P162 Damage survey of the Mayflower-Vilonia Arkansas tornado: 27 April 2014

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1. INTRODUCTION

During the evening of 27 April 2014, an EF4 tornado struck the communities of Mayflower and Vilonia, Arkansas. The tornado traveled 66 km, passing just northwest of the Little Rock Metropolitan area, and had a maximum path width of about 1200 m (Fig. 1). During its 56 minute lifespan, the tornado killed 16 people, including one person who sought refuge in an above ground storm shelter. The fatality occurred when a hard object struck the storm shelter door causing it to deform excessively into the shelter.

Aerial and ground damage surveys were performed following the event to determine the path length, width, and intensity of the tornado. The EF (Enhanced Fujita) scale was utilized as a way to rate the severity of the damage. This scale lists increasing DoDs (degrees of damage) to 28 DIs (damage indicators). Damage indicators involve various building types as well as electrical transmission towers and trees. The EF-scale was developed initially by the Wind Science and Engineering Research Center (2006) at Texas Tech University and adopted by the National Weather Service in 2007.

Much of the tornado track traversed rural areas where there were few structures. This made it difficult to assign EF-ratings due to the relatively small number of DIs. There also were a number of destroyed structures and objects that were not listed as DIs. In this paper, difficulties will be discussed in rating tornado damage due to the lack of DIs and poor quality construction.

In addition, the performance of storm shelters will be discussed. Many shelters had been installed after an EF2 tornado occurred three years earlier. That tornado followed the same general track as the more recent tornado. Many residents installed their own storm shelters and fitted them with steel doors which did not meet the ICC-500 (International Code Council, 2008) criteria. A detailed study of the failed shelter door will be presented near the end of this paper.

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2. DAMAGE SURVEY

The tornado developed in a sparsely populated, wooded area near Brush Mountain within the Ouachita Range around 0006 UTC on 28 April 2014. Brush Mountain rises about 60 m above the adjacent Little Maumelle River. The point of touchdown was about 35 km west of downtown Little Rock, but only 15 km west of the urban area. Trees (mainly pine, oak, and hickory) toppled in converging lines that pointed northeast. The first residential damage occurred on Turkey Trail where a portion of the roof was removed including the southeast (windward) wall (Fig. 2). The house was elevated on a basement/crawlspace covered with a wooden floor platform. Wall failure occurred where the bottom wall plate was straight nailed into the floor. As soon as the roof was removed, the wall simply fell over pulling the straight-nailed connections from the floor. Damage to the house was rated EF2.

The tornado destroyed three homes along Deer Drive including one home that was swept clean from its concrete slab foundation. Steel anchor bolts were meant to fasten the wall bottom plates to the slab, however, the bolts did not have nuts or washers (Fig. 3). Since the home was not anchored, it was rated EF3 instead of EF5. Also, vehicles adjacent to the home did not move but did sustain window and body damage from wind-borne debris.

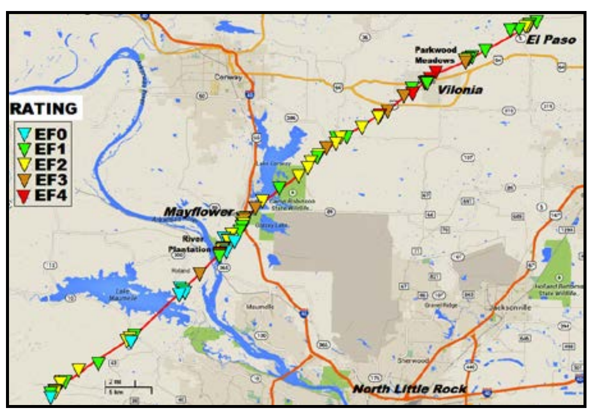

Figure 1. The tornado path with EF scale locations. Courtesy of the Little Rock National Weather Service.

