Designing for Tornado Alley

CORESLAB® STRUCTURES (ATLANTA) INC.

1655 Noah's Ark Road, Jonesboro, GA 30236
Ph: 770-471-1150
www.coreslab.com

It's no surprise that tornadoes are one of, if not the most destructive forms of severe weather. They often form rapidly giving residents in an affected area little to no warning. With that in mind, it's understandable that designers working on projects in the central and central-southern United States pay close attention to the protection of lives and property resulting from tornados and have requested performance data for structural elements being considered for storm shelter design.

Designing for windborne debris is a big part of that approach, particularly when kids are involved, putting school storm shelters squarely in the center of that thinking. It took some time to find a partner able to handle testing of representative full size precast hollow core plank samples. Working with Clemson University, Coreslab Structures (Atlanta) Inc. submitted our 10- and 12-inch hollow core for testing in general accordance with the 2020 ICC 500 ICC/NSSA Standard for the Design and Construction of Storm Shelters. A number of 15-pound 2x4 missiles where shot at 8-foot and 16-foot units in both simple-span and three-side-support conditions.

Needless to say that when striking 5,000 psi plus concrete, reinforced with steel prestressing strands, and a cross-section intended to support significant design loads, those projectiles stood little chance. The attached report highlights the findings, and we are pleased to confirm that Coreslab hollow core met or exceeded the requirements of ICC 500 for tornado shelters both with and without edge pours, and that edge pours and topping slabs (both a standard part of most hollow core designs) will increase impact resistance when used.

The Coreslab family shares community concerns for safety, especially in the critical area of school storm safety. After all some of our children may attend those same schools, or ones very much like them. Having the knowledge that this testing was performed and passed further enhances our firm belief that hollow core is not only suitable but should indeed be the preferred choice for school and public storm shelter roofs.

Debris Impact Testing of Coreslab Hollow Planks

July 2026

Prepared by:

Brandon E. Ross, PE, PhD

Cottingham Professor

With assistance from:

Aaron Smtih, EIT

Graduate Research Assistant

GLENN DEPARTMENT OF CIVIL ENGINEERING

CLEMSON® UNIVERSITY

1. Executive Summary

Clemson University conducted debris impact testing of Coreslab Hollow Planks (CHP) intended for use in tornado shelter roofs and elevated-floor systems. The testing was performed in general accordance with the 2020 ICC 500 ICC/NSSA Standard for the Design and Construction of Storm Shelters, using 15-pound 2x4 lumber missiles and a target impact speed of 67 mph for horizontal surfaces associated with a 250-mph design wind speed. The test program evaluated 10-inch and 12-inch CHP sections, 8-foot and 16-foot spans, simple-span and three-side-support conditions, and systems with and without edge pours and topping slabs.

The program was conducted in two phases. Phase 1 tested CHP alone to establish a lower-bound impact resistance, while Phase 2 tested CHP with edge pours and topping slabs to better represent typical tornado shelter construction and to evaluate corner impacts. Across the tested conditions, CHP specimens met or exceeded ICC 500 debris impact requirements for impacts in field areas, above bearings, at supported edges, and at unsupported edges. Many impacts were performed at speeds above the ICC-required value, providing additional confidence in the observed performance.

The primary vulnerability observed during Phase 1 was corner impact damage when CHP was tested without edge pours or topping slabs. Several specimens exhibited corner spalling or cracking, particularly when the missile impacted over hollow-core regions. Based on these results, CHP without edge pours and topping slabs should not be used for tornado shelter applications. However, this condition is not expected to reflect typical shelter construction, in which edge pours and topping slabs are understood to be included.

Phase 2 testing demonstrated that CHP systems with edge pours and topping slabs met or exceeded the debris impact requirements for corner impacts. Overall, the results indicate that Coreslab Hollow Plank systems, when used with appropriate edge pours and topping slabs, meet the ICC 500 debris impact requirements for tornado shelter applications, within the limits of the tested sections, spans, support conditions, missile weights, and missile speeds.

2. Scope and Approach

Coreslab Hollow Planks[1] (CHP) were tested for impact loads from windborne debris according to the *2020 ICC 500 ICC/NSSA Standard for the Design and Construction of Storm Shelters*[2]. Requirements for impact testing are found in sections 305, 306, 802, and 803 of the Standard. CHP are used as roof and elevated-floor members, including intended use in *tornado shelters*. As such, a design wind speed of 250 mph was considered, which corresponds to a 67-mph missile speed for impact loads on horizontal surfaces. During the tests, 67 mph was the minimum speed, with missile impacts also performed at faster “code-plus” speeds. The scope of the work was limited to impact testing.

The test program was conducted in two phases. Phase 1 evaluated only CHP, and Phase 2 evaluated CHP systems with edge pours and topping slabs. It is reasoned that the presence of edge pours and topping slabs increases the impact resistance, and that the Phase 1 results correspond to the lower bound of CHP impact resistance. In other words, if CHP complies with the impact testing requirements on its own, it will also comply when tested as a system. Phase 2 focused in particular on corner impacts, which were a problem for some Phase 1 specimens.

The structural engineering labs at Clemson University, including the debris impact testing facilities, are not accredited testing agencies. Aside from the Clemson team’s lack of accreditation, the test program presented in this report met or exceeded the requirements of ICC 500. In some cases, minor deviations from ICC 500 were used. Deviations are explicitly noted and were implemented to fit the geometry of CHP.

[1] “Hollow core” precast members are available in different configurations and with different concrete mixes. This report is specific to the Coreslab Hollow Planks.

[2] A newer version of ICC 500 is currently in development but has not been official released and adopted.

3. Specimens and Variables

Test variables, including cross-sections, spans, support conditions, and edge details, were designed to mimic typical field conditions[3], simplify the test program, and comply with practical limitations of the testing lab. Table 1 summarizes the test variables and their basis for the section. Bearing lengths and edge supports in the test frame were designed in accordance with the typical CHP-to-CMU wall details shown in Figures 1 and 2.

