Pressure and Impact Test Performance of Above-Ground Non-Complying Tornado Shelter Doors

A NSSA/NWI DIF Sponsored Project

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Abstract -- The above-ground tornado shelter concept was first published in 1974. After the Oklahoma City (OKC) Tornado of 1999, the Federal Emergency Management Agency (FEMA) began providing incentive grants to fund a portion of the cost to construct or purchase tornado shelters. Since then, FEMA has provided millions of dollars for thousands of shelters. No deaths were reported in above-ground shelters until April 27, 2014, when a woman in Mayflower, Arkansas, was killed when her shelter door failed when impacted by storm debris. National Storm Shelter Association (NSSA) personnel acquired the failed door and brought it to the National Wind Institute's Debris Impact Facility (NWI DIF) at Texas Tech University. NWI DIF researchers performed a detailed analysis, and determined that the door, though metal skinned, was a non-complying (untested) door, not designed for safe room application. Observations of storm shelter installation practices revealed that the installation of lesser priced, non-complying shelter doors, might be prevalent in otherwise complying shelters. The NSSA, along with the NWI DIF, therefore sponsored this demonstration project to show the hazard of using untested doors and enlisted the NWI DIF to conduct the demonstration. Mitigation strategies were attempted to improve commonly used, untested doors, unfortunately, no dependable mitigation strategies were found, thus reinforcing previous guidance, that the only dependable safe room door is a specifically manufactured and tested assembly.

1. Introduction:

Records of great thunderstorms, hurricanes, tornadoes, and floods have been maintained for centuries. Perhaps one of the first storms recorded in North America was John Winthrop's Journal, "History of New England" 1630-1649. In it, he recounts the "Sudden Gust" in 1643 which "lifted upon their meeting house at Newbury, the people being in it" (Winthrop 1959). Much of the early work on tornado climatology in the United States was done by John Park Finley in his book "Tornadoes," published in 1887 (NOAA 2016). However, tornado statistic keeping, general public awareness, communications, and technological advancements have dramatically improved since the early 1950's when tornado data keeping began. Typical annual estimates indicate that 1,000 tornadoes occur each year producing approximately 100 deaths. However, in 2011 NOAA statistics recorded 1,700 tornadoes and 553 deaths, the second highest in history (Wikipedia 2011). Since no anemometers had survived a tornado, early estimates of tornado wind speeds varied. Even esteemed meteorologist Dr. Ted Fujita added an additional category to his F Scale, F6, which he classified as "Inconceivable Tornado" rated at 319-379 mph (Wikipedia 1971).

On May 11, 1970, the City of Lubbock, Texas, was struck with two F5 tornadoes damaging a quarter of the city, much of downtown and killing 26 people. It was these storms that became the inspiration and justification for the establishment of Texas Tech University's National Wind Institute (initially the Institute for Disaster Research, succeeded by the Wind Science and Engineering Research Center) today (NOAA 1970). Young Texas Tech University researchers, working in collaboration with Dr. Fujita, investigated numerous severe storms over the next few years, and investigations continue to date with new researchers. More than 200 storms have been investigated in the last 46 years.

During their early research, these Tech professors routinely found surviving small structures among the destruction, and the surviving structure in *Figure 1* from the 1974 Super Outbreak reinforced the above-ground shelter concept.

Figure 1: Surviving Structure, Xenia, Ohio Tornado, 1974.

Using damaged structures from the 1974 investigation, the researchers analytically determined ground level wind speeds based on known pressure coefficients and dead loads, and their "conclusions were that ground level wind speeds exceeding a range of 250 mph (112 m/s) could not be substantiated and were probably considerably less (Mehta 1976)." They stated that most of the structures analyzed were designed to the current building codes, but that poor attention to connections and debris impacts increased the probability for building failure.

