction of schools and emergency facilities as far north as central Minnesota, as far south as southern Mississippi, and stretching east to western Pennsylvania and western Texas to the west.

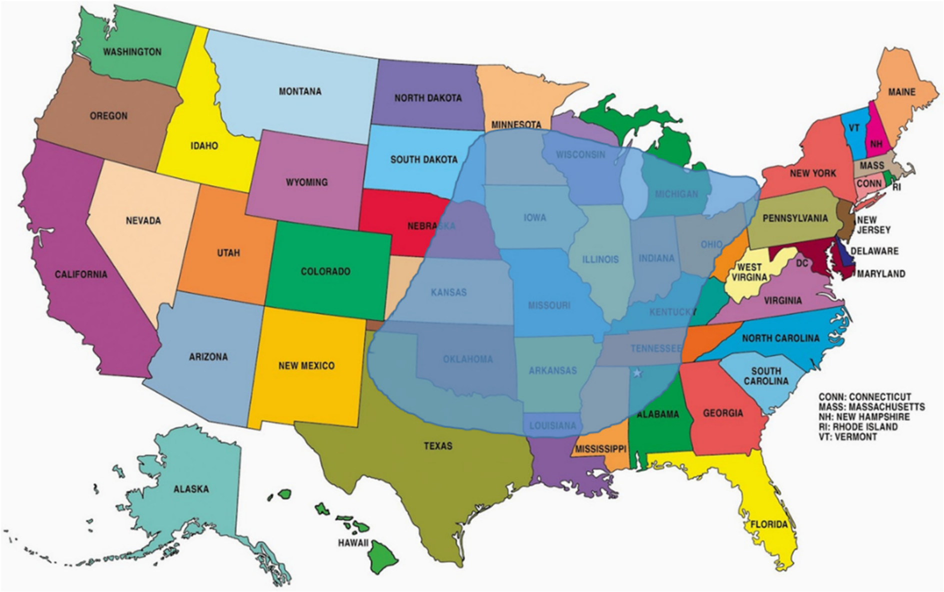


Figure 2: 402 Km/hr (250 MPH) Tornado Shelter Zone (Consistent for ICC 500 [3])

In recognition of the fact that many of the schools and emergency facilities have, and continue to be constructed using masonry, and masonry can provide safe, practical and cost effective solutions for sheltering from tornados and high wind events, the performance of additional exterior masonry wall systems under tornado wind loads and debris impacts was further investigated.

This paper describes an investigation of the use of several exterior masonry wall systems in typical school configurations in an effort to provide well designed and constructed tornado shelters that will resist 402 km/hr (250 mph) winds and tornado debris impact with minimum increase in costs and changes in design.

DEBRIS IMPACT TESTS

As described in the ICC 500 [3], exterior walls of tornado shelters must be able to withstand three test missile impacts without penetration of the interior surface of the wall. These missiles are comprised of 38 mm x 89 mm (2x4) wood elements, 6.80 kg (15 lb) in weight that are launched so they are travelling at 160.9 km/ hr (100 mph) at impact. Previous testing [4], [5], [6] [7] of single wythe, solidly grouted, partially grouted and hollow masonry walls showed that only the solidly grouted masonry walls were able to meet the tornado impact resistance requirements.

Because schools and emergency facilities often use two-wythe exterior masonry cavity wall systems, it was postulated that these cavity walls can provide significant debris resistance, even if the backing wall was not fully grouted. Thus, it was felt that the missile impact resistance of these wall systems needed to be evaluated. To address this need, a testing plan to investigate the missile impact resistance of cavity walls with a partially grouted concrete masonry unit (CMU) back-up and clay brick veneer was developed and executed.

