TORNADO OUTBREAK of 2011

IN ALABAMA, GEORGIA, MISSISSIPPI, TENNESSEE, AND MISSOURI

10

Conclusions of the 2011 Tornado MAT

The conclusions in this report are based on the MAT's damage observations and assessments, an evaluation of relevant codes and regulations, and meetings with Federal, State, and local officials and other interested parties.

Discussions with subject matter experts, State emergency management agencies from the five affected States, the Alabama Safer Schools Initiative, and local government representatives in the areas hit by the tornadoes were essential in verifying data observed in the field to prepare these conclusions. The conclusions of this report, upon which the recommendations in Chapter 11 are based, are intended to assist States, communities, businesses, and individuals who are recovering and rebuilding from the tornadoes by providing insight into protection of life and property.

10.1 Codes and Standards

This section summarizes the MAT's conclusions related to the effectiveness of model building codes and standards based on performance assessments of residential buildings, commercial and industrial buildings, critical facilities, infrastructure, and safe rooms and storm shelters damaged during the spring 2011 tornado outbreak.

The adoption and enforcement of a building code results in safer buildings and improved chances of survival should a tornado strike in the future. It is important to note that building code adoption will not prevent damage to buildings when strong tornadoes strike unless that building had extremely high wind design concepts applied. However, adopting and enforcing building codes and standards demonstrates the community's commitment to improving the quality of design and construction of structures and its belief that citizens' investment in their homes and businesses is important to protect.

10.1.1 Residential Buildings

Conclusion #1 – Failure to adopt a current version of code or having no uniform code leaves residential buildings vulnerable to wind damage: Much of the residential damage occurred in municipalities that had either no adopted building code (Hackleburg, AL) or outdated codes (Harvest, AL [2003 IRC] and Phil Campbell, AL [1998 SBC]) at the time of the tornado strikes. **At the time of publication of this report, current codes are the 2012 or 2009 IRC.** As of the publication of this report, Alabama and Missouri do not require individual communities to adopt a uniform residential building code. Three of the 17 Alabama communities the MAT visited had no residential building code whatsoever, and five others reported local adoption of residential building codes that predated the 2009 IRC. Adopting and enforcing any model building code is better than none, but as a rule, the more recent the code, the better. Since its introduction in 2000, the IRC has continuously improved its load path provisions, as demonstrated by the expanded wall bracing section in 2006, and has continued to evolve in subsequent editions.

While adopting the most recent version of the IRC does not affect existing building stock (unless building additions are considered), it does establish a benchmark for new construction. Furthermore, adopting model building codes at a statewide level protects individual communities that are unable to adopt newer building codes through their own community processes. In their 2012 report, *Cultivating a State of Readiness*, the Tornado Recovery Action Council of Alabama encourages the adoption of a statewide building code to save lives, increase cooperation between agencies, improve delivery of services, and reduce the negative economic impacts of future storms.

The newly published 2012 IRC contains enhanced provisions for mitigating wind damage for basic 90 mph (3-second gust) wind speed zones, including increased wall bottom plate-to-stud connections and new tables for rafter and roof truss-to-wall uplift resistance requirements, both of which improve a structure's resistance to wind forces by enhancing the continuous load path. Table 802.11 in the 2012 IRC provides prescriptive values for both low- and high-sloped roofs in wind Exposure Categories B and C.

Conclusion #2 – Failure to adhere to the structural provisions of the model building code as written can result in buildings that are vulnerable to structural damage: Buildings are made more vulnerable to damage when local communities weaken the structural provisions of the adopted model building code with amendments or do not rigorously enforce the structural provisions of adopted code. Allowing the continuous load path of a building to be compromised—either in the form of amendments or through enforcement practices—increases the likelihood of structural failure when buildings are exposed to high winds.

An example of non-rigorous enforcement of structural provisions would be allowing bottom wall plates to be attached with concrete nails or cut nails instead of IRC-specified anchor bolts. One reason concrete nails are used to anchor the bottom plate is because they are much easier to use than anchor bolts. Use of anchor bolts requires more planning than concrete nails because anchor bolts have to be embedded in the foundation before the framing is erected. However, concrete nails provide significantly less resistance to uplift and lateral forces than 0.5-inch-diameter anchor bolts with 7 inches of minimum embedment spaced a maximum of 6 feet on-center, as required by code, and therefore the substitution of concrete nails for anchor bolts significantly weakens the connection of the exterior framed wall to the foundation.

Failure of the connection between the wall bottom plate and foundation was observed in newly constructed residential buildings in Alabama, where concrete nails were used for bottom plate attachment (refer to Figure 4-30). Follow-up analysis revealed that the City of Tuscaloosa allows the use of concrete nails for attaching the bottom plate to foundations in lieu of using anchor bolts as required by the IRC. The City of Tuscaloosa continued to permit bottom plates to be nailed to foundations even after the April 2011 tornadoes (Figure 10-1).

The MAT also observed new residential construction in Jefferson County, AL, that was non-code-compliant in the connection of the framed wall plate to the foundation (Figure 10-2).

Figure 10-1: Concrete nails (red circles in left photograph) used in lieu of anchor bolts (absent in both photographs) on residential buildings under construction in the City of Tuscaloosa, AL, after the 2011 tornadoes

Figure 10-2:
Lack of anchor bolts on recently constructed slab foundation in Jefferson County, AL. Note that an anchor bolt is installed at the corner, but cut nails are installed elsewhere.