Given the continued reports from other storm investigations and wind speed analyses as discussed above, Dr. Ernst Kiesling and his Master's student, D.E. Goolsby, worked to design above-ground shelters to resist wind speeds of 250 mph, utilizing commonly available construction materials and performing debris impacts (Kiesling 1974). The types of missiles and launchers varied, but further research led to the adoption of the 15 lb. wooden 2-in. x 4-in. launched by a pneumatic cannon. With a 250 mph maximum storm ground speed selected, the adopted wooden debris was calculated to travel approximately 100 mph horizontally and fall to the ground at about two thirds of that speed. The initial door design was constructed of a double layer of ¾-in. plywood with an 11 gage steel face sheet and the door installed as a pocket door hung on a heavy overhead railing system.

Door systems are particularly vulnerable to pressures and debris impacts, as seen in the photographs from numerous storms below. *Figure 2*, from the 2007 Central Florida Tornadoes, illustrates negative pressure exerted on a garage door. *Figure 3*, from the 1999 OKC Tornadoes, shows a typical residential entry door and sidelight perforated by storm debris. *Figure 4*, also from 1999 OKC Tornadoes, shows a solid core wood door located in an interior corridor at Kelley Elementary with multiple debris impacts. *Figure 5* is from the Moore, OK 2003 Tornadoes and shows a second floor outswing steel exit door knocked inward by debris impacts.

Figure 2: Negative pressure on OHD.

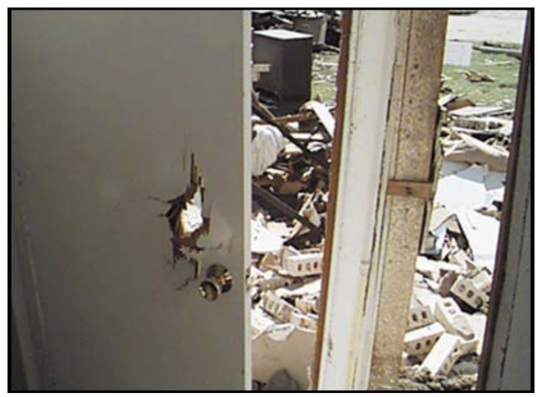

Figure 3: Residential entry debris

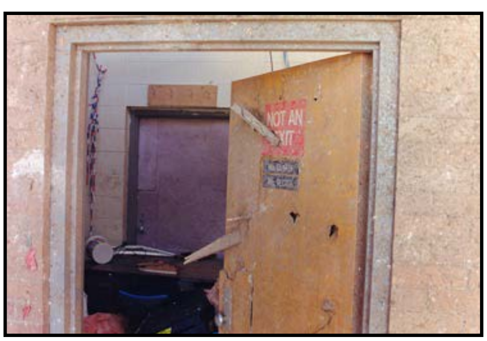

Figure 4: Multiple impacts on interior door.

Figure 5: Exterior HM door impacted.

No deaths were reported in above-ground shelters until April 27, 2014, when a woman in Mayflower, Arkansas, was killed when her shelter door failed when impacted by storm debris, as shown in *Figure 6* (KARNTV4 2014). With the assistance of the NSSA, researchers from the NWI DIF at TTU obtained the door and performed a complete dissection and analysis of the actual door and hardware to better understand why it had failed. It was determined that the light duty hollow metal (HM) door and frame with residential hardware was not designed or intended for tornado safe room installations (Tanner 2014).

Figure 6: Mayflower, Arkansas, Shelter.

The NWI DIF has tested numerous commercially available special tornado resistant door and hardware assemblies for many years and lists on its website those products that passed tests, NWI DIF Tested Commercial Doors (FEMA Door Testing, 2016). However, the death in Mayflower gave the NWI DIF researchers a fearful vision of many other shelters with substandard door assemblies. The NSSA/NWI DIF sponsored this research project to demonstrate the performance of other common types of door assemblies that may be installed in storm shelters across the country.