A search of the literature, revealed no previous testing of any masonry cavity wall systems. With funding limited to two wall tests, an attempt was made to determine what variables might influence the ability of a cavity wall system to resist the tornado debris impact test. It was postulated that the size of the brick veneer units may have influence on impact resistance (i.e. would a veneer with smaller units and more mortar joints behave differently?) As both modular and utility size brick units are commonly used for school cavity wall construction, these were tested to determine if the face size of the veneer unit and corresponding amount of mortar joints mattered. It was also suggested that the reinforcing configuration of the partially reinforced CMU back-up wall could have an influence on impact resistance. As it is highly unlikely that a partially grouted CMU wall reinforced at more than 813 mm (32 inches) on center vertically would be able to resist the mandated ICC 500 tornado wind speeds, one of the test specimens used this reinforcing spacing in its back-up wall. The second test specimen used a lower back-up wall reinforcing spacing, in the event that the larger spacing did not pass. Recognizing that we were changing more than one parameter between the specimens, we decided to change both brick size and reinforcement spacing on each specimen to garner the most information from this testing.

The specimen dimensions were limited by the testing system and construction constraints. Two different wall specimen configurations were developed and designed to be representative of a typical clay brick and CMU cavity walls used in conventional school designs. Figure 3 shows the first specimen configuration. This 1.42 m x 1.22m (4 ft-8inch wide by 4 ft) wall specimen represented a common exterior wall design for schools, with an 89 mm (3.5 inch) utility clay brick veneer over a 51 mm (2 inch) cavity and 203 mm (8 inch) partially grouted CMU backing wall. The CMU backing wall was reinforced with 15.9 mm (#5), 414 MPa (60 ksi) rebar, at 813 mm (32 inches) on center. There was a bond beam cast at the top of the wall to tie the specimen together. A heavy duty, 4.7 mm (3/16 inch), diameter eye and pintel, anchor system was used to attach the brick veneer to the backing wall and these anchors were spaced at (16 inches) both vertically and horizontally. The specimens were constructed using ASTM C 90 [8] CMU units (with an average compression strength of 3930 psi), ASTM C 216 [8] clay units (average compressive strength of 9096 psi) and ASTM C 270 [8] Type S Masonry Cement Mortar. Only fine grout was used and this was site mixed based on the proportion specification of ASTM C 476 [8].

Figure 4 shows the configuration of the second specimen. This specimen was configured the same as the first, except that 92 mm (4 inch) modular clay brick were used in the veneer and the vertical reinforcing spacing in the CMU backing wall was reduced to 610 mm (24 inches).