Table 1 – Test Variables

Variable	Test Conditions	Basis for Selection
CHP cross-section	10” thick w/ 5 strands	Common designs for school roof and floor structures
	12” thick w/ 8 strands	
CHP span	8’	Common designs for school roof and floor structures, 8’ is representative short spans and 16’ is the max span based on the lab
	16’	
Support conditions	Simple span	Based on typical construction details, see Figures 1 and 2
	Simple span + edge	
Edge pour and topping slab	Without (phase 1)	Testing without edge pours and topping slabs simplifies testing while providing a lower bound result; see discussion in Section 1
	With (phase 2)	

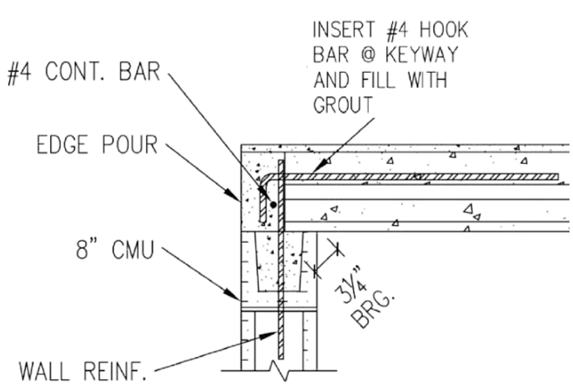


Figure 1 – Typical CHP bearing on CMU wall.

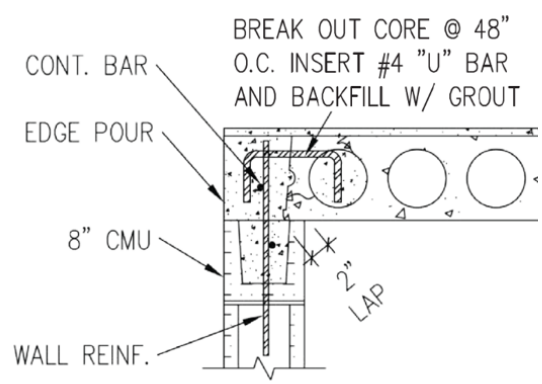


Figure 2 – Typical CHP edge at CMU wall.

Specimen labels and test variables are summarized in Table 2. Labels are based on the cross-section, span length, and replicate number. For example, “10-08-2” has a 10-inch-

[3] To aid in selecting variables, the Clemson team considered drawings of CHP-framed floors and roofs in schools. CHP design guidelines were also consulted. The plans and guidelines were provided by Coreslab.

tall cross-section, an 8-foot-long span, and is the #2 replicate for those conditions. A total of 10 specimens were tested, enabling evaluation of different combinations of variables and impact locations.

Table 2 – Test Specimens

Label	Phase	Section	Span	Supports	Edge + Topping
10-08-1	1	10" + 5 strands	8'	3 sides	No
10-08-2	1	10" + 5 strands	8'	Simple span	No
10-16-1	1	10" + 5 strands	16'	Simple span	No
10-16-2	1	10" + 5 strands	16'	Simple span	No
12-08-1	1	12" + 8 strands	8'	3 sides	No
12-08-2	1	12" + 8 strands	8'	Simple span	No
12-16-1	1	12" + 8 strands	16'	Simple span	No
12-16-2	1	12" + 8 strands	16'	Simple span	No
10-08-3	2	10" + 5 strands	8'	3 sides	Yes
12-08-3	2	12" + 8 strands	8'	3 sides	Yes

CHP specimen cross-sections are shown in Figure 3. All specimens were fabricated at the Coreslab facility in Jonesboro, GA and trucked to Clemson for impact testing. Personnel from Coreslab confirmed that the specimens were fabricated on the same equipment and with the same materials as their production planks[4]. Material properties are reported in Table 3.

The edge pours and topping slabs for Phase 2 specimens, 10-08-3 and 12-08-3, were placed by the Clemson team. Photos of the formwork, reinforcement, and concrete placement are shown in Figures 4 and 5. Details and material properties for the edges and topping slabs were determined in consultation with Coreslab[5] to reflect typical field conditions and Figures 1 and 2. Rather than dedicated chairs typically used for positioning reinforcement, wood blocks were used. This change will tend to decrease the strength of the edge pours.

Impact testing for Phase 2 was conducted two weeks after placing the edges and topping; this timing ensured that the concrete strength was at the low end of the range typically used in practice. The topping slabs were 3.5 in. thick and reinforced with 6x6-W1.4xW1.4 Welded Wire Fabric purchased from a retail building supply store. The topping slabs were placed only over one corner of the CHP and had an area of approximately 28 in. x 28 in.

[4] Based on email from Jay Rubinson to Brandon Ross, June 30, 2026
[5] Based on email from Jay Rubinson to Brandon Ross, June 30, 2026

Before placing the topping slab, the CHP surface was swept off to remove large debris, but otherwise left as received.

According to Coreslab's descriptions, it is typical for concrete to fill the hollow cores partially. Measures were taken to allow some concrete into the cores, but to limit the amount. The hollow cores in specimen 12-08-3 were blocked with plastic film and foam adhesive (Figure 4); however, no attempt was made to block the hollow cores in 10-08-3. The concrete was very stiff at placement and was only lightly consolidated in locations adjacent to the core openings.