Figure 2. One of the first houses damaged by the tornado lost a portion of its roof and perimeter walls. This home was rated EF2.

Figure 3. This house was swept clean from its concrete slab foundation as: a) anchor bolts did not have nuts or washers. Because of this deficiency, the unanchored home was rated EF3 instead of EF5.

Figure 4. One of several collapsed steel transmission towers that was rated EF-2.

After crossing Kanis Road, the tornado downed several electrical transmission lines that cut through the forest. The lines were supported by open-trussed, steel towers (Fig. 4). The towers collapsed, but bases remained connected to their support piers. These towers were rated as EF-2 damage.

The tornado continued northeast, flattening the forest reaching its maximum width of 1200 m (Fig. 5). Trees were uprooted and laid down in a pair of converging arcs with the centerline pointing northeast. By the time the tornado reached Highway 10, the damage path had narrowed. A few homes in this area lost roofs on Somersett Court and Goodson Road and were rated EF2.

The tornado continued through unpopulated forested areas traversing between the Maumelle Pinnacles, a pair of geologic outcrops that rise 200 m above the surrounding terrain. The intensity of the tornado remained unchanged as it passed between these topographic features.

The tornado then crossed Lake Maumelle, a man-made lake that serves as the primary drinking water supply for Little Rock. The tornado remained relatively weak, causing only EF0 to EF1 damage to trees on the north shore of the lake. After crossing Highway 300, the tornado traveled through bottom land east of the community of Roland. Eyewitnesses reported the tornado grew to a wedge-shape as it crossed the Arkansas River (Fig. 6). The tornado was visible at this stage although hills and trees obstructed visibility.

Figure 5. Flattened forest with most trees being uprooted and laid down in a converging arc pattern.

Figure 6. Large tornado as it approached the Arkansas River. Image from KATV video.

2.1 *Mayflower, Arkansas damage*

The tornado traveled through the River Plantation subdivision on the north shore of the Arkansas River destroying several homes (Fig. 7). This community was comprised of upscale, one- and two-story, wood-framed homes on large lots. Houses were constructed on concrete slab foundations or split-level, concrete (basement) wall foundations. These newer and larger homes had basic foundation attachment issues which prevented a rating of EF5 damage. Many homes had wall bottom plates attached with cut nails around the slab perimeters instead of anchor bolts. The plates either pulled through the nails leaving the nails in the slabs or were removed along with the plates. Some homes did have wall bottom plates properly bolted to the slabs (with nuts and washers), but failed where studs were nailed to the plates.

Figure 7. Homes sustained up to EF4 damage in the River Plantation subdivision.

Google Street View was an important tool in determining what houses looked like before the tornado, especially for homes that had EF3 or greater damage. Items like the number of stories, type of roof, locations of large windows, and size/orientation of the garage were quickly determined using Google Street Views (Figs. 8 through 10).

Figure 8. A one-story home: a) before and b) after the tornado. The home was rated EF3 damage. The top image is from Google Street View.

Figure 9. A two-story home: a) before and b) after the tornado. The home collapsed when basement walls supporting the first floor toppled. This home was rated as EF3 damage. The top image is from Google Street View.

Figure. 10. A two-story home: a) before and b) after the tornado. All walls collapsed leaving a pile of debris in the front yard. Damage to this home was rated EF4. The top image is from Google Street View.

Many homes in the River Plantation subdivision had attached garages. Garage doors failed allowing internal wind pressure to lift the roof and/or blow out the sidewalls. Marshall and McDonald (1982) recognized the detrimental effects of attached garages to homes. When the garage door fails, internal wind pressure usually results in the failure of a sidewall or portion of the roof. In the River Plantation subdivision, radial inflow on opposite sides of the tornado caused the same types of garage failures (Fig. 11). Thus, houses with attached garage doors facing the wind had greater DoDs than houses with garage doors leeward to the wind. Garage walls failed in three ways: 1) when the wall bottom plate split, 2) when the wall studs pulled out of the wall bottom plate, or 3) when the wall studs pulled out of the wall top plate.