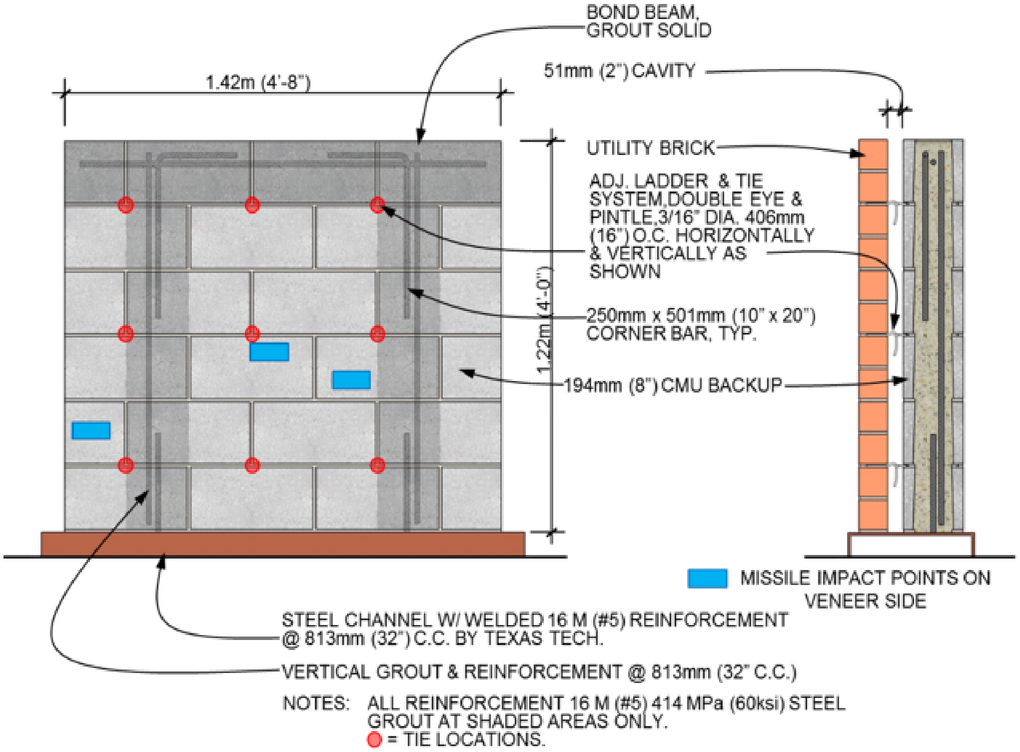


Figure 3: Cavity Wall Specimen 1 Utility Brick

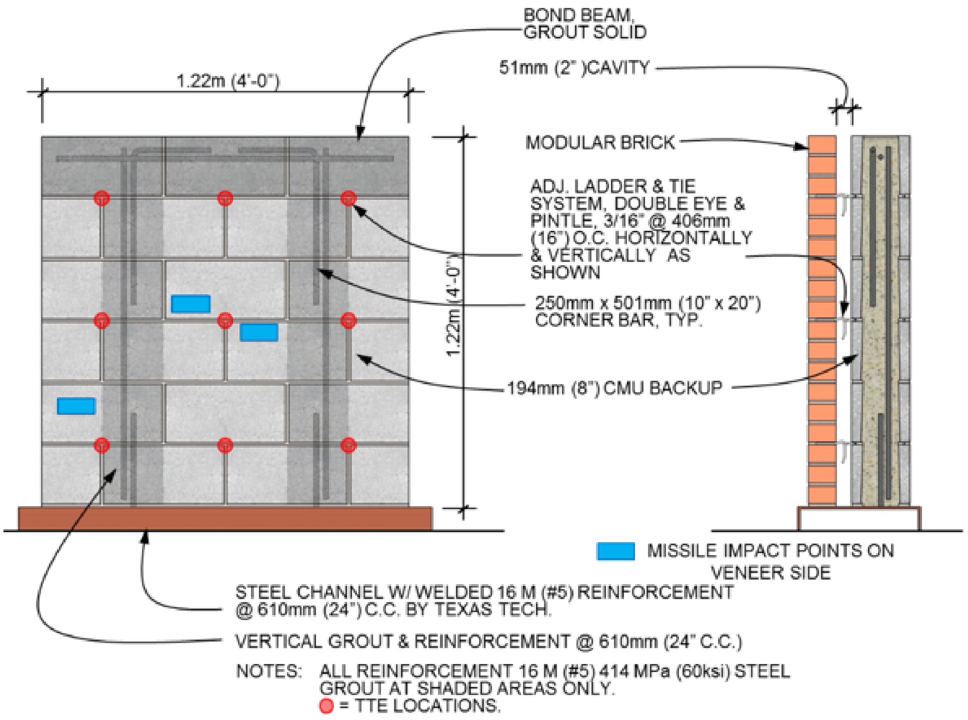


Figure 4: Cavity Wall Specimen 2 Modular Brick

Each of these specimens were tested at the Wind Testing Laboratory at Texas Tech University in Lubbock Texas [9]. The first specimen was placed in the missile testing apparatus (see Figure 5) and a total of three, 15 lb, 2 x 4 wood missiles were fired at the specimen. The missile speed was adjusted to be at least 160.9 km/ hr (100 MPH) (the minimum required by ICC 500 for a 402 km/hr (250 MPH) tornado) when it impacted the wall face.

The first missile strike was aimed at the middle of an ungrouted CMU core near mid-height and mid-width of the specimen. Figure 6 shows the results of the first missile impact. Upon impact, the 2 x 4 missile shattered the clay brick veneer units on each side of the missile impact location, passed through the brick veneer but bounced off the exterior surface of the CMU backing wall. There were also cracks in the brick masonry veneer wythe radiating from the impact site. Two additional missiles were fired at this specimen; one missile was directed to the lower outer edge of the vertically grouted CMU cores on the right side of the specimen and one missile was directed to the inner edge of the vertically grouted CMU cores on the left side of the specimen.