2. Tornado Products Test Standards:

a. Texas Tech benchmark 250 mph tornado and 15 lb. wooden 2-in. x 4-in. missile (Mehta 1976).
b. ASTM E1886 *Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Storm Shutters Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials* (ASTM 2013).
c. ASTM E1996 *Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Windborne Debris in Hurricanes* (ASTM 2014).
d. ASTM E330 *Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, Doors by Uniform Static Air Pressure Difference* (ASTM 2014).
e. FEMA 320 *Taking Shelter from the Storm, Building a Safe Room in Your Home* (FEMA 2014) (NWI contributing authors Ernst Kiesling, Russell Carter, and Larry Tanner).
f. FEMA 361 *Design and Construction Guidance for Community Safe Rooms* (FEMA 2015) (NWI contributing authors Kishor Mehta, Ernst Kiesling, and Larry Tanner).
g. National Storm Shelter Association Standard (NSSA 2001).
h. ICC/NSSA-500 *Standard for the Design and Construction of Storm Shelters* (ICC 2014).

3. Testing Protocol, Specimens, and Results:

The static pressure and impact tests conducted by the NWI DIF were consistent with the guidelines of FEMA 320 (FEMA 2014) and ICC-500 (ICC 2014), and static pressure tests were conducted in accordance to ASTM E330. Design pressure, using a tornado ground speed of 250 mph, was calculated using ASCE 7-10, "Minimum Design Loads for Buildings and Other Structures," considering the door to be located on a corner zone with a wall height of 10-ft. The calculation further included a 1.2 Safety Factor, per ICC-500. The computed test pressure was 1.512 psi held for 10 seconds.

These standards require three debris impacts by a 15 lb. wooded 2-in. x 4-in. propelled at 100 mph. These impacts relate to the standard projectile being propelled horizontally by a 250 mph ground speed tornado. The Pass/Fail Criteria for the impact test was initially included in the earliest printings of FEMA 320/361 (FEMA 2000) and is further described in ICC-500 (ICC 2014), and this criteria is outlined as follows:

a. Doors must have six points of attachment (3 dead bolts and 3 hinges). Passing will allow disengagement of one lock and one hinge.
b. Doors must not be perforated or have a missile protruding through the door backside.
c. Parts or components that become disassociated from the door assembly cannot perforate a 70# Kraft witness screen installed within 5-in. of the back of the door.
- Door deformation cannot exceed 3-in. An opening or separation of the door and frame must not be of such size that would allow passage of the test missile or allow excessive spall that would perforate a 70# Kraft witness screen installed within 5-in. of the back of the door.

Door Series Description:

a. *Series 1*: 26 ga. (gage) metal clad wood framed door with open cell Styrofoam core, mounted in a wooden frame. Hardware included (3) Residential Grade deadbolts, entry lockset, and residential hinges.
b. *Series 2*: 6 Panel 1 ¾-in. solid core wood Hurricane Resistant (Dade Co. 201/203), door mounted in 18 ga. HM (hollow metal) frame. Hardware included (3) Residential Grade deadbolts, entry lockset, and residential hinges.
c. *Series 3*: 18 ga. HM Door with open cell Styrofoam core, door mounted in 18 ga. HM frame. Hardware included (3) Residential Grade deadbolts, entry lockset, and residential hinges.

d. *Series 4*: 16 ga. HM Door with open cell Styrofoam core, door mounted in 18 ga. HM frame. Hardware included (3) Residential Grade 1 deadbolts, entry lockset, and Commercial Heavy Duty (HD) hinges.

e. *Series 5*: 16 ga. HM Door, similar to Series 4, but stronger, with vertically steel stiffened core, door mounted in 18 ga. HM frame. Hardware included (3) Commercial Grade 2 deadbolts, entry lockset, and Commercial HD hinges. Door opening was mitigated with (3) 1 ½-in. x 1 ½-in. x 3/16-in. HSS tube steel hung on ¼-in. x 2-in. hangers bolted through the frame. The tube steel was further pinned with 3/8-in. shear pins. (See *Figures 7* & *8* for Series 5 mitigations.)

