Storm Shelter Design

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STRUCTURE magazine published *Structural Design and Coordination of ICC 500 Tornado Shelters* in July 2020, summarizing when a storm shelter is required, design criteria, and lessons learned. The authors of the July 2020 article provide guidance on design criteria, including the significantly increased basic wind speed, the increased internal pressure coefficient which presumes a breach in the building envelope, the increased directionality factor, and increased minimum roof live load, among other design criteria. To supplement the information in the previous article and illustrate the implications of storm shelter design criteria, the *Table* summarizes and compares wind load design parameters for a fictitious building used conventionally or as a storm shelter.

One of the most important aspects of storm shelter structural design is providing a robust load path for extreme wind loads. Loads need to be transferred from the roof, into the walls, and down into the foundation; the designer must ensure that each structural component along this path can withstand the load demands. This article focuses on typical structural systems and details used for storm shelter design and best practices for delegated design to complement the July 2020 article. This article references the 2014 ICC 500/NSSA *Standard for the Design and Construction of Storm Shelters* (ICC 500), referenced by the 2015 and 2018 *International Building Code* (IBC). ICC/NSSA recently published the 2020 ICC 500, which is referenced in the 2021 IBC.

Roof Systems

Roof framing systems in a tornado storm shelter need to be more robust than conventional framing systems to resist increased roof live load, wind uplift pressures, and diaphragm forces in addition to debris and missile impact forces. Roofs of storm shelters are often constructed with structural steel, precast prestressed concrete, cast-in-place concrete, or a combination to accommodate the increased loads.

Structural steel-framed roofs typically consist of wide-flange beams and girders, open-web steel joists, custom-fabricated steel trusses, or a combination. These primary framing elements are subjected to significant wind uplift pressures, often resulting in compression in bottom flanges or joist and truss bottom chords. Consideration of unbraced lengths and required bracing and/or bridging is critically important for a successful design to resist wind uplift pressure.

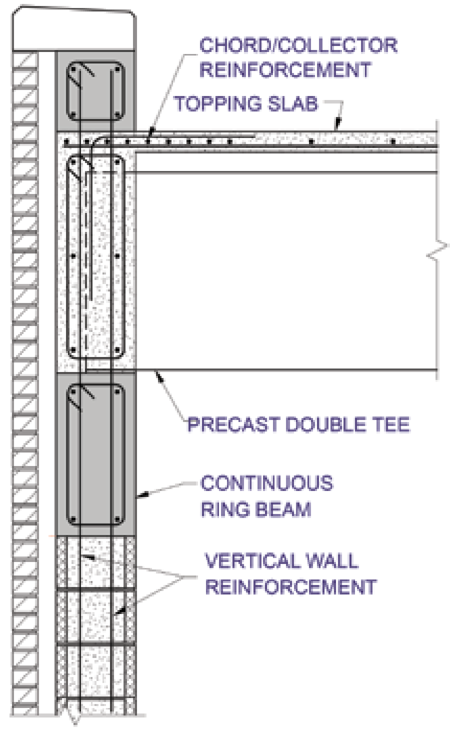

Figure 1. Exterior wall section at double-tee roof.

Concrete slabs on steel framing are typically placed on a composite steel deck. Adequate strength and missile impact resistance can ordinarily be achieved with a concrete-on-steel deck, as long as the concrete over the upper flutes of the deck exceeds the minimum established by debris impact testing. Additionally, concrete slabs on steel deck require substantial reinforcement to resist uplift loads, diaphragm shear, and chord and collector forces.

Reinforced concrete framed roofs may be cast-in-place or precast prestressed. Cast-in-place roofs are often an economical choice for unique geometries or shorter spans. Precast prestressed concrete roofs (typically double-tees) are generally the economical choice for rectangular buildings with low-sloped roofs and where longer spans, such as gymnasiums, preclude efficient cast-in-place concrete options.