Figure 11. Identical garage failures on the: a) east side and b) west side of the tornado path.

Just as the tornado was leaving the River Plantation subdivision, it toppled seven concrete highway barriers near the approach to a bridge (Fig. 12). The barriers are not listed as a DI, however, they afforded an opportunity to approximate the wind forces necessary to overturn them. Barriers were free-standing, not connected to each other. Each concrete barrier weighed about 1800 kg, was 81 cm tall, and 3 m long. The center of gravity was approximately 37 cm above the ground (Fig. 13). From this information, the resisting moment was calculated, then equated to the moment created by the applied wind pressure, solved for wind pressure, then computed the failure wind speed. The wind speed necessary to overturn the concrete highway barriers was determined to be approximately 83 m/s (185 mph). However, it was assumed that the wind load was static (which it was not) and that pressure coefficients were known, (which they were not). Pressure coefficients were derived using standard values from buildings (not a barrier) in a wind tunnel (not a tornado). These coefficients were +0.8 front, -0.7 top, and -0.5 back. Also, the computed wind speed was for an instantaneous load (not averaged over three-seconds) and centered on a beam much lower than the 10 m height used for the EF-scale. That said, the highway barriers were adjacent to homes that experienced EF3 and EF4 damage. So, the calculated wind speeds were at least consistent with those estimated for nearby homes.

Figure 12. Toppled concrete highway barriers in the River Plantation subdivision.

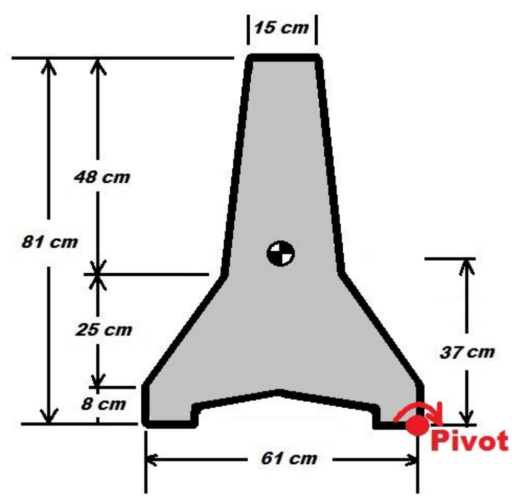

Figure 13. Cross section of a standard concrete highway barrier. Seven of these were toppled in the River Plantation subdivision.

Several homes in the River Planation subdivision had above ground tornado shelters. The shelters were constructed with steel-reinforced CMU blocks and had hollow core steel doors. The shelters survived. However, the steel doors did not meet ICC-500 standards. One steel door failed resulting in a fatality. Analysis of this door will be discussed later.

The tornado continued through south portions of the town of Mayflower, destroying several homes and collapsing a metal building (Fig. 14). Total destruction of a metal building system (MBS) yielded an EF3 rating (DoD 10). Many truck trailers in an adjacent parking lot were flipped or moved. One truck trailer ended up on top of the metal building. Nearby homes sustained EF3 damage.

Figure 14. Complete collapse of a metal building with moved truck trailers. Damage to this building was rated EF3.

The tornado crossed Interstate 40, tossing a number of vehicles. According to eyewitnesses, the tornado was rain wrapped at this time and difficult to see until it was quite close. The tornado struck an RV business on the east side of the Interstate, tossing many RVs. Three RVs were wrapped around a toppled billboard (Fig. 15).

Figure 15. Three recreational vehicles wrapped around a toppled billboard adjacent to Interstate 40.