Figure 7 shows Specimen 1 after all three missile strikes. Figure 8 shows that the clay unit pieces were simply pushed against the block face. Similar behavior was observed in all the impacts; with the missile shattering the brick, pushing the brick pieces against the CMU face and rebounding without causing any damage to the CMU wall. There is significant damage to the brick veneer but no visible damage to the CMU backing wall and, most importantly, upon careful inspection, no missile penetration of the interior face of the CMU.

Figure 5: Utility Brick Unit Specimen 1 in Testing Apparatus Prior to Testing

Figure 6: First Missile Strike on the Utility Unit Specimen

Figure 7: Veneer Damage on the Utility Unit Specimen 1 after Three Missile Strikes

Figure 8: Brick Pieces Pushed Against the Block Face on the Utility Unit Specimen 1

Figure 9 shows the front of the backing wall behind the first missile strike area and, although the tie is damaged, there is no visible damage to the exterior surface of the CMU backing wall and no missile penetrations of the face of the CMU. As shown in Figure 10, there was no damage to the interior (back) surface of the CMU backing wall after all three tests. Holes were drilled into the wall at select locations confirming that the backing wall was not grouted at the impact sites (see Figure 10).

Figure 9: CMU Surface Behind Missile Strike on the Utility Unit Specimen 1 After Testing

Figure 10: Back Surface of CMU on the Utility Unit Specimen 1 After all Three Missile Strikes

The above tests were repeated for the Cavity Wall Specimen 2 which had the modular clay brick veneer and closer spaced vertical reinforcement in the CMU. Figure 11 shows the veneer after first impact. During this strike, only one veneer unit was shattered and the missile rebounded from the CMU face, causing no visible damage to the CMU backing wall. Similar behavior was observed for the other two missile strikes on this specimen. Figure 12 shows the veneer damage of this specimen after all three missile strikes. Although there was significant damage, none of the missile strikes caused visible damage to the CMU backing wall on either face (see Figures 13 and 14) and there was no missile penetration of the interior face of the CMU.

The results of these tests clearly show that the brick veneer absorbs a significant amount of the missile's energy. The shattering of the clay brick unit, the presence of the air cavity between the veneer and backing wall and the ductile failure of the 4.7 mm (3/16 inch) diameter wire anchors, reduced the strike energy to levels low enough that the ungrouted sections of the partially grouted CMU back-up are able to resist the missile impact with no penetration of the CMU. Thus, the two brick veneer and partially grouted CMU cavity wall configurations tested, passed the code-mandated, tornado debris impact testing requirement, even though the outer veneer is damaged. This is in contrast to single wythe masonry walls where the masonry must be grouted solid to provide this level of missile impact resistance.

Figure 11: First Missile Strike on Modular Clay Veneer Specimen 2

Figure 12: Modular Brick Veneer Specimen 2 After All Missile Strikes

Figure 13: Front face of CMU Wall on Modular Brick Veneer Specimen 2 Behind Missile

Figure 14: Back of CMU Wall on Specimen 2 After All Missile Strikes

Thus, based on these [9] and earlier tests [4] [5] [6] [7], fully grouted single wythe masonry walls and partially grouted masonry cavity walls (for the range of configurations tested), provide sufficient resistance to debris impacts to be used for exterior tornado shelter walls.

SHELTER DESIGN

The ICC 500 [3] requires that when sheltering is mandated, a series of design requirements must be met. Tornado shelters have structural, civil, and architectural requirements, along with increased documentation and inspection. As an example, tornado shelters must provide a minimum 0.464 m^2 (5 sf) usable floor area per occupant, minimum ventilation, sanitary facilities, fenestration impact resistance, handicap access, and meet minimum egress requirements. Structurally, the exterior walls of the shelter and the roof must pass debris impact tests designed to preclude interior surface penetration of debris and must be designed to resist wind loads from 402 km/hr (250 MPH) winds. Shelter roofs and walls must be designed to resist a 4.79 kPa (100 psf) minimum roof live load.