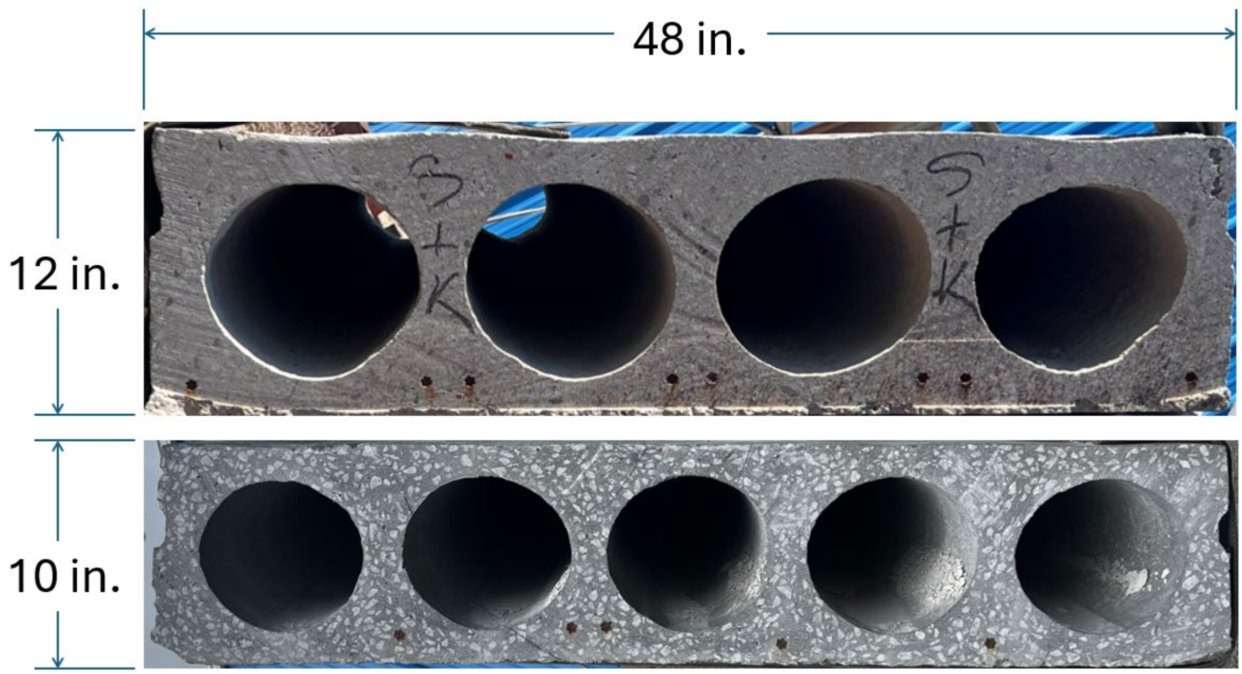


Figure 3 – End view of test specimens with nominal dimensions

Figure 4 – Photos of edge pour construction and concrete placement

Figure 5 – Photos of topping slab placement

Table 3 – Material Properties[6]

Material	Source	Descriptive Property
CHP concrete	Coreslab	5000 psi compressive strength (specified)
CHP strands	Varies	1/2 in. nominal diameter (nominal) 270 ksi tensile strength (specified)
Edge/topping concrete	Quickcrete	3540 psi (tested)
Edge rebar	CMC	60 ksi tensile strength (specified)
Welded wire mesh	WMC	Unknown

[6] Based in part on email from Jay Rubinson to Brandon Ross, July 29, 2026

4. Equipment and Test Setup

All testing was conducted using the pneumatic cannon shown in Figure 6. The cannon dates to circa 2000 and has contributed to numerous research projects over the years. Missile velocity is controlled by air pressure in the cannon, and valves and a gauge control the pressure. The cannon is mounted on a steel frame that can be wheeled into position to maintain a missile's flight path perpendicular to the test specimen. A schematic plan view of the test area is shown in Figure 7, and a photo in Figure 8.

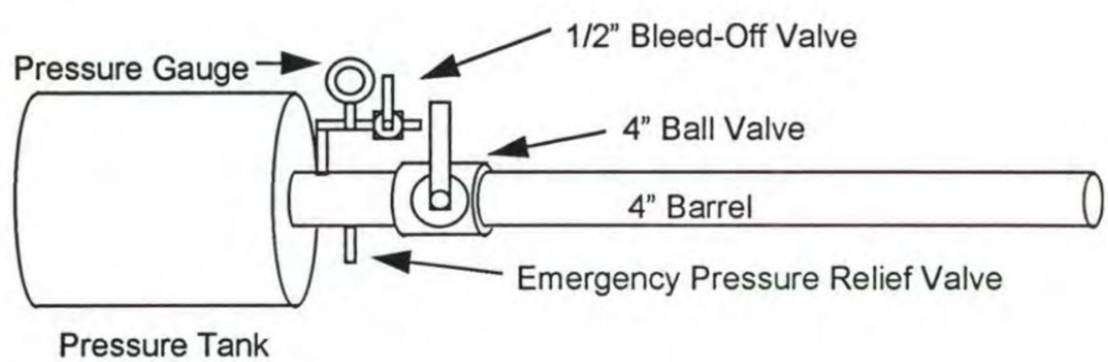


Figure 6 – Clemson University debris cannon[7,8]

[7] https://open.clemson.edu/all_dissertations/2639/
[8] https://open.clemson.edu/arv_theses/4207/