The RV dealership was located just north of the tornado center and experienced strong east through north winds. The rectangular-shaped building was constructed with loadbearing CMU block walls with steel roof joists. Portions of the south and west walls fell outward (Fig. 16) and the roof was removed. Close examination revealed that foundation rebar was 1.3 cm (#4) in diameter and spaced 1.2 m apart. Foundation rebar extended only 30 cm into the base of the CMU wall. Normally, rebar should extend much further into the walls. Regardless, the walls were weak against lateral loads and the foundation rebar bent easily as the walls fell. The closest building type was that of a large isolated retail building (LIRB). A DoD of 6 was selected. So, this building damage was rated as EF3 damage.

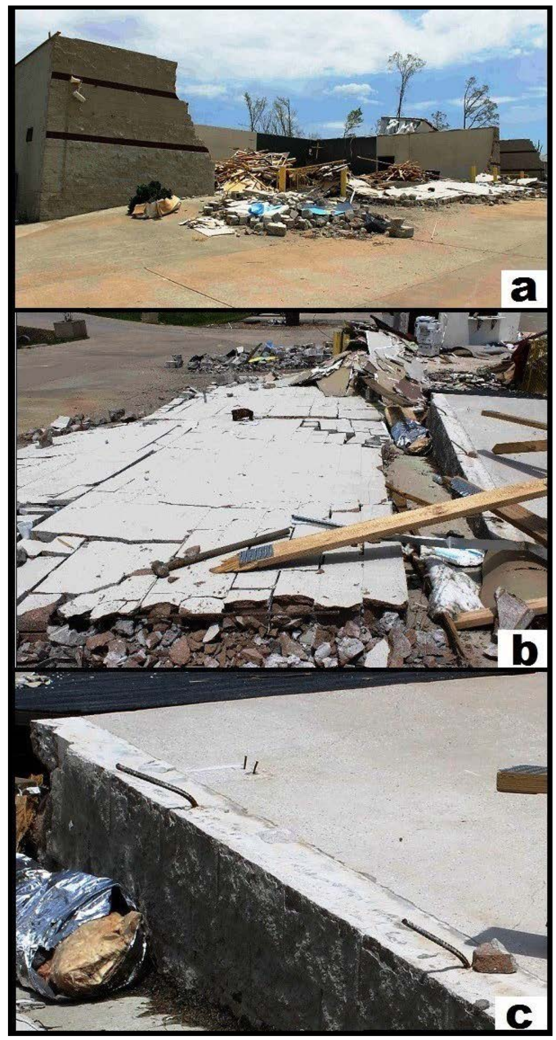

Figure 16. CMU walls fell over at this RV dealership: a) front (west) elevation view, b) front wall fell outward, and c) close-up of foundation rebar. The building was assigned an EF3 rating.

The tornado crossed Lake Conway, located just east of Mayflower, and destroyed several lakefront homes (Fig. 17). These homes had concrete slab or perimeter concrete masonry foundations and were smaller in area than River Plantation homes. However, each home had the same foundation attachment deficiencies. Thus, the maximum damage rating in this area was EF3. Some debris from the destroyed homes ended up in the lake. Reportedly, the Arkansas Game and Fish Commission removed 569,000 kg of tornado debris from the lake.

There were several single- and double-wide mobile homes that were destroyed by the tornado, and were assigned a maximum EF2 damage rating. Several cars were rolled and flipped by wind forces as well as battered by wind-borne debris (Fig. 18). Vehicles are not listed as a DI due, in part, to variations in size, weight, and orientation to the wind. Marshall et al. (2008a, 2008b, 2012a) found substantial variability in vehicle performance after several violent tornadoes.

Figure 17. Destroyed homes on the shores of Lake Conway, just east of Mayflower.

Figure 18. Vehicle tossed by wind forces and battered by wind-borne debris near Lake Conway.