f. *Series 6*: 16 ga. HM Door, similar to Series 4, but stronger, with vertically steel stiffened core, door mounted in 18 ga. HM frame. Hardware included (3) Commercial Grade 2 deadbolts, entry lockset, and Commercial HD hinges. Door opening was mitigated with (3) 1 ½-in. x 1 ½-in. x 1/4-in. HSS tube steel hung on ¼-in. x 2-in. hangers bolted through the frame. The tube steel was further pinned with 3/8-in. shear pins with 1/8-in. safety pins.

g. Series 7: 14 ga. HM door with vertical stiffened core, mounted in 18 ga. HM frame with reinforced strike and lock boxes. Hardware included (3) Commercial Grade 1 deadbolts, entry lockset, and Commercial HD hinges.

Figure 7: Series 5 Mitigations

Figure 8: Shear Pins without Safety Pins
1 ½-in. x 1 ½-in. x 3/16-in. HSS

Door Series 1 & 2 are routinely obtainable from Big Box home improvement stores and represent the least expensive of the group tested. Series 3-6 HM doors are only obtainable from commercial door dealers and routinely are stocked items. The Series 7 HM door is a complying (tested) tornado door assembly (door, frame, locks, and hinges) and is normally only available as a special order through a commercial door dealer. This is the most expensive door in the group.

Separate doors were installed in a heavy steel channel test fixture, out-swinging to exhibit negative pressure and in-swing for impact testing. (See *Figure 9*.) Doors were bolted into the fixture with 3/8-in. bolts, seven in each jamb and three in the door head. Each door was pressure tested until the desired pressure was achieved and held 10 seconds or until failure. Pressure testing was accomplished with an air bladder installed between the door and a pressure resistant wall. (See *Figures 10* & *11*.)

Figure 9: Series 1 Out-swing Pressure Door Left and In-swing Impact Door Right.

Figure 10: Bladder Installed for Pressure Test.

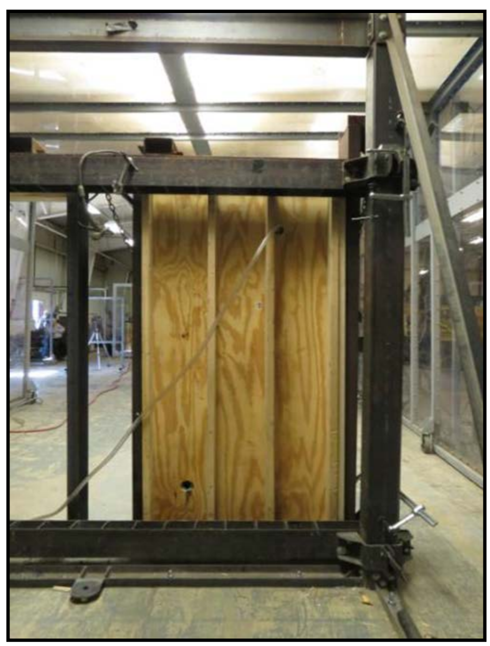

Figure 11: Pressure Resistance Wall

Table 1. DOOR PRODUCTS & TEST RESULTS.