10.1.2 Commercial and Industrial Buildings

Conclusion #3 – Wind provisions of the current codes and standards are insufficient to manage building performance in overload events: The MAT observed numerous instances of failure that occurred when various levels of overload were experienced by the structure. With the exception of storm shelter design and construction per ICC 500, the wind load provisions of the code do not address tornadic events. The ASCE commentary to the wind load provisions speak to the limitations of the wind provisions with respect to tornadoes, but this language is not clear.

10.1.3 Critical Facilities

Conclusion #4 – IBC-compliant facilities can be susceptible to building damage: Buildings built to the current IBC are still susceptible to significant building damage and disruption if struck by strong or violent tornadoes, as evidenced by the damage sustained by Joplin East Middle School (see Section 6.1.4).

Conclusion #5 – Many of the critical facilities observed lacked safe rooms and/or storm shelters: The MAT visited 41 critical facilities located in the path of tornado tracks or track peripheries. None of these facilities had an area designed as a FEMA 361 tornado safe room or an ICC 500 shelter.[1]

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[1] Unless otherwise specified, this chapter references the 2008 versions of FEMA 320, FEMA 361, and ICC 500.

First responders typically stay in their buildings to facilitate post-disaster community response and are at risk when there are no safe areas to go to during tornadoes (see Section 7.2).

10.1.4 Infrastructure Facilities

Conclusion #6 – Wind-displaced materials affected communications towers: The MAT observed that wind-displaced materials can collect on communications towers and increase the wind loads on those towers. Chapter 8 describes how latticed free-standing towers are vulnerable to the effects of wind-displaced materials that increase the tower's exposure to wind by adhering to the tower surface. Two cases are summarized where those increased loads likely contributed to observed tower collapse.

Section 2.6.9.1 of ANSI/TIA-222-G *Structural Standard for Antenna Supporting Structures and Antennas* (2009) uses Effective Projected Area (EPA) method to determine wind loads. With the EPA method, the sum of the areas of antennae and their supporting structures that are perpendicular to the wind direction is totaled. The total projected area is first scaled by a drag coefficient. Next, the drag coefficient, the EPA, and the design wind speed are used to determine wind loads on the tower and its components. When wind-displaced materials adhere to a latticed tower, the tower's EPA increases, and wind loads on the tower also increase. Presently, ANSI/TIA-222-G does not address the increase in EPA and wind loads from wind-displaced materials that adhere to latticed structures. There is no guidance in ASCE 7-10 in either the standard or the commentary that deals with the issue of increased loads caused by wind-displaced materials.

10.1.5 Tornado Refuge Areas, Hardened Areas, and Safe Rooms

Conclusion #7 – State of ICC 500 adoption and enforcement: With the exception of the Seneca Intermediate School in Seneca, MO, all of the safe rooms and storm shelters inspected by the MAT, for both residential and community uses, were constructed prior to the publication of the ICC 500. Many of the observed safe rooms and storm shelters were deficient when measured against the ICC 500 standard. Sections 10.6.2 and 10.6.3 describe some of the more common inadequacies in greater detail. Communities can improve the quality of new safe rooms and storm shelters by adopting and enforcing ICC 500 by itself or through the provisions of the 2009 or 2012 I-Codes. Those editions of the IBC (Section 423) and IRC (Section 323) require that "in addition to other applicable requirements in [the] code, storm shelters shall be constructed in accordance with the ICC/NSSA-500."

Conclusion #8 – There is a lack of proper labeling and signage: The MAT observed areas within existing non-residential buildings labeled as "tornado shelters." However, these areas were not designed and constructed in compliance with FEMA 320/361 or ICC 500 to provide a clear level of protection from tornadoes. While it may result from a lack of understanding of the terminology used in safe room guidance such as FEMA 320/361 and ICC 500, such mislabeling may mislead and endanger potential occupants during a tornado event.

10.2 Performance of Residential Buildings

The MAT inspected various degrees of damage to residential buildings. The primary difference between whether a building suffered only minor damage, such as loss of siding or shingles, or total destruction, such as a slab swept clean, was tornado strength and location of the building with respect to the storm swath. Simply put, greater wind pressures led to greater damage. An illustration of this difference is described in Sections 4.2.1 and 4.2.3 using the contrast in damage between Chastain Manor Apartments (Tuscaloosa, AL) and Mercy Village Apartments (Joplin, MO).

While these factors, as well as variables related to building code adoption and enforcement, and construction materials and methods, directly influence building performance, they are often beyond the control of individual homeowners. The best means of providing life-safety protection for building occupants is to have quick-response access to a safe room compliant with FEMA 361 or a storm shelter compliant with ICC 500 (see Section 10.6).

Implementing and enforcing current codes and standards resulted in enhanced building performance in several locations, one such being Mercy Village Apartments in Joplin, MO (described in Section 4.2.3). The level of detailing and engineering incorporated into the construction of the apartment building contributed to its enhanced performance under tornado-force winds.

The load paths and structural systems used in the construction of the Mercy Village project allowed the transfer of the high wind loads to the foundations. The building suffered damage, but the structural integrity of the gravity systems remained stable and protected the building inhabitants.