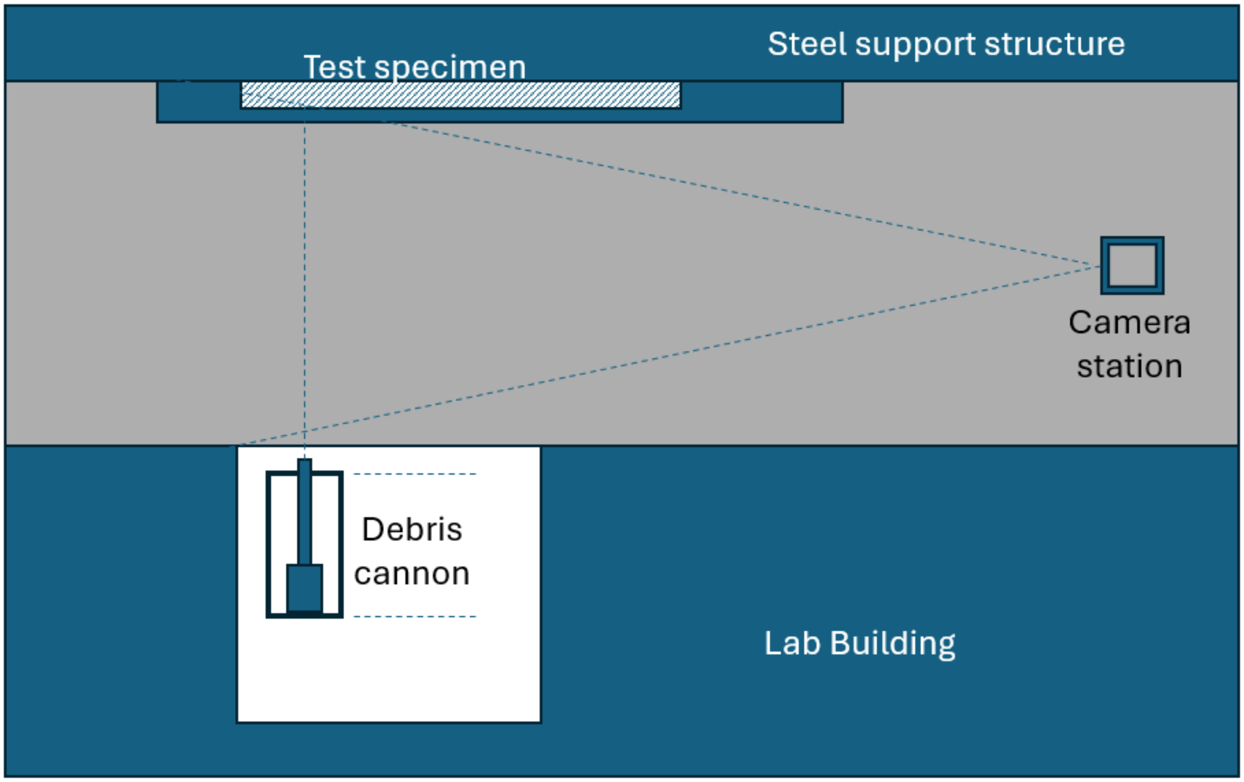


Figure 7 – Plan view of test area (not to scale)

Figure 8 – Photo of the test area as viewed from the camera station

For testing, the specimens were oriented vertically as shown in Figure 9. While CHPs are typically used for floor and roof members, the vertical orientation was necessary because the debris cannon launches the missiles horizontally. The specimens were supported in this position by resting them on a steel ledge and test frame. The frame is shown in Figure 10 without a specimen in place. Once the specimen was placed in the frame, it “spanned” horizontally between bearing supports in the frame. The orange pieces shown in Figure 10 were adjustable to accommodate different span lengths and edge bearing conditions. For tests with simple-span conditions, the edge supports were removed from the frame.

When positioned in the test frame, the specimen's self-weight was supported by a steel ledge. Wood spacers on the ledge allowed the specimens to be positioned using a forklift. Rubber bearing pads and low-friction plates were placed between the specimen and spacers to mitigate restraining effects. As shown in Figure 9, clamps and straps were used to secure the specimen to the load frame during setup and testing. Clamp and strap locations were adjusted as needed to avoid conflicts with impact locations.

Figure 9 – Specimen positioned in test frame

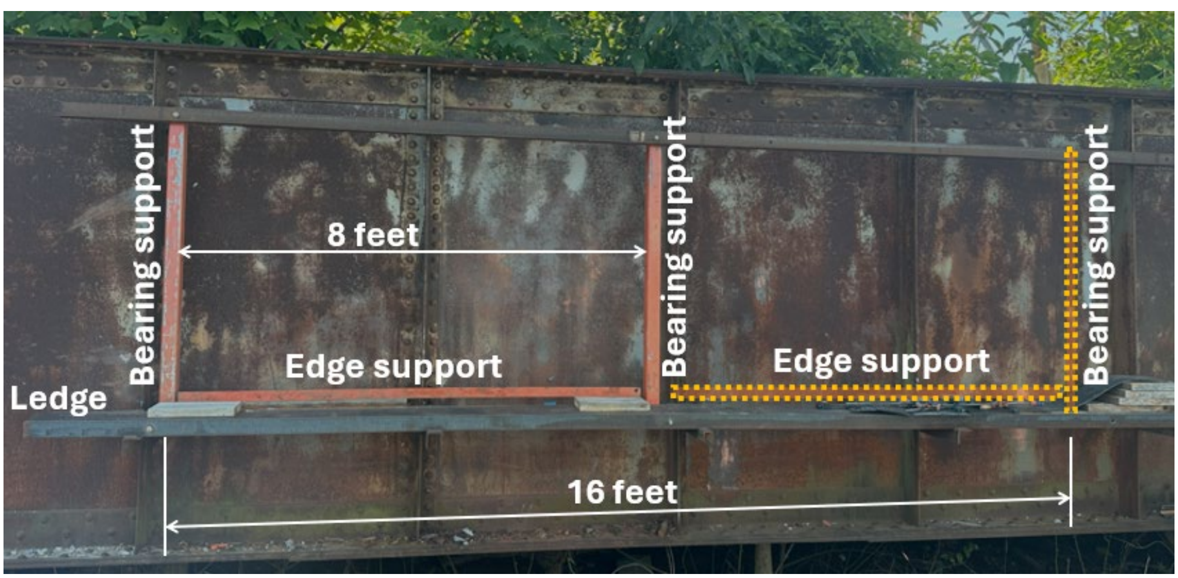


Figure 10 – Test frame without specimen in place

As prescribed in ICC 500, the missiles were 15-pound pieces of No. 2 2x4-dimension lumber (Figure 11). Missiles were weighed and trimmed as necessary immediately before testing. Plastic sabots were screwed onto the ends of the missiles to reduce air leakage around them during launch. To comply with the weight requirement, treated boards were used in most cases because they have a higher density than untreated boards. Boards were weighed using the scale in Figure 12.