Door Series	Description	Pressure (psi)	Impacts	Results
Series 1	26 ga. metal clad wood frame door with open cell Styrofoam core	1.20 Failed	Door knocked out of frame on first impact.	**Failed**
Series 2	1 ¾-in. 6 panel wood solid core hurricane impact resistant. (Envelope Protocol – Dade Co. TAS (201/203) Door.)	0.90 Failed	Total missile perforation of each (3) impact.	**Failed**
Series 3	18 ga. HM door with open cell Styrofoam core	1.512 Passed	(2) impacts destroyed top 2 locks and folded top corner 12 ½-in.	**Failed**
Series 4	16 ga. HM door with Styrofoam core	1.512 Passed, see Series 4	(2) impacts folded top corner 12 ½-in. and separated door face sheets 40-in.	**Failed**
Series 5	16 ga. HM door with vertical stiffened core, with mitigations	1.512 Passed, see Series 4	Top cross bar was ejected and door top corner folded 4 ¾-in.	**Failed**
Series 6	16 ga. HM door with vertical stiffened core, with mitigations	1.512 Passed	Top cross bar and top lock was ejected by impact.	**Failed**
Series 7	14 ga. HM door with vertical stiffened core with reinforced frame	1.512 Passed	The door faces were deformed by the impacts, but door remained locked.	**Passed**

4. Discussion:

Pressure Failure Modes and Causes:

a. The Series 1 Metal Clad wood frame door and the Series 2 Solid Core Wood door failed to hold the required pressure. The Series 1 door frame cracked vertically along the door edge, along the lock line allowing the residential deadbolts to bend past the frame strikes. The hinge jamb was split which released the entire door and half of the jamb frame. (See *Figures 12* & *13*.)

b. The Series 2 door failure was the result of excessive bending of the bottom two residential deadbolts which were withdrawn from the strike boxes in the HM frame. (See *Figures 14-17*.) The Series 3-7 doors each held the required pressure for 10 seconds, per ASTM E330.

Figure 12: Series 3 Pressure Failure.

Figure 13: Series 3 Hinge Jamb Split.

Figure 14: Series 2 Pressure Failure.

Figure 15: Upper Deadbolt Failure.

Figure 16: Lower Deadbolt Failure.

Figure 17: Deformed Deadbolt Strike.

Impact Failure Modes and Possible Causes:

a. Impact 1 on the Series 1 Metal Clad door produced a catastrophic failure by knocking the door from its hinges and lock strikes and twisting it 180 degrees, as seen from photographs taken from high speed video in *Figures 18* & *19*. *Figure 20* shows the door condition produced by the impact.

Figure 18: Series 1 impacted.

Figure 19: Series 1 door twisted 180 degrees by impact.

Figure 20: Series 1 door knocked from frame and twisted by first impact.

b. All three impacts on the Series 2 Wood Solid Core Hurricane Impact Resistant Door passed through the door face, see *Figures 21 & 22*.

Figure 21: Perforation at center hinge.

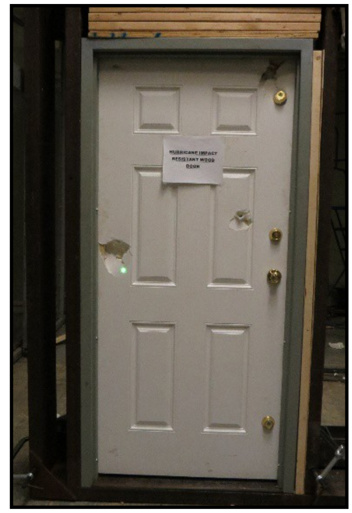

Figure 22: Door perforated by 3 impacts.

c. The failure of the Series 3 18 ga. HM door was similar to the Mayflower shelter door. The Mayflower door had a cardboard honeycomb core, which is somewhat stiffer than the Series 3 open cell Styrofoam core. However, the Series 3 door was fitted with Residential Grade 1 hardware, which should have been superior to the Mayflower residential hardware. The mode of failure of the Series 3 door was similar to that of the Mayflower door, but the prescribed standard sequence of impacts (1-near top lock, 2-near center lock, and 3-near center hinge) initially bent the top lock corner over, separating it from the frame 48-in. and extracting the top deadbolt, see *Figures 23-25*.

Figure 23: Series 3 Impact 1.

Figure 24: Door folded over 48-in.