Conclusion #9 – Voluntary implementation of better design and construction practices could mitigate damage: The MAT did not observe many instances of enhanced wind-resistant construction in the residences damaged by the tornadoes. As stated in Chapter 4, according to NOAA tornado statistics from 1950 to 2006, almost 95 percent of all recorded tornadoes were EF2 or less. Some of the damage observed by the MAT resulted primarily from tornadoes rated as EF2 or less or to buildings located in the periphery of a more severe event. This damage can be mitigated through voluntary implementation of recommended best practices for wind-resistant construction.

The design wind speed in the current model building codes for all areas the MAT observed is 90 mph. Since model building code minimum requirements for continuous load path connections increase with design wind speeds, designing buildings to withstand higher wind loads will increase their resistance to wind damage. While it is neither economical nor practical to construct an entire home that is resistant to tornadoes of all strengths, improved design and construction and implementation of details and techniques that are already required in coastal high-wind regions will significantly reduce property damage caused by tornadoes rated EF2 or less (i.e., estimated wind speeds of 135 mph or less). An example of such improved building performance was observed after Hurricane Katrina, where the MAT noted that buildings designed and constructed to resist wind loads greater than 90 mph, as prescribed in ASCE 7 and the I-codes for coastal areas, performed better than the general building stock (FEMA 2006).

The following conclusions focus on the types of residential building damage observed by the MAT that could be mitigated if enhanced wind design and construction practices already used in hurricane-prone regions are voluntarily applied to tornado-prone regions with lower model building code design wind speeds. These types of damage included:

- *Loss of Roof and Wall Covering:* Roof and wall covering blown away by high winds and uplift forces became wind-borne debris that endangered surrounding buildings and their occupants as shown in Figure 4-1. Buildings that suffered roof covering loss were often further damaged by water intrusion.
- *Component Damage:* Component damage, whether shattered glazing or collapsed garage doors, often led to other structural and non-structural damage because of increased pressurization and water intrusion that followed breaching of the building envelope (Figures 4-9 and 4-10). Unprotected glazing and wide garage doors (16 or 18 feet wide) were particularly vulnerable (Figures 4-7 and 4-8), as was expected from previous MAT assessments.
- *Uplift of Roof Decking:* Loss of roof decking often appeared to be triggered by increased pressurization resulting from damaged soffits and gable end walls (Figures 4-13 and 4-16). Poor fastening of roof decking to the roof structure also appeared to play a role in the loss of roof decking as shown in Figure 4-15.
- *Loss of Roof Structure:* The weak link most often identified as responsible for loss of roof structure was the roof-to-wall connection (Figures 4-18 through 4-22).
- *Wall Collapse:* Wall collapse was observed to result from failed attachment of floor and ceiling systems to walls (Figures 4-23 and 4-24) and inadequate bracing of framed walls (Figures 4-25 and 4-26).
- *Failure of Wall Bottom Plate Attachment:* Foundations typically performed adequately, but in some instances the connection of walls to the foundation system failed because of inadequate connection of the bottom plate, as shown in Figures 4-27 through 4-31.

10.3 Performance of Commercial and Industrial Buildings

The MAT noted that, during the tornado events, people came from other locations to take refuge in commercial buildings because they perceived them to be safer than other types of buildings. However, in many cases, this perception was unfounded and misguided. Although multi-story framed structures did not experience disproportionate damage or collapse (although there was significant glazing damage), single-story commercial buildings did; the MAT inspected many failures of such buildings. Further, not all building owners and operators understood that commercial structures may not be safe in certain environmental or climatic conditions, such as during violent weather. The MAT's conclusions on communications and operations, as well as building performance as a function of design, are presented in the section that follows.

Refer to Section 10.1.3 (Codes and Standards: Critical Facilities) for conclusions on the susceptibility of IBC-compliant critical facilities.

10.3.1 Communications and Operations

Conclusion #10 – There was inadequate signage in commercial buildings: In an effort to increase survivability and lower injury and loss of life, building users and occupants need a better understanding of a building's design capacity and limits through adequate signage. Increased awareness of relevant building design parameters such as importance factor, design wind speed, ground snow load, seismic criteria, rain fall intensity criteria, and other relevant information will help individuals decide where to take refuge and the attendant risks.

Conclusion #11 – Emergency operations flip charts can aid in decision making: According to management personnel the MAT interviewed at a Lowes in Tuscaloosa, AL, flip charts helped the response of the store operators during the high stress and confusion of the tornadoes event by providing emergency protocols. Use of a preplanned strategy helps manage the people instead of having to make decisions about issues that they are not trained or educated in, specifically building performance. The use of a tool such as a flip chart allows the store operator to rely on the best information available while leaving the issues of engineering and risk analysis to people with those skill sets.

10.3.2 Building Performance/Building Design

Conclusion #12 – URM performed poorly as primary support: Buildings that used unreinforced masonry in the exterior walls and primary load carrying system did not perform well (see Figure 5-18). Unreinforced masonry should not be used in any primary load support system or any critical area of a building used for the protection of people.

Conclusion #13 – Connections between primary structural members were often the initial point of failure: The MAT noted that the connections between primary structural members on many buildings were the initial point of failure of the structural systems (see Figure 5-6 and Figure 5-8). Puddle welds that attached the roof deck to the joists were found to have inconsistent performance. This is consistent with past findings of roof deck connection performance in high-wind events.

Additionally, the performance of the primary structural member connections could be improved to be more robust and ductile. It is neither difficult nor expensive to increase the design load capacity of these connections. However, it is sometimes more involved to properly construct and inspect the connections.