Precast concrete elements often require a topping and significant reinforcement to resist uplift loads, diaphragm shear, and chord and collector forces. The topping slab can also serve to develop the missile impact resistance of the roof. *Figure 1* depicts a topping slab on a roof constructed with precast double tees. Precast concrete elements are usually a

K-12 School Gymnasium[1] in Springfield, IL		
Design Parameter	**Typical Building**	**ICC 500 Tornado Shelter Design**
Basic Wind Speed, V	114 mph	250 mph
Directionality Factor, K_d	0.85	1.0
Internal Pressure Coefficient, GC_{pi}	±0.18	±0.55
Velocity Pressure, q_h	29 psf	166 psf
MWFRS[2] – Wall Pressure[3]	33 psf	184 psf
MWFRS[2] – Roof Pressure[4]	-28 psf	-219 psf
C&C[5] – Wall Pressure[6]	-38 psf	-275 psf
C&C[5] – Roof Pressure[7]	-73 psf	-474 psf
Roof Live Load	20 psf	100 psf

[1]Risk Category III; Exposure Category C; Topographic factor, K_{zt} = 1.0; Mean roof height, h = 40 feet; $L = B$ = 80 feet; Flat roof; rigid structure.
[2]MWFRS calculated in accordance with ASCE 7-16 Chapter 27 – Directional Procedure.
[3]Combination of leeward and windward wall pressures for MWFRS design.
[4]Maximum roof uplift at horizontal distance of 0 to h/2 from windward edge.
[5]Components & Cladding (C&C) pressures calculated in accordance with ASCE 7-16 Chapter 30, Part 1 for component with effective wind area = 10 ft^2.
[6]Wall pressure at Zone 4 (field of wall) per ASCE 7-16 Figure 30.3-1.
[7]Roof uplift pressure at Zone 2 per ASCE 7-16 Figure 30.3-2A.

delegated design, aspects of which are discussed later in this article.

All roof systems must include a robust connection of the framing elements to the wall systems below.

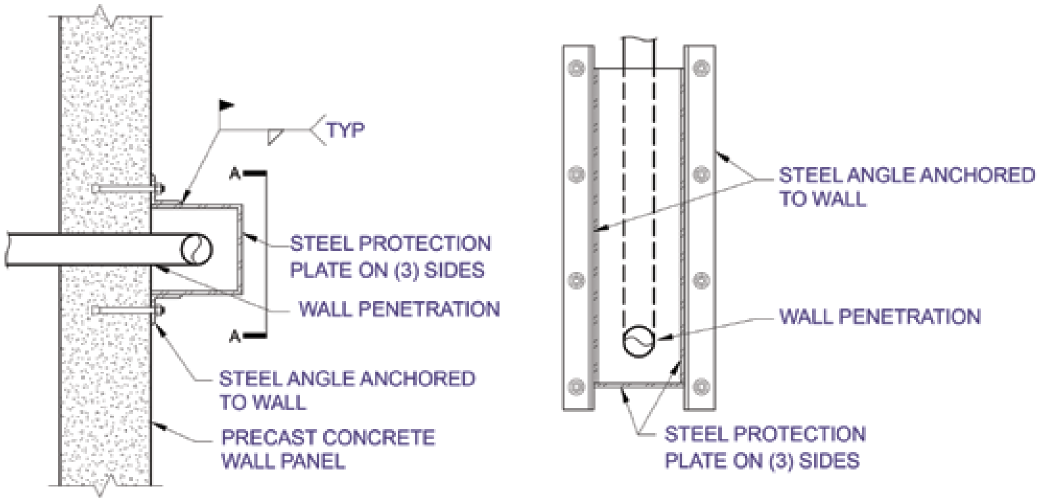

Figure 2. Plan view – pipe penetration in exterior wall (left); Elevation view A-A (right).

Wall Systems

Exterior walls of storm shelters are often used to support roof structures due to their inherent robustness to resist debris and missile impacts and their ability to transfer uplift loads to foundation elements efficiently. The exterior load-bearing walls of a community storm shelter can also serve a dual purpose as both gravity-bearing walls and lateral load-resisting walls (shear walls). Due to high shear demands, large openings in shear walls should be avoided. In addition to in-plane shear, exterior shear walls need to be designed for concurrent out-of-plane wind loads. Where roofs transfer wind uplift loads into shear walls, the effects of uplift and overturning must be combined when designing wall boundary elements and hold-downs.