Figure 11 – Grade mark of 2x4 missile

Figure 12 – Scale for weighing missiles

Missile speed was measured with a radar gun accurate to 0.1 mph (Figure 13). Backup measurements were also made using slow-motion videos and by correlation with the cannon air pressure. An image from one of the videos is shown in Figure 8. Missile speed was calculated using the travel time measured from the video and the known travel distance. To avoid the acceleration phase, time and distance values from the videos were taken after the missile exited the cannon barrel. Backup values were within ±4.3 mph of the radar gun with 70% confidence and ±8.8 mph with 95% confidence.

Figure 13 – Radar gun used to record missile speed

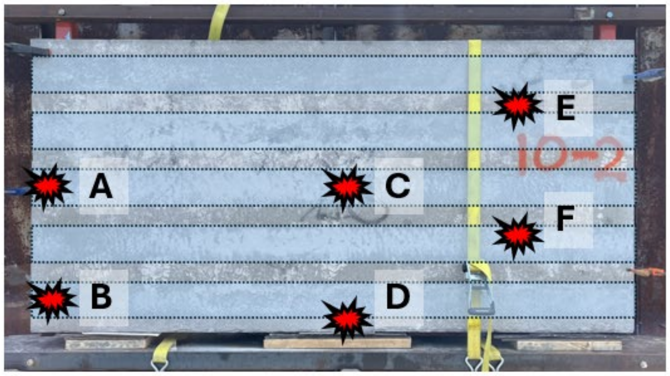
5. Test Procedures

The list below is a sequential list of tasks the Clemson team followed during testing. Notes and quantitative data were recorded immediately using a spreadsheet and a physical datasheet. Video and picture data were uploaded to a storage file at the end of each day of testing.

- ☐ Note the date, time, weather, and specimen variables on the data sheet.
- ☐ Take pictures of the specimen front, back, and sides before testing
- ☐ Take pictures of the specimen in the frame support conditions.
- ☐ For each impact test, record the following:
  - Observations of specimen condition before impact
  - Missile weight
  - Cannon position relative to the lab floor and specimen
  - Paint the missile's end; this helps mark the impact location on the specimen
  - Cannon air pressure
  - Missile speed recorded by radar gun
  - Slow-motion video of the missile
  - Calculated missile speed based on slow-motion video
  - Location of impact relative to test frame
  - Photo of impact location (impacted face)
  - As needed/possible, photos of the impacted location from the side and back
  - Observations of specimen condition after impact
- ☐ Take pictures of the specimen front, back, and sides after testing

Figure 14 shows the target impact locations. Precast concrete hollow core members, including CHP, are not specifically addressed in ICC 500. As such, the impact locations were selected to comply with ICC 500 (Figure 15), with a minor adjustment to the corner impact to account for CHP geometry. Specifically, the CHP corner impact was adjusted so that the missile hit directly over the hollow portion. As reported in the next section, this location was found to be vulnerable when CHP was tested without edge pours and topping slabs.

Not every specimen was impacted at every location. ICC 500 limits the number of impacts per specimen to three, unless the testing lab and sponsor agree to additional shots. Based on mutual agreement between the Clemson and Coreslab teams, most specimens were subjected to more than three shots. Many of the "extra" impacts were exploratory and intended to test missile speeds above the ICC required value.



A - Over support and hollow core
B- W/in 6 in. of end and over hollow core (~corner shot)
C- Center of panel
D- Edge of panel
E- "Field" location over solid
F- "Field" location over hollow core

Figure 14 – Impact locations targeted in the test program

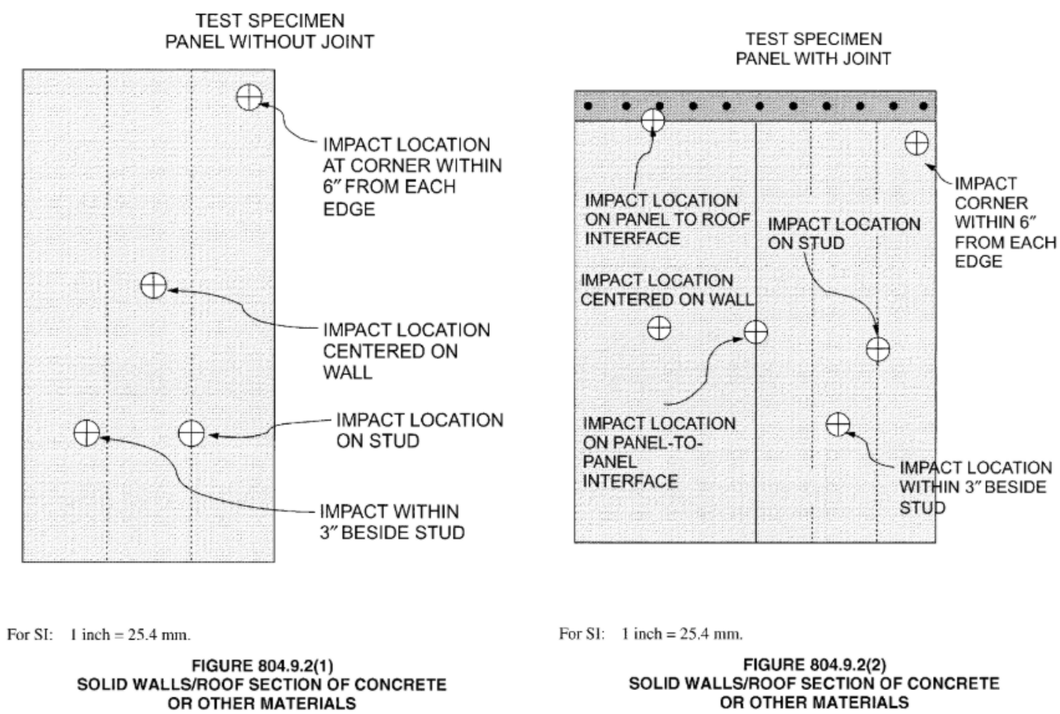


Figure 15 – Impact locations from ICC 500

6. Significant Findings

Overall Findings

- The CHP specimens and systems used in the test program met or exceeded the debris impact requirements of ICC 500 for tornado shelters.
- CHP tested alone (i.e., without edge pours or topping slabs) met or exceeded debris impact requirements for impact locations in the field, above bearings, above supported edges, and above unsupported edges. It is reasoned that the presence of edge pours and topping slabs will only increase impact resistance at these locations.
- When tested alone (i.e., without edge pours or topping slabs), most of the CHP specimens exhibited spalling or cracking due to corner impacts. Based on this observation, CHP without edge pours and topping slabs should not be used in tornado shelters.[9]
- Specimens comprised of CHP, edge pours, and a topping slab met or exceeded the debris impact requirements associated with corner impacts.