Conclusion #14 – Lack of redundant stability systems or non-discrete structural systems contributed to progressive collapse: The MAT inspected several one- and two-story, large-footprint commercial structures with long-span roofs that suffered catastrophic failure when smaller portions of the structure were progressively overloaded and failed. These smaller local failures then progressed to larger areas of failure that then led to entire building collapse. Buildings with non-redundant structural systems that served multiple functions (such as weather barrier and stability) did not perform well. Such failures were observed in several locations in Alabama and Missouri. Per ASCE 7, buildings should be designed to not experience disproportionate collapse.

10.4 Performance of Critical Facility Buildings

The MAT visited a total of 41 critical facilities in the path of tornado tracks or track periphery areas across five States. The tornadoes in April and May of 2011 significantly affected many critical facilities, totally destroying some of them and severely interrupting the operations of several others. Critical facilities such as schools, healthcare facilities, police and fire stations, and EOCs are vitally important to communities that have been struck by tornadoes. Functional schools are needed for educational continuity and they are often used as space for recovery operations. Functional hospitals and other healthcare facilities are needed to treat injuries and provide routine ongoing care to the community. Functional police and fire stations and EOCs are needed to manage their normal mission, along with response and recovery operations after an event.

Conclusion #15 – Glazing is susceptible to damage: Damage to critical facilities constructed since the adoption of the IBC is still possible because of wind-borne debris that damages the glazing and building envelope. Although the design wind speed for IBC-compliant facilities in the areas visited by the MAT is greater than EF0 speeds and only slightly below upper EF1 speeds, such facilities were observed to be susceptible to extensive glazing damage (as illustrated by Figures 6-26 and 10-3)[2] and facility disruption due to wind-borne debris generated by the weaker tornadoes. IBC design wind speeds and glazing requirements only apply to the wind-borne debris regions in hurricane-prone areas along the Nation's coastlines.

Figure 10-3 shows a police station in Tuscaloosa, AL (see Figure 7-1 for location) that experienced roof covering damage and extensive glazing damage. Most of the exterior windows were impacted by wind-borne debris (primarily aggregate from a built-up roof). The debris chipped and cracked the glazing, as shown in the Figure 10-3 inset, but because the glazing was bullet resistant, the glazing remained in the frame. Figure 10-3 shows plywood (red arrows) placed over the damaged glazing.

Conclusion #16 – Older facilities were susceptible to damage from weak tornadoes: The MAT observed older critical facilities with significant wind-resistance vulnerabilities.[3] Unless mitigated, older facilities are susceptible to considerable building damage and disruption of facility operations if struck by even weak tornadoes. Ringgold High School and Ringgold Middle School (see Section 6.1.3), Webster's Chapel Volunteer Fire Department (see Section 7.2.3), and the Smithville Police Department (see Section 7.3.4) are all examples of older critical facilities that demonstrated significant wind-resistance vulnerabilities when struck by weak tornadoes.

Conclusion #17 – There was a lack of adequate signage directing occupants to refuge areas: The MAT noted many critical facilities with no signage directing occupants to refuge areas in the building. The MAT observed some critical facilities that had tornado refuge areas identified by signs. In some instances, the signage indicated the refuge area was a "shelter" even though the area had not been designed as a FEMA 361 safe room or an ICC 500 storm shelter. Joplin East Middle School (see Section 6.1.4), the Fultondale Municipal Complex's Library and "Shelter" (see Section 7.2.1), as well as the Tuscaloosa EOC (see Section 7.3.1) all had signage that indicated the marked

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[2] Although the facilities shown in Figures 6-27 and 10-3 were constructed prior to the publication of the IBC, the exterior glazing in IBC-compliant buildings is no more resistant to wind-borne debris than the glazing in older buildings in locations where the basic wind speed is 90 mph.

[3] Older facilities are those for which codes, standards, design, and construction practices did not adequately address non-tornadic wind resistance.

MAT EF Rating: Using DI 9 (Small Professional Building), the MAT selected DOD 3 ("broken windows, including clear story windows or skylights") for the Tuscaloosa, AL, police station.[1] Using the expected wind speed for DOD 3, the MAT derived the tornado rating as EF1 (86–110 mph) based on the damage to this building. Hence, the estimated wind speed experienced by the building was not substantially above the current basic wind speed of 90 mph.

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[1] There is no DI for police stations. The type of construction listed for DI 9 is applicable to this facility.

Figure 10-3: Red arrows show plywood placed over damaged glazing at this police station; inset shows chipped glazing and illustrates the quantity of wind-blown roof aggregate that struck the facility. Because of the building damage, a mobile command vehicle (yellow arrow) was brought to the site (Tuscaloosa, AL).

refuge area was a "shelter." However, none of these refuge areas had been designed as a FEMA 361 safe room or an ICC 500 storm shelter.

Conclusion #18 – There was a lack of safe rooms and storm shelters in critical facilities: The MAT inspected 41 critical facilities in tornado tracks or along the track periphery. None of these facilities had an area designed as a FEMA 361 tornado safe room or an ICC 500 storm shelter. First responders typically stay in their buildings to facilitate post-disaster community response and are at risk when there are no safe areas to go to during tornadoes (see Section 7.2).

10.5 Performance of Infrastructure Facilities

The tornadoes not only damaged buildings, but also disrupted community infrastructure. The MAT inspected damage to public utilities, including water distribution systems, waste water treatment plants, and communications towers.