Figure 25: Deadbolt extracted.

a. Since two deadbolts remained engaged, the door was impacted a second time near the center deadbolt. This impact removed the deadbolt from the strike and bellied the door in the middle, similar to the Mayflower door impact, and then delaminated the face sheet from the edge channel, see *Figures 26-28*.

Figure 26: Series 3 Impact 2.
from frame.

Figure 27: Deadbolt withdrawn

Figure 28: Series 3 door bellied and delaminated.

b. Series 4 door was constructed the same as the Series 3 door, but was faced with 16 ga. face sheets, and the Residential Grade 1 hardware was also the same. Modes of failure were basically the same as the Series 3 assembly, but extents of deflection and deformation were less due to the increased door stiffness produced by the stronger face sheet. Impact 1 near the top lock produced bending of 12-in. and withdrew the deadbolt, see *Figures 29* & *30*. Impact 2 produced delamination of the impacted face sheet and withdrew the middle and bottom deadbolts, see *Figures 31* &*32*.

Figure 29: Series 4 Impact 1.

Figure 30: 12-in. door corner deflection.

Figure 31: Bottom two deadbolts withdrawn.

Figure 32: Delamination of face sheet.

c. The Series 5, 16 ga. HM door was vertically steel stiffened, locked with Commercial Grade 2 deadbolts, and had mitigations installed to control door deflections and lock failures. The mitigation included (3) 1 ½- in. x 1 ½-in. x 3/16-in. HSS tube steel hung on ¼-in. x 2-in. hangers bolted through the frame. The tube steel was further pinned with 3/8-in. shear pins. Safety pins were available for insertion into the shear pins, but left off, with the assumption that a panicked occupant might forget to install the pins. (See *Figures 33* & *34*.) The first impact near the top lock withdrew the shear pin and the crossbar, see *Figure 34*. A safety pin was installed in the shear pin on the center cross bar for the second impact. The safety-pinned center cross bar held the second impact. (See *Figures 35-37*.)

Figure 33: Series 5 crossbar mitigations.

Figure 34: Shear pin without safety pin.

Figure 35: Cross bar removed by Impact 1

Figure 36: Impacts 1 & 2 on Series 5

Figure 37: Impact 2 on Crossbar w/ shear & safety pin

d. The Series 6 was the same type of 16 ga. HM door and was a vertically steel stiffened door and locking hardware as Series 5. Mitigations were installed to control door deflections and lock failures. The mitigation included (3) thicker HSS (1 ½-in. x 1 ½-in. x 1/4-in.) tube steel hung on ¼-in. x 2-in. hangers bolted through the frame. The tube steel was further pinned with 3/8-in. shear pins which were restrained from withdrawal with safety pins. These mitigations represented the stronger of the two mitigation installations. Impact 1 sheared the safety pin and allowed the shear pin to withdraw and the crossbar to fall. Impact 2 produced the same behavior. (See *Figures 38-43*.)

Figure 38: Series 6 mitigations.

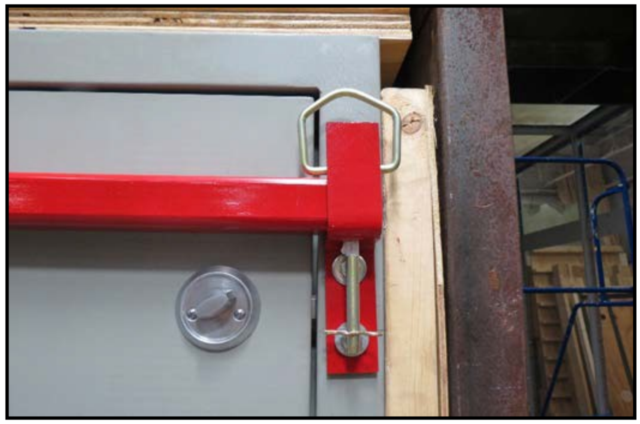

Figure 39: Safety pins installed on all shear pins.

Figure 40: Impacts 1 & 2 on Series 6.