2.2 *Vilonia, Arkansas damage*

The next community impacted by the tornado was Vilonia. The tornado struck the Intermediate School that was under construction and nearing completion. The school complex consisted of three, steel-framed structures with masonry veneer exterior walls and metal panel roofs (Fig 19). Masonry walls fell inward on windward sides, and outward on leeward sides, exposing the classrooms to wind-borne debris (Fig. 20). Steel purlins and girts buckled. However, most of the large steel frame remained intact except for the west building which had successive frames collapse. Metal roof panels were removed when they became unclipped from steel purlins. Center hallways would have been the only places of relative safety for occupants had school been in session (Fig 21). Overall, damage to the elementary school (ES) building was rated EF3 (DoD 8).

Figure 19. Aerial view of the Vilonia Intermediate School.

Figure 20. Masonry walls fell into the classrooms on the windward side of the Vilonia Intermediate School. Obviously, these classrooms would not have been places of safe refuge during the tornado.

Figure 21. The only relatively safe place for occupants in the Vilonia Intermediate School were the center hallways.

The tornado destroyed several businesses as it crossed Main Street in Vilonia, including a large, isolated retail building (LIRB) on the west side of the tornado track. This building was a steel-framed structure with perimeter CMU walls built on a CMU stem wall foundation capped with a concrete slab. As the tornado passed, north and south walls fell to the south while east and west walls fell to the east (Fig. 22). Foundation rebar pulled out of the grouted cells and the walls failed along horizontal joints aligned with the top of the slab. Since these walls had little resistance to lateral wind forces, damage to the building was rated as EF3 (DoD 10 lower bound).

Figure 22. Collapse of a large, isolated retail building: a) wall failure at the top of the slab, and b) foundation rebar pulled out of the CMU foundation. Damage to the building was rated as EF3.

Just east of the large, isolated retail building was a strip shopping center. The strip shopping center had poured-in-place, 20 cm thick concrete walls (instead of typical light-steel framing) and open steel web roof joists. The building was oriented east-west, facing Main Street. The center of the tornado passed directly over this location. South walls of the strip shopping center fell inward, while north walls fell outward, leaving interior shear walls intact (Fig. 23). Close examination revealed that wall rebar was 1.3 cm (#4) diameter and spaced 1 m apart. Although the walls were poured concrete, there was minimal reinforcement, and the walls crumbled. Therefore, damage to the strip mall (SM) was rated EF3 (DoD 8).

Figure 23. Collapse of the Vilonia Shopping Center constructed with 20 cm thick, poured-in-place, concrete walls. Damage to this building was rated as EF3.

A large, steel tank was deposited in the alley behind the shopping center (Fig. 24). The tank was 10 m tall and 5 m in diameter. According to the owner, the tank was empty at the time of the tornado, and was one of five liquid fertilizer tanks lying on the ground. The tank reportedly weighed 13,607 kg and traveled 1192 m, before coming to rest along the tornado centerline.

Figure 24. A large steel tank that traveled 1192 m and was found behind the strip shopping center.

On the east side of the tornado track, at the southeast corner of Church and Main streets, was the Vilonia United Methodist Church. There were three buildings at this location: the main church, parsonage, and Life Center. The main church and parsonage were one-story, wood-framed structures constructed on concrete foundations. They sustained only minor roof damage, and were rated EF0. However, the Life Center was a two-story, metal building constructed on a concrete slab foundation. The east end wall was pushed inward resulting in the collapse of successive bays (Fig. 25). Failure occurred where steel columns were torn from their welded base plates. The steel plates remained bolted to the concrete slab. Damage to this metal building was rated as EF3 (DoD 7). Internal pressure build-up was vented when the west wall panels blew outward.

Figure 25. Collapse of this metal church building: a) south wall was pushed inward, and b) torn welds at the base plate. Damage to this building was rated as EF3. However, the adjacent one-story, wood-framed building sustained only EF1 damage.