Conclusion #19 – Lost utility power caused loss of system function: The MAT noted that when water treatment and distribution systems relied exclusively on utility power, the systems failed when utility power was lost. When tornadoes destroyed portions of the electrical utilities' distribution systems, the reliance of the systems on utility power to operate lift pumps to fill storage tanks or booster pumps to increase water distribution pressures resulted in the tanks draining and the loss of system pressure. Both the Tuscaloosa Water Works in Alabama (Section 8.1.1) and the Smithville, MS, water treatment and distribution system (Section 8.1.2) were affected in this manner.

Facilities with sufficient back-up power supply remained functional. The Tuscaloosa Waste Water Treatment Plant (Section 8.2.1) was able to continue operations after the tornado in the region knocked out its local power source. The facility was equipped with enough emergency generators to sustain enough of the lift stations to prevent overflow or discharge of untreated effluent.

Conclusion #20 – Guy anchors failed when struck by wind-displaced materials: The MAT inspected the failure of guy anchors when wind-displaced materials struck the guy wires of a guyed communications tower, resulting in tower collapse. With guyed structures, all anchors must function to make the tower structurally stable. The lack of structural redundancy inherent in guyed towers makes them particularly vulnerable to collapse when one or more guys or their anchors fail. The 300-foot guyed cellular tower in Smithville, MS experienced that mode of failure (Section 8.3.2.1).

Conclusion #21 – Wind-displaced materials affected tower performance: There were numerous examples of how wind-displaced materials can increase loads on communications towers. Wind-displaced materials were observed to have adhered to latticed free-standing towers. Once adhered, the wind-displaced materials increased the area of the latticed towers exposed to wind loads and increased the total wind forces on the towers themselves. While insufficient data were available to confirm that the wind-displaced materials *caused* tower collapse, wind-displaced material increased wind loads on the tower and likely *contributed* to tower collapse. Examples include:

Solid free-standing cell towers survived the event that destroyed guyed and latticed cell towers. One such tower, discussed in Section 8.3.1.3, did not collapse even though it was located near the center of the tornado track, where maximum winds generally occur.

- A 250-foot EMS communications tower in Tuscaloosa, AL (Section 8.3.1.1) that collapsed during the tornado had wind-displaced materials adhered to the latticed tower. Collapse of the EMS tower disrupted communications and impeded response and recovery in the Tuscaloosa County.
- A 300-foot free-standing cellular tower in Tuscaloosa, AL (Section 8.3.1.2) also collapsed. While there were no wind-displaced materials noted that were physically adhered to the fallen latticed tower, there were large amounts of debris surrounding the tower. This suggests that some wind-displaced materials may have struck the tower but were dislodged after the tower fell.

Solid free-standing towers are less affected by wind-displaced materials than other types of towers since their entire surface is already exposed to wind pressures and therefore the wind loads are not increased even when materials adhere to the towers. Solid towers are less vulnerable to wind-displaced materials since ANSI/TIA-222-G requires solid free-standing cell towers to be designed to resist higher wind loads (due to greater EPAs) than latticed towers. Also, since they are free-standing, solid towers do not rely on vulnerable guys and anchors for structural stability.

The few numbers of cellular towers assessed prevent the MAT from drawing definitive conclusions about tower performance. However, based on the fact that solid cellular towers must be designed with near-maximum EPAs and do not rely on guys for support, properly designed solid cellular towers should perform better than latticed or guyed towers during wind events that create high winds and wind-displaced materials.

10.6 Performance of Tornado Refuge Areas, Hardened Areas, and Safe Rooms

The MAT observed several community safe rooms and storm shelters constructed to criteria that have been in place since 2000, but only one that had been constructed since the release of the 2008 safe room and storm shelter guidance. Numerous residential safe rooms and storm shelters throughout the areas were impacted by the tornadoes. More can be done to promote the design and construction of safe rooms and storm shelters in all building types and uses to provide life-safety protection during tornadoes.

Refer also to Sections 10.3 (Commercial and Industrial) and 10.4 (Critical Facilities) for specific sheltering conclusions related to those building types.

10.6.1 General

The best life-safety protection from tornadoes is a safe room or storm shelter, specifically one designed and tested to the FEMA criteria (FEMA 320 / FEMA 361 or the ICC 500 standard). There were no fatalities in any of the observed safe rooms or storm shelters, and none of the occupants of these specially designed structures were injured in spite of the strength of the tornadoes. Although the residential and community safe rooms had generally been designed, constructed, and tested to meet FEMA 320/361 guidelines, there were numerous compliance issues with signage, doors, ventilation, and square footage space allocation.

The performance of tornado refuge areas, hardened rooms, safe rooms, and storm shelters highlights the need for the construction of more safe rooms and storm shelters in tornado-prone regions. The following statements related to the use and performance of safe rooms and storm shelters are based solely on the MAT's observations. Specific conclusions related to residential and community safe rooms and storm shelters are presented in the following sections.

Conclusion #22 – 2010 Alabama State school tornado safe room requirement: FEMA supports the State of Alabama Building Commission and Alabama House Bill 459 that requires new school buildings constructed after July 2010 to provide mandatory safe spaces for tornado protection in all

K-12 public schools. The Building Commission further identified the ICC 500 as the standard to which the safe spaces are to be constructed for providing protection from tornadoes.