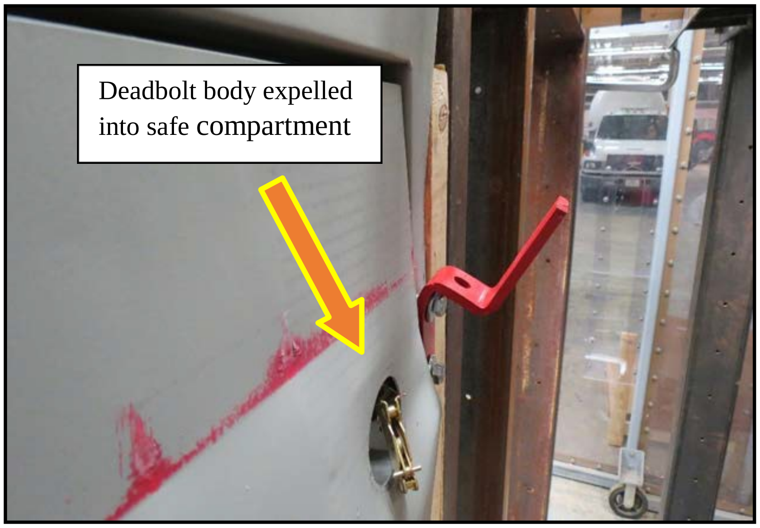

Figure 41: Series 6 top crossbar knocked loose by Impact 1.

Figure 42: Frame crushed by hanger plate

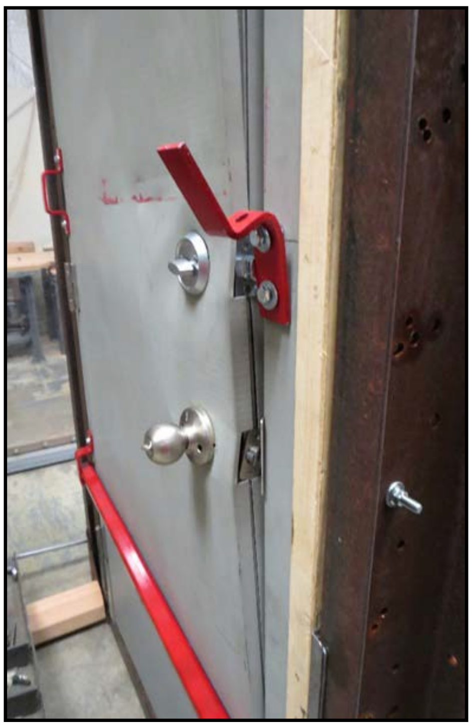

Figure 43: Center crossbar knocked loose by Impact 2.

e. The Series 7 door was 14 ga. HM, vertically steel stiffened, and was hung in an 18 ga. HM frame with reinforced strike and lock boxes. All hardware was Commercial Grade 1. Though not affecting the test results, the deadbolt hardware was installed with the thumb turns on the impact face and the keyway side on the shelter side of the door. Three protocol impacts were conducted on the door (*Figure 44*). Damage from the first two impacts included imprinting a vertical internal stiffener on the back face sheet (*Figure 45*), and bending of the center deadbolt, which remained engaged (*Figure 46*). The third impact directed near the hinge tore the face sheet at a vertical stiffener (*Figure 47*). The most notable damage was separation of the back face sheet along the hinge side (*Figures 48* & *49*).

Figure 44: Series 7 door after three impacts.

Figure 45: Backside damage after Impact 1.

Figure 46: Vertical stiffener imprint after 2 Impacts.

Figure 47: Sheet tear by Impact 3.

Figure 48: Sheet separation produced by Impact 3.

Figure 49: Delamination of back face sheet.