One way to provide tornado shelters for the occupants of schools is to use a class room wing shelter as shown in Figure 15. This has the advantage of providing for student comfort with a familiar classroom appearance. It also provides sheltering in place for many, is cost effective, and uses the space for both classroom space and sheltering use. This space also provides restrooms as part of the typical classroom wing design.

Figure 16 shows a typical design for an exterior load bearing masonry wall using 203 mm (8 inch) CMU walls. A comparison of the wall designs for the classroom wing acting as a shelter versus not acting as a shelter shows an increase in bar size from a 16 mm diameter (#5) to a 19 mm diameter (# 6) bar with a decrease in spacing from 1,620 mm (64 inches) to 610 mm (24 inches) (based on typical State of Ohio design conditions).

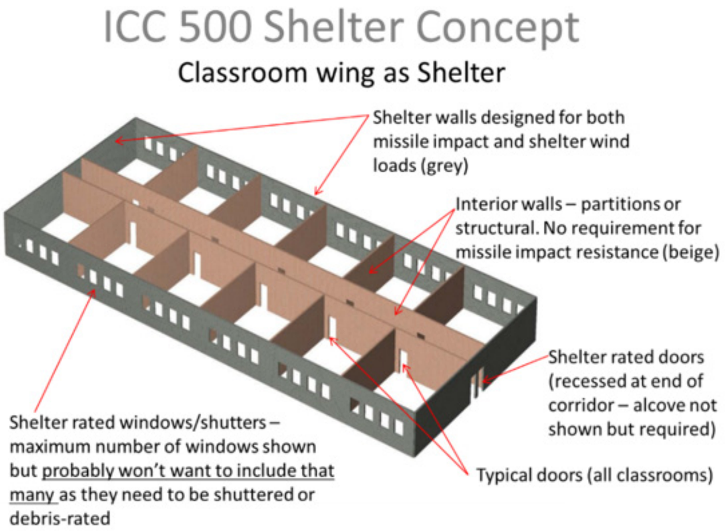
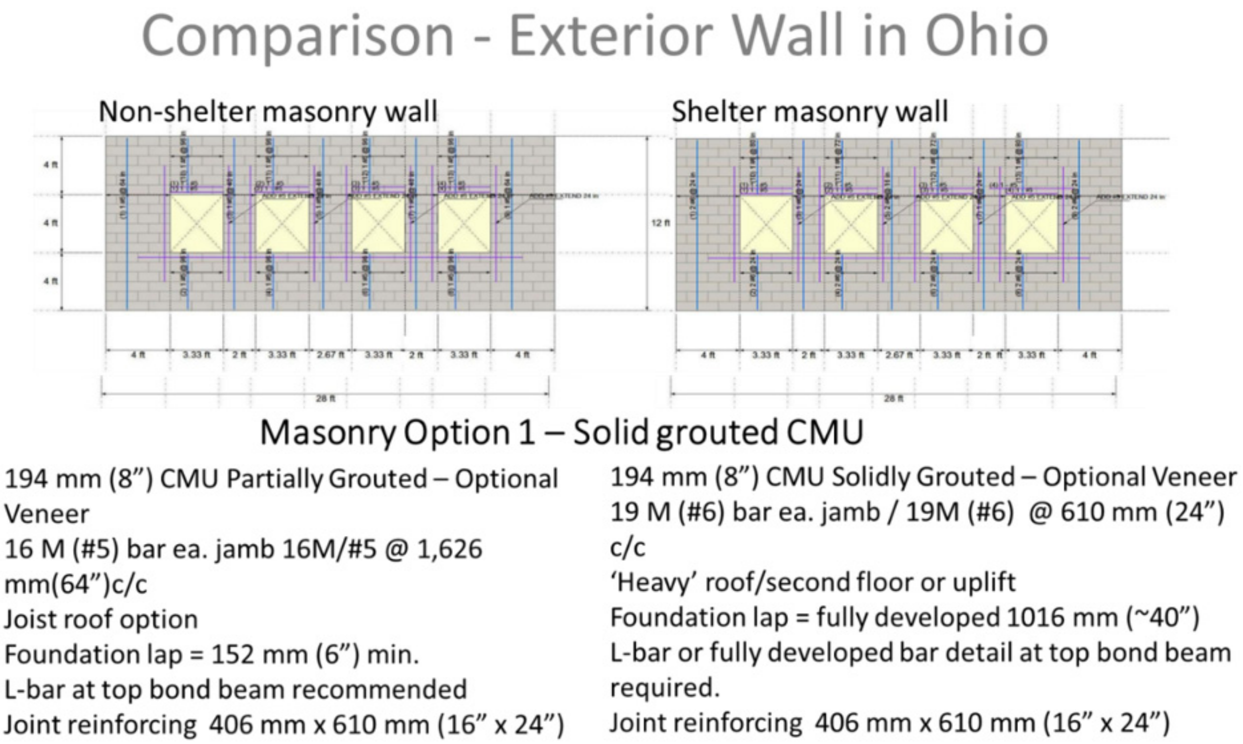