Conclusion #23 – Above-ground safe rooms performed as well as those below ground: Despite broad public perception to the contrary, above-ground safe rooms, when constructed properly, provide the same level of protection and perform just as well as below-ground safe rooms.

Conclusion #24 – People traveled excessive distances to community shelters and safe rooms: People may travel great distances to get to a community safe room or shelter, especially when they have ample warning time as was the case in many communities on April 27, 2011. Travel distances to community safe rooms and shelters on that day were reported to be between 5 and 10 miles, greatly exceeding the ½-mile maximum driving distance or 5-minute maximum walking time advocated by FEMA. Whether walking or driving, prospective safe room occupants must be able to safely reach the facility within 5 minutes of receiving a tornado warning or notice to seek shelter.

Conclusion #25 – There is a poor understanding of public actions/movement patterns during tornadoes: Based on statistics from the NOAA SPC, over 65 percent of all fatalities on April 27, 2011 occurred in homes, 6 percent occurred in commercial/public buildings, and 3 percent occurred in vehicles. By comparison, 40 percent of the fatalities on May 22, 2011 in Joplin, MO, occurred in homes, 42 percent in commercial/public buildings, and 9 percent in vehicles.

While the time of day and day of the week definitely influenced where people were when the tornado struck, it is difficult to establish if movement patterns related to sheltering were consistent during the April 27 tornadoes (which included both large tornadoes with atypical warning times, many upwards of 60 minutes as well as rapidly forming tornadoes with minimal to no warning times). During the Joplin tornado, which was a large tornado with warning times at or below average, a much higher percentage of fatalities occurred outside the home. Although greater availability of safe rooms or storm shelters in non-residential buildings may have prevented loss of life during this event (which provided less than 20 minutes warning time), behavioral studies and research are lacking to help explain or predict the movements of people during tornadoes.

Conclusion #26 – Guidance for identifying how to provide community-wide protection is lacking: Based on the MAT's observations, the determination of whether or not to protect a vulnerable community using a single, large safe room or storm shelter (versus smaller, dispersed safe rooms and storm shelters) is currently based on conjecture and anecdotal evidence. Behavior during storms that spawn tornadoes is not well studied. There is a lack of data and research that clearly states or defines the risk individuals take when they travel long distances to seek refuge during a tornado. Technical storm elements and social science (behavioral) issues such as warning time, presence of multiple funnel clouds, track variation movement patterns across the tornado path, lack of safe areas at current location, and the time available to make the decision to shelter or seek shelter are examples of inputs to the decision making process that warrant further study. Currently, there is a lack of consistent guidance on how to provide protection when the potential occupants are traveling more than 5 minutes (walking time). As such, it is up to the community to determine if they will support or promote the use of a single, large community safe room, dispersed smaller community safe rooms, or smaller private and residential safe rooms throughout the community.

Conclusion #27 – Design and construction guidance for storm shelters and safe rooms is consistent, though somewhat different in scope: The ICC 500 for storm shelters and the FEMA technical guidance (FEMA 320 and FEMA 361) for safe rooms provide the same or nearly identical levels of protection for tornado hazard protection. Notable differences exist between the documents for hurricane hazard protection, but a review of the hurricane provisions was beyond the scope of this tornado MAT report. Both these documents provide important guidance and FEMA continues to educate designers, emergency management officials, property owners, and people in the community seeking to find protection from tornados on the benefits of FEMA 320, FEMA 361 and ICC 500 and how they complement one another. The fact that FEMA references an engineering design standard (ICC 500) and uses it as part of their much larger emergency management program shows FEMA's commitment to use voluntary consensus standards to the maximum extent possible in carrying out its programs.

ICC 500 is an engineering standard and in its first edition; it does not provide a commentary to support the requirements of the standard. The standard is adopted by reference by the 2009 and 2012 I-Codes. By comparison, the technical criteria from the FEMA guidance documents—although not ANSI-certified consensus standards—include an extensive commentary addressing not just design considerations, but also operational and maintenance issues of safe rooms. While the FEMA documents are not adopted by the I-Codes, the FEMA criteria may be adopted by a jurisdiction to govern the construction safe room and storm shelters. The authority having jurisdiction must clearly state who is responsible for reviewing and accepting the design of and construction of a safe room or storm shelter to ensure compliance with the technical criteria or standard.

Conclusion #28 – There is a lack of proper labeling and signage: There were areas within existing non-residential buildings labeled as "tornado shelters." However, these areas were not designed and constructed in compliance with FEMA 320/361 or ICC 500 to provide a clear level of protection from tornadoes. Such labeling may result from a lack of understanding of the terminology used in safe room guidance (such as FEMA 320/361 and ICC 500). This labeling can, however, mislead and endanger potential occupants during a tornado event.

Conclusion #29 – There were unregistered safe rooms: There is a potential for people to become trapped in their safe rooms (see Section 9.4.3.1). While most community safe rooms and storm shelters are managed by local or county governments (as they are public facilities), almost none of the residential safe rooms and storm shelters observed by the MAT in the five affected States were registered or listed with local emergency management agencies or police/fire departments.

Conclusion #30 – Safe rooms and storm shelters lacked tools to open or dismantle door if blocked: Most safe rooms and storm shelters did not have tools available to open or dismantle the door from within should egress routes become damaged, inoperable, or blocked by debris.