Typically, exterior walls for community storm shelters are constructed of either reinforced concrete masonry units (CMU) or concrete. Exterior load-bearing CMU walls for storm shelters are usually solid-grouted to resist missile impacts. Due to the significantly increased out-of-plane wind pressures, the walls may need to be doubly-reinforced, with one bar on each side of the CMU cell. For constructability, the authors recommend using 10-inch or 12-inch-thick CMU if using two layers of reinforcement. While a typical CMU wall for a gymnasium structure might consist of 12-inch partially-grouted CMU reinforced with a single #5 bar spaced on 32-inch centers, a typical wall for a storm shelter might consist of 12-inch fully-grouted CMU reinforced with two #5 bars spaced on 8-inch centers.

Concrete walls for storm shelters can be cast-in-place, but precast tilt-up panels are cost-effective solutions. Wall panels can be solid or insulated sandwich panels as long as they comply with an approved list of missile-tested assemblies.

Both concrete and CMU walls require special detailing at the bottom and top of the wall to resist uplift. Additional steel reinforcement dowels are often required at the bottom of the wall to transmit uplift and shear loads into foundation elements. Congestion of large diameter bars in CMU cells can be eliminated using mechanical couplers in lieu of lap splices. A cast-in-place concrete ring beam is often cast at the top of CMU walls to transfer diaphragm shear, wind uplift loads, and support of locally high bearing loads from long-span elements. *Figure 1* depicts a typical concrete ring beam at the top of a CMU wall supporting precast double tees.

Foundation Systems

ICC 500 Section 308 contains provisions for the connection of storm shelters to foundations. In cases where the weight of the structure, cladding, and other permanent dead loads is less than the wind uplift, foundation elements need to be designed for uplift. In many cases, spread footings buried underneath a sufficient depth of soil are adequate, but deep foundations may need to be considered in extreme situations. Uplift capacities of deep foundation elements should be determined with the aid of a geotechnical engineer.

In addition to uplift loads, storm shelter foundations experience elevated lateral loads, which are imparted to the underlying soils. Deep and shallow foundation elements should be designed to resist these lateral loads. Shallow spread footings are particularly susceptible to combined uplift and lateral loads since wind uplift reduces the sliding resistance due to friction.

Community storm shelters with below-grade spaces need to be designed for buoyancy forces and hydrostatic loads. Per ICC 500 Section 303.3, underground portions of storm shelters require designing to loads "assuming the groundwater level is at the surface of the ground at the entrance to the storm shelter." An exception to this increased load is allowed by the ICC 500 if "adequate drainage is available to justify designing for a lower groundwater level." This may include dry wells or storm sewers but is ultimately based on recommendations from the geotechnical engineer.

Structural Coordination with Other Trades

Although unavoidable, penetrations through roof and wall systems of storm shelters should be limited. Where piping, conduit, ducts, or similar penetrations are required, ICC 500 Section 309.1 stipulates that rectangular penetrations greater than 3½ square inches in area or circular penetrations greater than 2$^{1}/_{16}$ inch in diameter be protected. Similar to those depicted in *Figure 2 (page17)*, protective steel plates can be installed to achieve this protection at wall openings for mechanical, electrical, or plumbing lines. ICC 500 Section 306.8 also requires protecting wall joints between adjacent tilt-up or precast concrete panels unless they are ⅜ inch or less in width. Similarly, at openings in roofs where roof vents and duct shafts are required, the structural engineer of record (SER) should provide details for steel plates or other framing to protect the penetration.

Larger openings in walls and roofs should be minimized. As these openings typically support a manufactured component, such as a window, door, or louver, the SER should ensure the structural elements around the opening are designed and detailed sufficiently to receive the minimum anchorage used during the manufacturer's missile impact test reports for each component. If the wall or roof system differs from that used in the manufacturer's test reports, increased strength of the surrounding structure is likely required.