Mitigation and Retrofitting Options:

a. There were numerous options considered for the mitigation and retrofitting of non-tested safe room door installations. The crossbar option was considered to be an easy and inexpensive installation with through bolting of the hangers and utilization of tube steel crossbars with the crossbars located at the most critical points across the door exposure, and ¼-in. steel selected for the hangers, bar loops, and bolt cover plates. Though cold bending of steel maintains the integrity of the steel properties, the hangers tested were heat bent in the laboratory. Two thicknesses of 1 ½-in. x 1 ½-in. tube steel was tested with the 3/16-in. thickness being the most desirable for its weight and ease of installation and used for the Series 5 test. The stronger and heavier ¼-in. thick tube steel was reserved and tested for Series 6. Displacement of the crossbar from the loop and hanger was a major concern, and thus 3/8-in. shear pins were utilized for both series of tests. Safety pins to lock the shear pins in place were considered to be a nuisance to shelter occupant and likely to be overlooked by an occupant in a state of panic. After the failure of the top crossbar on Series 5 without the shear pin/safety pin, safety pins were installed and impacts were successful without further loss of crossbars. All shear pins were secured by safety pins for the Series 6 tests. However, the first and the second impacts sheared the safety pins and displaced the crossbars. It is considered that the improved performance of the lighter HSS crossbar in Series 5 with the safety pin is due to the ability of this bar to bend more freely than the ¼-in. HSS crossbar, thereby absorbing more energy.

Recommendation for Manufacturers, Consumers, and Building Officials:

a. It would be extremely informative to building officials, retailers, and consumers if manufacturers of exterior doors and hardware products labeled and catalogued their non-tornado products as “Not for Use in Tornado Shelters.” Furthermore, products intended for hurricane protection (i.e., those meeting ASTM E1886/E1996 and/or Miami/Dade Co. TAS 201/203 (FBC 2010) standards) should be similarly labeled and catalogued.
b. Consumers, builders and homeowners should understand that the door assembly in their Tornado Shelter is potentially the weakest portion of the shelter, and that compromising on the door and hardware selection will likely compromise the safety of the shelter occupants. Furthermore, an out-swing door is significantly more resistant to debris impacts than the in- swinging door.
c. Building officials should understand that tornado-tested assemblies are inclusive of door, frame, hardware, and the equivalence of the tested anchoring system. The NWI DIF and other major testing laboratories maintain a list of tested door assemblies, and FEMA has tasked the NWI DIF to maintain a list of all tested assemblies by all laboratories. This work is currently in progress.

5. Conclusion and Future Work:

The list of available exterior doors and hardware are too numerous to test, and many were out of the scope of this project. The Mayflower shelter door analysis team produced a list of door assemblies (Series 1-7) that represented a reasonable sampling of assemblies that might be currently installed in above-ground storm shelters. Series 1 & 2 assemblies were low cost and available at home improvement stores, but they both failed to hold the design pressure and missile impacts. The Series 3-18 ga. and Series 4-16 ga. doors are intended for commercial installations and are normally only available from commercial door and hardware suppliers, and both the Series 3 & 4 assemblies held the required pressure, but failed under missile impacts. Even mitigated versions of the Series 4 assembly, Series 5 & 6, failed to pass the impact criteria of the FEMA 320/361 & ICC-500 guidelines and standards. Only Series 7, the specifically manufactured tornado assembly, prevailed against the stringent criteria of the guidelines and standards.

One desired outcome of this research was to determine an acceptable and affordable method of mitigating current non-complying door assemblies that are installed in shelters. This research indicates that even stock commercial HM doors (16-18 ga.) with commercial hardware (Commercial Grade 1 or 2), and stock 18-ga. HM frames, properly installed, cannot be safely and practically mitigated by using crossbars, the only mitigation technique attempted.

Future work should address further types of mitigations of door assemblies for above-ground shelters to help control the price in new shelters and improve performance of doors already installed. These mitigated designs would require laboratory testing, just like current tornado door assemblies, and it is most likely that the customer would probably sacrifice attractiveness and ease of locking for price.

6. Acknowledgement:

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