Conclusion #31 – Some safe rooms were difficult to locate with given coordinates: The MAT had difficulty locating FEMA-funded safe rooms even when latitudes and longitudes were provided. It seemed that coordinates were either incorrect or outdated, and had not been verified in the field prior to the tornado.

10.6.2 Residential Safe Rooms and Storm Shelters

There were design and construction issues observed with the residential safe rooms, storm shelters, and tornado refuge areas assessed by the MAT. For best available tornado refuge areas, it is difficult to ensure that "above code" improvements are implemented correctly. The MAT observed numerous attempts to construct hardened rooms that were misidentified as "tornado shelters" where voluntary compliance with the criteria and standards from FEMA and ICC was not achieved. An opportunity exists for communities to enable improved compliance with the safe room and storm shelter criteria by adopting the ICC 500 as a minimum standard for storm shelter construction (alone or along with adoption of the latest edition of the IRC).

All of the safe rooms or storm shelters inspected by the MAT during the field visits were constructed prior to any adoption of the 2009 I-codes and ICC 500, which require building departments to be involved in the design, construction, and installation of safe rooms and storm shelters. However, there were numerous discrepancies noted between the observed construction and the FEMA guidance documents on safe rooms or the ICC 500 criteria, that going forward, need to be corrected. The most common deficiencies in the residential safe rooms and storm shelters noted during the field assessments are described below.

Conclusion #32 – Safe room door quality observed was often inadequate: Doors that did not meet the FEMA or ICC criteria were the most dominant deficiency in residential safe rooms. Door quality was lacking in many observed residential safe rooms and storm shelters. Many of the doors would not pass the debris impact tests from FEMA 320/361 and ICC 500, and many that were installed had not been tested to show compliance with the criteria. The presence of substandard doors places occupants at risk. If substandard doors fail, the occupants in these areas can be exposed to wind and wind-borne debris.

Conclusion #33 – Safe room door hardware observed was often inadequate: Door hardware, specifically latching mechanisms, was observed to be inadequate in many older shelters and hardened rooms (but also in some new storm shelters and safe rooms). FEMA 320 requires three hinges and three latches. FEMA 361 recommends six points of connection (typically three hinges and three latching mechanisms), but allows for other alternatives if the door and door hardware are tested to meet stated debris impact criteria. ICC 500 requires only that the door and door hardware be tested to meet stated debris impact criteria. Most of the older doors (both above- and below-ground) installed in hardened rooms and older shelters had inadequate latching; these doors performed with varying levels of success during the storms.

Conclusion #34 – There was a lack of adequate ventilation in shelters: Ventilation pipes and vents were altered or removed in many older below-ground shelters. This is an unsafe practice and places occupants at risk.

Conclusion #35 – Safe rooms were observed that had inadequate or no anchoring: A few prefabricated safe rooms were installed but not anchored to a foundation; specifically, the structures observed were heavy, precast concrete safe rooms. Although these safe rooms/storm shelters are massive and stated by sellers and manufactures to be FEMA- and ICC-compliant structures, they must still be restrained to resist high wind forces. The MAT was unable to obtain documentation to show these structures were adequately anchored to resist overturning.

Conclusion #36 – Safe room locations were not documented and occupants had no ability to communicate from within: Many tons of debris can be blown on top of or around a safe room or storm shelter during a tornado. Many safe room owners did not coordinate with their local government, so first responders may not have known the locations of private and individual safe rooms and storm shelters. Furthermore, safe room and storm shelter occupants were not always able to communicate with first responders from within their safe rooms and storm shelters when egress was disabled or blocked by debris.

10.6.3 Community Safe Rooms, Storm Shelters, and Tornado Refuge Areas

There were design and construction issues with the community safe rooms, storm shelters, and tornado refuge areas inspected by the MAT. The MAT deployed after the April 25–28, 2011 tornadoes observed numerous safe rooms and storms shelters where voluntary compliance with the criteria and standards from FEMA and ICC was not achieved. An opportunity exists to improve compliance with the safe room and storm shelter criteria by adopting the ICC 500 and a minimum standard for storm shelter construction (alone or along with adoption of the latest edition of the IRC). Further, the few non-stand-alone designated “tornado shelters” or designated refuge areas the MAT observed were in portions of buildings that were not constructed to any higher level of protection than the other portions of the building. The MAT could not verify if any of these areas had been evaluated or assessed for their vulnerability to tornadoes prior to their use as a tornado refuge area.

All of the safe rooms and storm shelters inspected by the MAT during the field assessments were constructed prior to any adoption of the 2009 I-codes and ICC 500 (in which building departments would have been required to be involved in the design, construction, and installation of the structures). The lone exception was the Seneca Intermediate School in Seneca, MO (see Section 9.4.4.3). The most common shortcomings of tornado refuge areas and deficiencies in the community safe rooms and storm shelters noted during the field assessments are described below.

Conclusion #37 – Tornado refuge areas located in large, single-story buildings performed poorly: Tornado refuge areas in large, single-story commercial buildings and retail buildings did not perform well. Although some winds were at or above design wind speeds, disproportionate collapses (and almost complete collapses) occurred in several instances (refer to Section 10.3). Although emergency planning efforts by building owners and operators identified specific areas to be used during a tornado event, the MAT could not verify whether any of these areas were defined as best available refuge areas by design professionals who specifically identified vulnerability to wind and wind-borne debris.