Equipment for "critical support systems" on the storm shelter roof is required to be storm rated or housed in rooftop structures that will allow the equipment to remain functional in the event of a tornado as described in ICC 500 Section 701.1.

Delegated Design of Shelter Components

Storm shelter design frequently relies on delegating structural and non-structural component design to the contractor. Delegated structural components commonly include a combination of precast concrete roof or wall elements, open-web steel joists, and structural steel connections. Non-structural components include pre-manufactured windows, doors, louvers, and associated hardware. While these delegated items are typical for most building types, the magnitude of the loads is unique in community storm shelter design. Therefore, the SER should be diligent in clearly detailing the loads and design requirements in the drawings. Similarly, the specifier of other non-structural components in the storm shelter should do the same.

Design delegation is typically achieved through performance-based specifications authored by various design professionals. The SER's specifications should require the contractor to engage a specialty structural engineer (SSE) for structural components. For non-structural components, the architect's specifications should require pre-manufactured components tested for compliance with ICC 500 impact requirements.

The interrelation between the project's design professionals and the contractor's SSEs and component manufacturers is complex. The 2018 IBC is vague on the requirements for communication and responsibilities of these parties. Section 107.3.4 refers to the delegated design process as Deferred Submittals. This section requires the design professional in responsible charge to identify deferred submittals within the construction documents and review deferred submittal documents for general conformance to the design of the building. However, several industry-developed documents, such as the Coalition of American Structural Engineers (CASE) National Practice Guidelines for Specialty Structural Engineers, provide guidelines to enhance communication during the design and construction process.

The following is a list to consider for storm shelter delegated design:

- Require manufacturer and SSE qualification submittals to demonstrate experience with storm shelter design and construction.
- Include a delegated design matrix that delineates design responsibilities between the SER and SSE.
- Define ICC 500 roof live load, rain load, wind loads (MWFRS and C&C), and other debris and missile hazard loads for use by the contractor's SSE. Where a topping slab is anticipated to resist diaphragm shears or other loads, define these loads.
- Perform preliminary designs of delegated components to validate critical dimensional parameters such as concrete wall panel thickness, double tee profile, and steel open-web joist depth, spacing, and minimum bridging.
- Construction documents should include minimum thickness and reinforcement required in precast concrete elements to meet the missile impact criteria of ICC 500 Section 305.1.
- Define foundation design assumptions such as continuity between adjacent concrete wall panels that may impact panel overturning moments or require panel interconnectivity. Provide design loads at foundation embed plates and design supplemental reinforcement within foundation elements to resist concrete anchorage limit states.
- Provide details for supplemental steel at precast concrete openings that comply with ICC 500 Section 306.8 or 309.1, similar to *Figure 2*. The authors do not recommend deferring supplemental steel design to the precast manufacturer's SSE.
- Where it is unavoidable to create a structurally independent building, provide capacity-based connection forces at storm shelter interface with non-shelter components such as the host building, canopies, or other appurtenances.
- Review and coordinate performance-based specifications with those of other subconsultants for the building envelope.

In general, the authors do not recommend blanket statements that the SSE's design shall comply with ICC 500.

Summary

The successful design and construction of a storm shelter require active coordination between all parties from the very early conceptual stage to the final construction. More so than traditional buildings, all the systems and components of the storm shelter rely on the others regardless of the traditional lines of scope demarcation between design consultants and/or designers and constructors. Therefore, it is paramount that the design consultants clearly articulate loads and design requirements to be used by the SSE for their design of delegated design items.▪

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Previous articles on ICC 500:

Tornado Shelters in Schools. Harris, STRUCTURE, September 2016

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Tornado Debris and Impact Testing. Throop et al., STRUCTURE, May 2018

Structural Design and Coordination of ICC 500 Tornado Shelters. Simon and Dziak, STRUCTURE, July 2020