Limitations

The findings described above are limited to the conditions of the test program, including:

- Coreslab Hollow Planks[10] (CHP) having the cross-sections, stand layouts, and concrete mixes represented in the test specimens,
- The presence of edge pours and topping slabs for impact resistance at panel corners,
- Missile speeds and weights used in the test program, and
- Support conditions and spans in the test program.

---

[9] It is the Clemson team's understanding that edge pours and topping slabs are always used in CHP-framed structures designed as tornado shelters. As such, the corner spalling failure should not affect compliance with ICC 500. It is extremely unlikely that an engineer would consider using CHP without edge pours and topping slabs in a tornado shelter; however, corner spalling is noted here to discourage even the possibility that edge pours and topping slabs would be omitted.

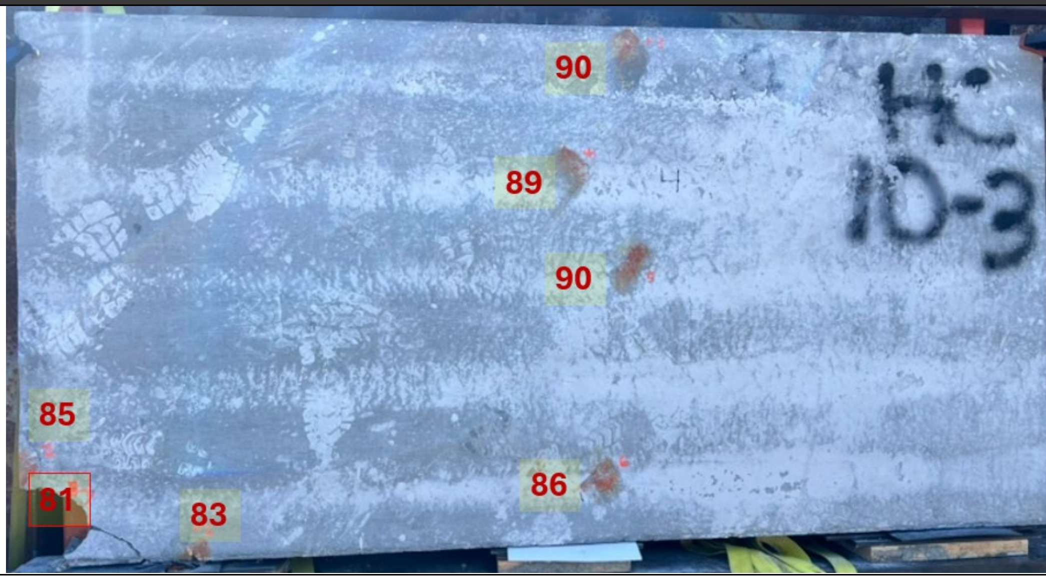
[10] Testing by Naji 2014 showed that smaller hollow core specimens can be more critical than longer specimens for impact resistance. Hence, it is likely that span lengths longer than the test specimens will also provide sufficient impact resistance.

7. Appendix: Data Summaries

Figures and tables in the appendix summarize the test results for each panel. The numbers on the figures correspond to missile speeds in miles per hour and are placed near the associated impact locations.

The tables document the test date, test variable, impact sequence, impact locations, missile speeds, missile weights, and results. A few observations are provided for each panel. The observations for the first few summaries in the appendix are lengthier as they provide context regarding corner impacts and speed measurements. The same context applies to summaries listed later, even though it isn't explicitly discussed.

Specimen 10-08-1



Tested 03/27/26

Supported 3 sides

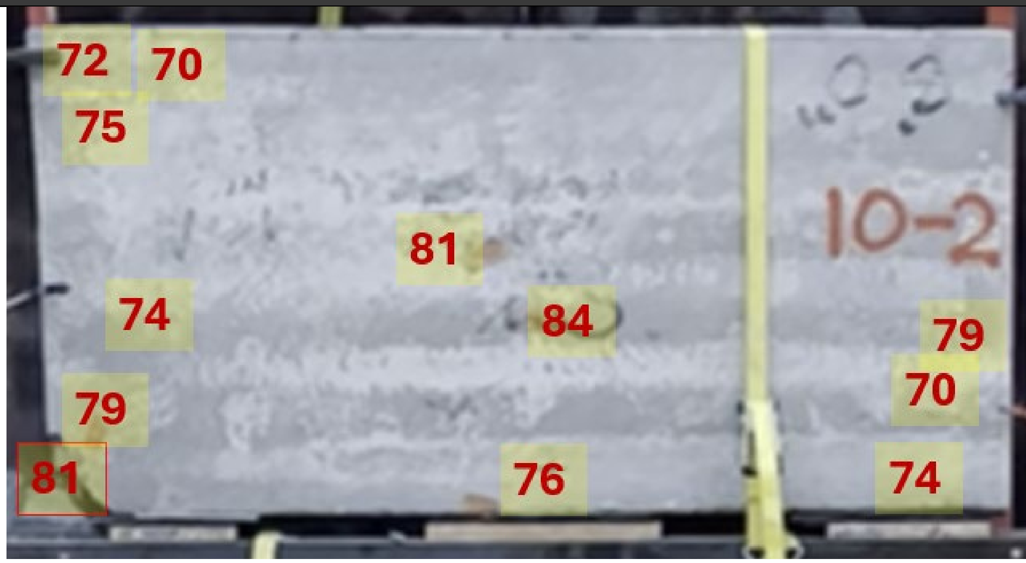
Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Supported edge	83 (backup)	15.02	No damage
Bearing, above solid	85 (backup)	15.02	
Unsupported edge	90.6	14.97	
Field, above solid	89 (backup)	15.06	
Center	90 (backup)	15.04	
Field, above hollow	85.9	14.99	
Corner, above hollow	81.4	15.04	Corner spall