There was a parking lot north of the main church building where several concrete parking stops slid sideways in the tornadic winds (Fig. 26). Parking stops measured 1.9 m long and weighed 111 kg. Each parking stop was 12.6 cm tall and 23.9 cm wide (Fig. 27). There were two vertically-oriented holes in the parking stops for anchoring with rebar. However, no rebar was installed. Thus, the parking stops were lying loose on the pavement surface. Marshall et al. (2012b, 2014) had observed lofting and lateral movement of parking stops in the Joplin and El Reno tornadoes, respectively.

Figure 26. Lateral movement of several unanchored concrete parking stops in front of the Vilonia United Methodist Church. Damage to the main church building was rated EF0.

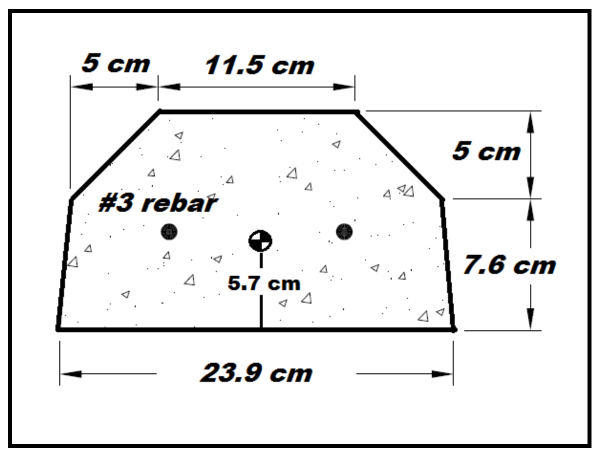

Figure 27. Dimensions of the concrete parking stops in the lot north of the church.

The wind speed necessary to slide the parking stops depended on the coefficient of friction (COF). Also, there would also be an uplift component from wind traveling over the top of the parking stop. Assuming wet pavement, the COF is about 0.5. Using the same assumptions as the highway dividers mentioned earlier in this paper, including the same pressure coefficients, the wind speed necessary to slide the concrete parking stops was calculated to be

36 m/s (80 mph). This was reasonable given the EF0 rating to the main church building.

There were at least two residential subdivisions north of Main Street in Vilonia. Dozens of wood-framed homes were swept clean from their concrete slab foundations in the Parkwood Meadows subdivision (Fig. 28). At first glance, it appeared these homes were candidates for EF5 damage ratings. But closer examination revealed poor quality construction of these houses. Cut nails were found around the perimeters of the concrete slabs indicating where wall bottom plates had been attached. These connections had little lateral or rotational strength. When wall failure occurred, cut nails either were pulled out of the slabs or wall bottom plates (Fig. 29). Because of this deficiency, damage to these homes were rated EF4 instead of EF5. It should be noted that the damage is a lower bound rating, and doesn't preclude the possibility that EF5 winds could have occurred.

Figure 28. Aerial view of the Parkwood Meadows subdivision in Vilonia where dozens of homes were swept clean from their concrete slab foundations. This appeared to be EF5 damage. However, closer inspection from our ground survey found poor attachment of the houses to their foundations.

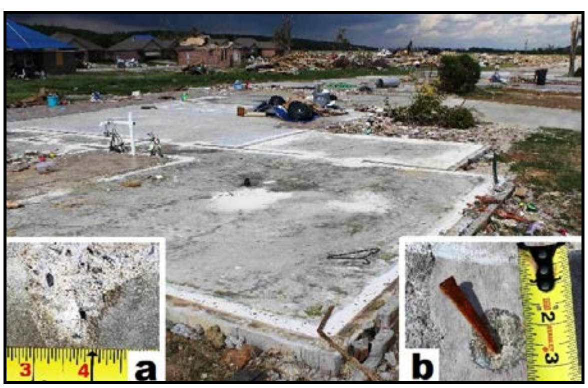

Figure 29. Two modes of failure where cut nails were used to secure the wall bottom plates: a) a nail pulled out of the slab, and b) a wall plate pulled away from the nail leaving the nail bent in the slab.