Conclusion #38 – There was inadequate doors and door hardware on safe rooms/storm shelters: Some FEMA-funded community safe rooms were observed to have inadequate doors and door hardware, similar to problems the MAT observed with residential safe rooms and storm shelters. This is a compliance issue that building departments would have been required to evaluate during the design, construction, and installation of the structures had the construction of these protected spaces been required by the State or local building code.

Most tornado refuge areas the MAT observed also had doors that would not pass the FEMA/ICC criteria (tests) for wind and debris-impact resistance. These weak doors and door systems place occupants at risk during a tornado.

Conclusion #39 – There was a lack of alternate means of communication in community safe rooms: Few community safe rooms were equipped with alternate communication systems as recommended in FEMA 361. Where alternative means of communication were observed, not all safe rooms provided backup power for these systems in the event power was lost during the event.

10.7 EF Scale

At each site visited, the MAT independently determined an EF scale rating based on one of the 28 DIs and DOD described in *A Recommendation for an Enhanced Fujita Scale* (TTU 2006), which was officially adopted by NOAA/NWS and first used in February of 2007. Information on the EF scale is provided in Chapter 2 and Appendix E. The following conclusions relate to the EF scale rating system based on the MAT's observations.

Conclusion #40 – DI lists are incomplete: To effectively use the EF scale, the construction description should reasonably match the building or structure being rated. There were some types of buildings, such as fire stations, that did not have specifically assigned DIs. Therefore, the MAT used DI 14 (Automobile Service Building) or DI 21 (Metal Building System), depending on which construction type was most closely approximated, to rate fire stations. By contrast, schools are accounted for reasonably well in the existing format, and are separated into DI 15 (Elementary School) and DI 16 (Junior or Senior High School).

Conclusion #41 – DOD categories are inadequate for specific DIs: For some of the current 28 DIs, there are up to 12 DOD indicators, allowing the user to choose the specific level of damage based on observations. However, for some DIs, such as free-standing towers, there are only two DOD indicators. Freestanding communications towers (DI 25) were rated by the MAT. The existing format of the EF scale only lists three DODs under DI 25, which limits the number of estimated wind speeds that can be deduced. While free-standing towers have a limited number of possible failure modes and related DODs, other DIs such as DI 5 (Apartments, Condominiums, and Townhouses) have more DODs to better rate tornado wind speeds.

Conclusion #42 – The process for assessing varying DODs in the same DI is not well explained in EF guidance: Large buildings, such as Ringgold High School in Ringgold, GA, often exhibited marked differences in damage from one portion of the building to another because the tornado only struck a portion of the building. The lack of guidance for how to assess large buildings where only a portion of the building is struck can make the application of the EF scale different among different users. For example, DI 16, DOD 5, is for "… significant loss of roofing material (>20%) …" If only one end of a large building is struck, the roof covering damage in that area could exceed 20 percent, but could be less than 20 percent of the total for the entire roof area. In this case, if the DOD were applied only to the portion of the building that was struck, then DOD 5 would be applicable. But if the DOD was applied to the entire building, then DOD 2 would be applicable (assuming the only damage was to the roof covering).

Conclusion #43 – Order of DOD choices for DI 2 (One- and Two-Family Residences) in the EF rating scale does not follow observed damage patterns: As noted in Chapter 4, most residences rated by the MAT followed the order of DODs prescribed by the EF scale closely, with the exception of DOD 5 (Entire House Shifts off Foundation). It was very unusual for DOD 5 to precede DOD 6. In the one documented case (Figure 4-17), the observed residence was older construction.

Conclusion #44 – Photographs of DODs would aid in determining EF ratings: *A Recommendation for an Enhanced Fujita Scale* (TTU 2006) does not include photographs for each of the DOD indicators, making it difficult for users to accurately interpret the guidance and evaluate structure damage.

10.8 Post-Tornado Imagery

Following the tornadoes, the NWS released aerial photographs and rated the intensity of the tornadoes along the tracks in certain locations. The following conclusions relate to the post-tornado imagery and the MAT's observations. These conclusions are not based on field observations, but rather the MAT's observations in developing this report and working with the information collected in the field.

Conclusion #45 – Post-tornado NWS aerial photographs were helpful in conducting damage analysis: The NOAA post-tornado aerial photographs were helpful to the MAT. The photographs provide context for wind performance of a given building with respect to building location within or on the periphery of the tornado track. The aerial photographs also show other damage in the vicinity of a given building. The view from the air provided insights that could not be discerned from ground-based observations.

Conclusion #46 – EF contours provided by NWS were useful: Having EF contours of the track was helpful to the MAT. Where contours were provided, a direct comparison between the NWS EF contour rating and the MAT EF rating for a specific building could be made. Development of EF contours is also important for risk modeling of facilities and other structures such as nuclear power plants, safe rooms, and power transmission lines.

Conclusion #47 – Accuracy of EF ratings used to develop track contours is important: For risk modeling, in addition to developing EF contours, it important that the EF ratings for the contours be accurate. Accurate wind speed determination is difficult for two reasons: 1) there is some uncertainty of the wind speed for given DODs, and 2) accurate selection of the wind speed between the lower- and upper-bound speeds associated with the DODs requires specialized knowledge. The MAT derived an EF rating for several buildings; the MAT's ratings for most of these buildings were different from the NWS track rating or contour rating in the vicinity of the building. The difference may be a function of the MAT's specialized knowledge of structural performance.