This is the first panel tested, and the Clemson team wasn't yet familiar with the radar gun operations. Thus, backup values were needed for missile speeds in four tests. Backup values are the average values calculated from two separate slow-motion videos and the pressure-correlated value. There is over 99% confidence that the missiles using backup speeds were traveling faster than the ICC value of 67 mph.

After the initial impacts, additional shots were fired. The final impact on the panel occurred in the lower-left corner over a hollow location. The final impact caused spalling of the corner at the front and back face. This result confirmed our suspicion that this location was vulnerable. While notable, this spalling is not of concern for ICC compliance because: i) the missile speed was faster than the ICC requirement, ii) the excessive number of previous impacts, iii) multiple previous impacts adjacent to the spalling location, and iv) the lack of edge pour and topping.

Specimen 10-08-2			



Tested 4/2/26 and 4/14/26			
Simple span			
Impacts (listed in chronological order)			
Impact Location	**Missile Speed (mph)**	**Missile Weight (lbs.)**	**Result**
Field, near hollow	81.4	14.95	No damage
Field, above solid	83.8	14.99	No damage
Unsupported edge	75.5	14.97	No damage
Corner near hollow	78.8	15.13	No damage
Corner, above hollow	80.6	14.99	Corner spalling
Bearing, near solid	74.1	15.06	No damage
Bearing, above hollow	74.6	15.13	No damage
Bearing, near hollow	72 (backup)	15.02	No damage
Bearing, above solid	70.4	15.19	No damage
Near bearing, near hollow	74 (backup)	15.06	No damage
Bearing, near solid	78.6	14.91	No damage
Field, near hollow	70.3	15.08	No damage

Many additional impacts were made beyond those required by ICC 500. These impacts were exploratory and conducted to evaluate different speeds and locations. The 5th impact was at the corner location above the hollow and caused spalling. For reasons listed in the summary of 10-08-1, the corner spalling is notable but does not impact ICC compliance.

Specimen 10-16-1

Tested 4/22/26

Simple span

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Unsupported edge, above solid	77.2	15.02	No damage
Bearing, above solid	79.0	15.06	No damage
Corner, above solid	85.3	14.93	Corner cracks

The cracked corner was easily removed by hand when the specimen was lifted from the test frame. It follows the same pattern as the specimens spanning 8 feet. The corner shot was ~25% faster than the ICC requirement. The missile speed was reduced for the next test, specimen 10-16-2.

Specimen 10-16-2

Tested 4/22/26

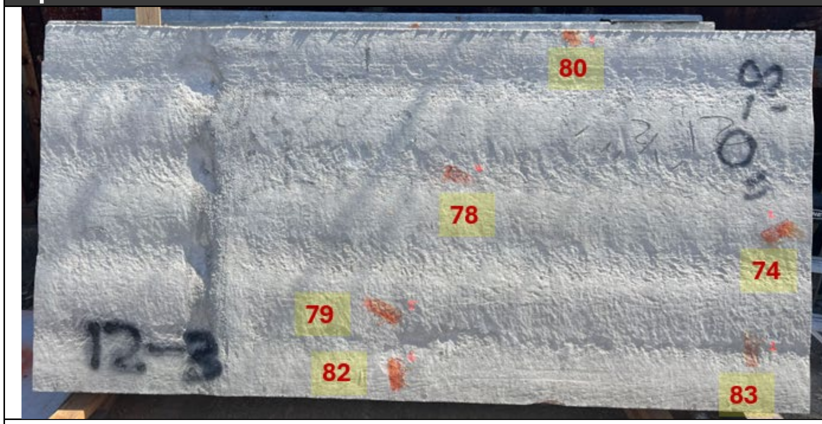
Simple span

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Near middle, above hollow	74 (backup)	15.02	No damage
Field, over solid	66.4	15.06	No damage
Corner, near hollow	74 (backup)	14.93	Corner spall

Pressure was reduced in the cannon so that the missile speeds would be closure to the ICC value of 67 mph. At the reduce speed, the corner shot still caused damage.