Standard building codes require that wall bottom plates be secured with anchor bolts fitted with nuts and washers. This would have provided stronger connections than cut nails.

After Vilonia, the tornado traveled another 10 km through the rural countryside and weakened before lifting just after it crossed Highway 5 north of the small community of El Paso.

3. STORM SHELTERS

There were dozens of above and below ground storm shelters in the path of this tornado. Several residents were interviewed who indicated the shelters had been installed after an EF2 tornado three years prior to this event. While storm shelters performed well, and many lives were saved, several deficiencies were found which included poor quality doors, locks, hinges, and frames.

One person was killed in an above ground shelter on Plantation Drive. A couple had sought refuge in the shelter just prior to the tornado. The shelter was constructed with steel-reinforced CMU walls and had a poured concrete slab roof. The entry door had three deadbolts and a steel skin, but had a hollow core. A piece of debris hit the middle of the door during the tornado causing a crease in the door (Fig. 30). The house was completely destroyed.

According to the lone survivor, the deadbolt at the bottom of the door remained intact while the top and middle bolts pulled out of the frame. The door never opened completely. Bending deflection of the door was sufficient to throw an occupant against the back wall in the shelter and she died of a head injury. The male occupant received broken bones and head lacerations, apparently from wind-borne debris. Both occupants were in contact with the door when the door failed.

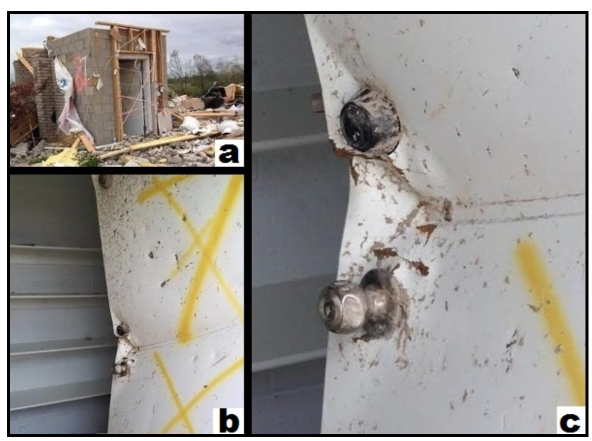

Figure 30. Failure of a shelter door which resulted in a fatality. The door was struck by wind-borne debris.

With the assistance of the National Storm Shelter Association (NSSA), the failed door and frame assembly were shipped to the National Wind Institute Debris Impact Facility at Texas Tech University and examined by a panel of experts (Fig. 31). The door was cut into three sections to examine the interior. No internal steel stiffeners were found, only a cardboard honeycomb core. Such a core did not strengthen the door. In conclusion, Tanner and Kiesling (2014) found that door failure resulted from improper usage of a door, frame, and hardware for a tornado safe room. They indicated that the steel door used in the shelter was not strong enough to be used as a shelter door.

In order for a door to be approved as a shelter door, it must meet or exceed the design and testing criteria established in the ICC-500 standard. Approved shelter doors typically are constructed with 14 gauge steel skin (1.9 mm). By comparison, the skin on the failed Arkansas shelter door was 18 gauge steel (1.2 mm), a thinner material. Approved shelter doors have hinges that typically are 7 gauge (4.76 mm). By comparison, the hinges on the failed Arkansas shelter door were 11 gauge (3.18 mm).

Part of the ICC-500 standard involves resistance to missile impacts, including door systems. Doors must be able to resist three impacts of 244 cm long 2x4 (nominal) traveling at 45 m/s. Impacts shall be within 15.2 cm of the primary lock, upper latch, and hinge. Doors shall not be perforated, opened, dislodged from the frame/hinges, or deformed more than 76.2 mm. These are stout requirements and not every steel door will pass.