Figure 15: Classroom Wing as Shelter



Comparison - Exterior Wall in Ohio

Non-shelter masonry wall

Shelter masonry wall

Masonry Option 1 – Solid grouted CMU

194 mm (8”) CMU Partially Grouted – Optional Veneer
16 M (#5) bar ea. jamb 16M/#5 @ 1,626 mm(64”)c/c
Joist roof option
Foundation lap = 152 mm (6”) min.
L-bar at top bond beam recommended
Joint reinforcing 406 mm x 610 mm (16” x 24”)

194 mm (8”) CMU Solidly Grouted – Optional Veneer
19 M (#6) bar ea. jamb / 19M (#6) @ 610 mm (24”) c/c
‘Heavy’ roof/second floor or uplift
Foundation lap = fully developed 1016 mm (~40”)
L-bar or fully developed bar detail at top bond beam required.
Joint reinforcing 406 mm x 610 mm (16” x 24”)

Figure 16: Classroom Wing as Shelter Exterior Wall Configuration

The results of the missile tests [9] indicated that some partially grouted brick veneer cavity walls can also be used as the exterior shelter walls. For this type of wall, the reinforcing of the CMU backing would be the same, but the backing wall would not have to be fully grouted (a significant consideration for seismic loading and thermal resistance). If partially grouted cavity walls are used, the veneer anchor systems must be engineered for the wind loading produced by 402 km/hr (250 MPH). Analysis of the typical CMU backed veneer and anchors suggest that a heavy duty version of typical anchor systems would be adequate for this application.

Another tornado shelter option in schools is to provide the shelter in the gymnasium area. Gymnasiums tend to have large open floor areas, locker rooms with sanitary facilities, and limited windows. However, if these areas are used, door locations must be carefully considered as double doors or corner door locations can be challenging structurally in high wall systems. In addition, if exterior masonry walls are used, they must either be solidly grouted or have brick veneer cavity walls that have been debris impact tested. The high out-of-plane wind loads and roof uplift forces will require larger wall thicknesses, shorter reinforcing spacing and larger bars sizes. Horizontally spanning walls with highly reinforced wall pilasters may provide a solution. It should be noted that it can also be difficult to design the structural roof system to resist the large 4.79 kPa (100 psf) live load, with the typical long spans used in gymnasium areas.

CONCLUSIONS

The results of the impact tests shows that some brick veneer CMU backed cavity walls provide sufficient resistance to impact resistance to be considered for exterior shelter walls without the need for solid grouting.

Masonry walls can be used to provide safe, practical and cost effective solutions for sheltering from tornados and high wind events. Presented in this paper were two possible applications of solidly grouted single wythe and brick/CMU cavity masonry wall systems in typical school configurations as a means to provide building code-mandated tornado shelters with minimum increase in costs and changes in design.

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