Specimen 12-08-1



Tested 03/27/26

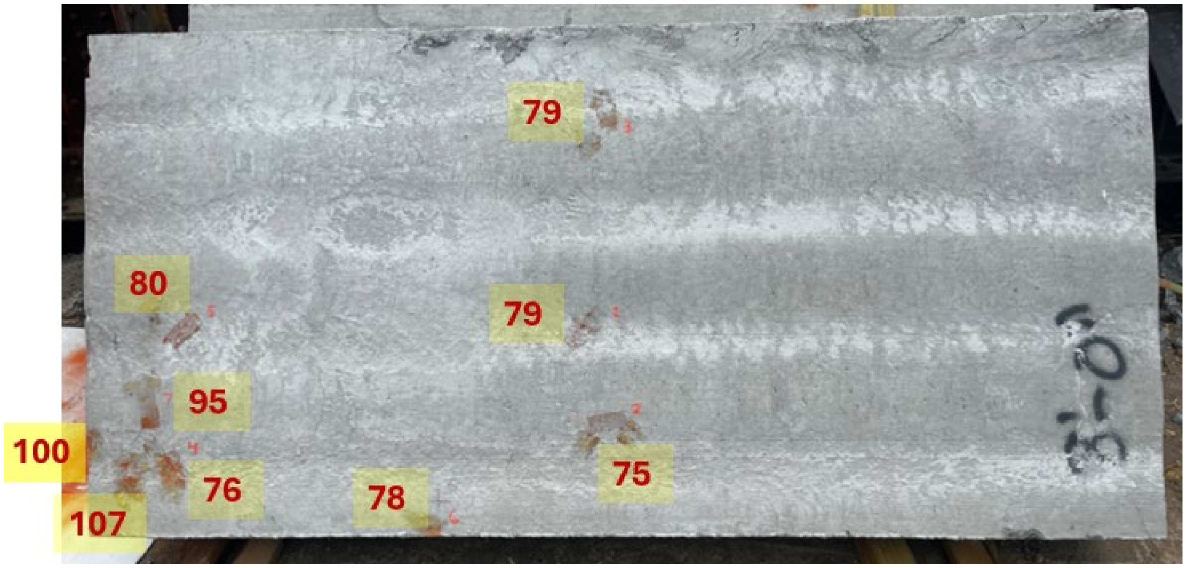
Supported 3 sides

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Near corner, above hollow	83.1	14.86	No damage
Bearing, above solid	74.3	15.10	
Unsupported edge above solid	80 (backup)	14.99	
Near middle, above hollow	78 (backup)	14.97	
Field, above soild	78.6	15.02	
Supported edge, near solid	81.5	15.10	

The speeds were ~20% higher than the ICC value, yet no damage was observed.

Specimen 12-08-2



Tested 3/27/26

Simple span

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Near middle, above hollow	78.7	15.04	No damage
Field, above solid	74.8	15.06	
Field, above hollow	78.5	14.95	
Near corner, above hollow	76 (backup)	15.06	
Near bearing, above hollow	79.6	15.02	
Unsupported edge, above solid	77.6	14.95	
Near bearing, above solid	94.6	15.04	
Above bearing, glancing impact	100.0	14.93	
Corner, above hollow	106.9	12.28	

This was the final specimen tested on 3/27/26. For the final three impacts, the cannon pressure was increased up, with the final to impacts using 100 psi. Even with the extreme speeds and multiple impacts near the corner, no damage was observed.

Specimen 12-16-1

Tested 4/22/26

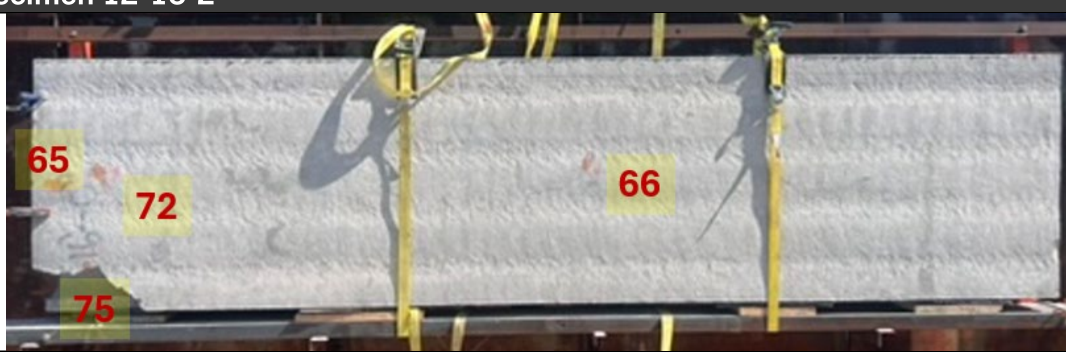
Simple span

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Corner, near hollow	83.2	15.26	No damage
Bearing, above hollow	71.3	15.04	No damage
Corner, above hollow	66.0	15.13	Corner spall
Unsupported edge, glancing impact	73.9	15.10	No damage

The upper corner spalled while the under and impact with missile speed near the ICC value.

Specimen 12-16-2



Tested 4/22/26

Simple span

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
Near corner, above hollow	75.2	14.84	Corner spall
Bearing, above solid	64.9	15.04	No damage
Field, above solid	71.6	15.08	No damage
Middle, above solid	66.4	15.04	No damage

The lower left corner had one of the largest spalls in the test program. The missile's impact caused damage while traveling at ~10% above the ICC-required speed.

Specimen 10-8-3 (phase 2)

Dashed lines in left image indicate the location of the edge pour/CHP interface.

Tested 6/24/26

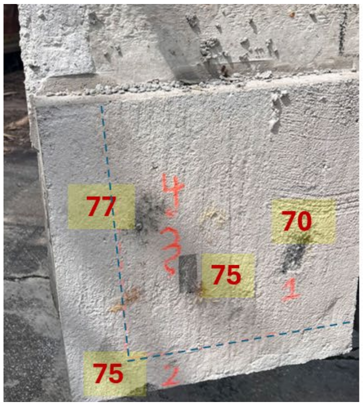
Supported three edges

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
On topping, above supported edge, above edge pour/CHP interface	75 (backup)	14.99	No damage
On topping, corner of CHP, above hollow	80.6	15.04	No damage
On topping, above bearing, above edge pour	75 (backup)	15.08	No damage
On topping, field	111.6	15.10	No damage

The second impact (80.6 mph) occurred at the critical location from phase 1. For the final impact, the missile speed was increased to approximately double the ICC 500 speed. Even with the critical locations and increased speed, no cracking, spalling, topping delamination, or other damage was observed.

Specimen 12-8-3 (phase 2)



Dashed lines in left image indicate the location of the edge pour/CHP interface.

Tested 6/24/26

Supported three edges

Impacts (listed in chronological order)

Impact Location	Missile Speed (mph)	Missile Weight (lbs.)	Result
On topping, in field, above hollow	69.9	15.10	No damage
On topping, supported edge, glancing impact	75 (backup)	15.02	No damage
On topping, corner of CHP, above hollow	75.4	15.06	No damage
On topping, near bearing, over CHP solid	77.3	15.13	No damage

The third impact matched the critical corner location observed in Phase 1. Even with impact at the critical location, no cracking, spalling, topping delamination, or other damage was observed.