Three additional above ground shelters were examined along Rocky Point Road in Vilonia. The shelters were constructed with steel-reinforced CMU walls and had poured concrete slab roofs. Steel doors had hollow cores. Two of the three doors had deadbolt locks while the third shelter door had three small, sliding barrel bolt locks attached to the inside of the door frame (Fig. 32). However, none of the three shelter doors had been struck by wind-borne debris, and the doors remained intact. A total of 22 people survived in the three shelters along Rocky Point Road.

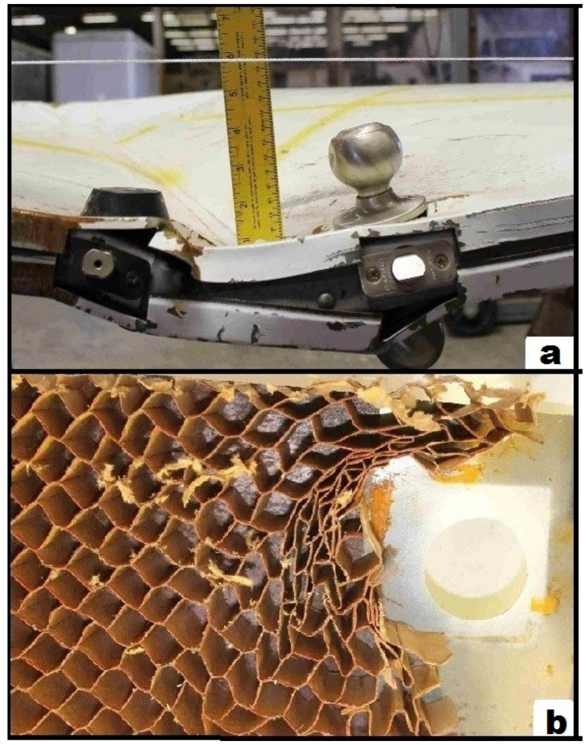

Figure 31. Examination of substandard door that failed resulting in a fatality: a) excessive door deformation (15.2 cm), and b) cardboard honeycomb core.

Figure 32. Shelter where six occupants survived the tornado. The substandard door had sliding barrel bolt locks (inset). Fortunately, this door was not struck by wind-borne debris.

4. SUMMARY

A violent tornado traveled 66 km through portions of Mayflower and Vilonia, Arkansas on 27 April 2014. Ground and aerial surveys were conducted to determine EF-scale ratings. Most of the damage track was through rural areas where there were few DIs, and most DIs consisted of poorly built homes. Cut nails were used primarily to secure wall bottom plates with homes on slab foundations. A few homes did have anchor bolts, but did not have nuts and washers to secure the wall bottom plates. Thus, the maximum rating assigned to this tornado was EF4. Although there were many trees damaged by the tornado, the maximum rating for tree damage is EF3. Overall, less than ten percent of the damage track contained buildings.

In order for a damaged house to be rated EF5, the house has to be "well-built" and swept clean from its slab foundation. The term "well-built" means different things to different people. In this instance, none of the homes examined in our survey were "well built". The EF5 description also implies that homes built on pier and beam foundations can't be rated EF5.

The only other DI that could have achieved an EF5 rating would have been the upper bound of the large, isolated retail buildings that were demolished. There were two such buildings found in our survey. However, both buildings had structural deficiencies regarding poor or insufficient rebar placement that prevented them from being rated EF5.

There also were several non-standard DIs that indicated this was a violent tornado. Some vehicles were tossed and crushed. Concrete highway dividers were toppled. A large steel tank traveled almost 1200 m. Sliding concrete parking stops indicated strong winds near the ground surface. However, building damage near these items was less than EF5.

Several above ground storm shelters were in the path of this tornado. All but one shelter performed well, even with substandard steel door assemblies. One door failed when struck by wind-borne debris, killing one of the occupants and injuring the other. Detailed analysis of this door revealed it would not have met the design criteria, specified by ICC-500 for use as a shelter door.

5. ACKNOWLEDGEMENTS

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