Midwest Tornado Outbreak
10 December 2021
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JOINT PRELIMINARY VIRTUAL RECONNAISSANCE REPORT AND EARLY ACCESS RECONNAISSANCE REPORT (PVRR-EARR)

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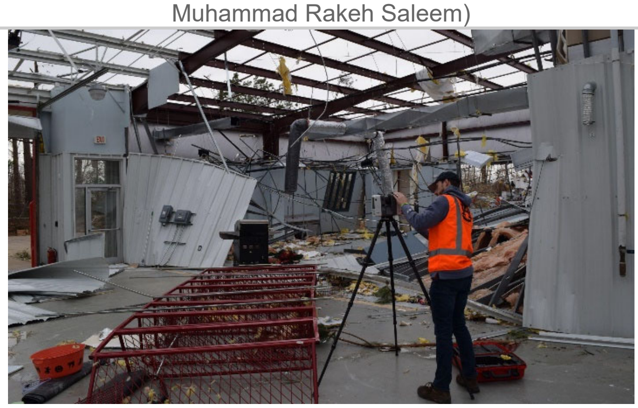

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PREFACE

The National Science Foundation (NSF) awarded a 2-year EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details), an effort now extended through renewal award CMMI 2103550. *StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities.* StEER achieves this vision by: (1) deepening structural engineers' **capacity** for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) **coordination** leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) **collaboration** that broadly engages communities of research, practice and policy to accelerate learning from disasters. StEER works closely with other extreme event reconnaissance organizations and the Natural Hazards Engineering Research Infrastructure (NHERI) to foster greater potentials for truly impactful interdisciplinary reconnaissance after disasters.

Under the banner of NHERI's CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium including the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Nearshore Extreme Event Reconnaissance (NEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEEER), Social Science Extreme Events Research (SSEER), and SUstainable Material Management Extreme Events Reconnaissance (SUMMEER) as well as the NHERI RAPID equipment facility and NHERI DesignSafe CI, long-term home to all StEER data and reports. While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER aspires to build a network of regional nodes worldwide to enable swift and high quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, leading StEER's Atlantic/Gulf Regional node and serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community and ensuring a robust capacity for multi-hazard assessments.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

ATTRIBUTION GUIDANCE

Reference to Analyses, Discussions or Recommendations

Reference to the analyses, discussions or recommendations within this report should be cited using the full citation information and DOI from DesignSafe (these are available at https://www.steer.network/products).

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Other images in this report were acquired by StEER FAST members. Thus it is appropriate to use the full citation information and DOI from DesignSafe (these are available at https://www.steer.network/products).

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI 2103550. Any opinions, findings, and conclusions or recommendations expressed in this material are those of StEER and do not necessarily reflect the views of the National Science Foundation. All authors and editors listed on the cover page participate as volunteer professionals. Thus, any opinions, findings, and conclusions or recommendations expressed herein are those of the individual contributors and do not necessarily reflect the views of their employer or other institutions and organizations with which they affiliate.

Special thanks to Spatial Networks for their ongoing partnership and generous support, making available, at no cost, the Fulcrum Community mobile platform for StEER Damage Assessments. StEER appreciates the support of NSF's Jack Meszaros in connecting StEER to other responding teams and for her willingness to assist in securing necessary approvals. The VAST wishes to express appreciation to Randall P. Bernhardt, of Bernhardt Forensic Engineering, who assisted us with understanding the building code and enforcement within Kentucky. The FAST also appreciates the assistance of the Kentucky Department of Emergency Management, the East Marshall District 1 fire station staff for giving us access to their station, and the many survivors, building owners, and occupants that were willing to give us access to facilities and/or share details related to structural performance. The ongoing collaboration with Prof. Frank Lombardo's research team out of University of Illinois Urbana-Champaign is also appreciated.

Data was collected in part using equipment provided by the National Science Foundation as part of the RAPID Facility, a component of the Natural Hazards Engineering Research Infrastructure, under Award No. CMMI: 2130997. StEER appreciates the RAPID EF's team's responsiveness to our request and particularly Andrew Lyda for his willingness to quickly deploy in support of this mission.

The sharing of logistical details, images/videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER especially welcomed the exchange of information between the various teams deploying under different federal agency mandates, with special thanks to Manuel "Manny" Perotin of CDM Smith, whose work with FEMA MAT has led to a sustained, fruitful collaboration with StEER. This sharing of potential targets and other intel via Slack was especially valuable to StEER's rapid deployment strategy for this event. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

Finally, StEER also recognizes its student administrator, Dinah Lawan of the University of Notre Dame, for her efforts in formatting this report, as well as other members who were not able to assist in the authorship of this report but shared vital information via Slack and email.

For a full listing of all StEER products (briefings, reports and datasets) please visit the StEER website: https://www.steer.network/products

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ACRONYMS

ASCE	American Society of Civil Engineers
BOCA	Building Officials and Code Administrators
CMU	Concrete Masonry Unit
DEQC	Data Enrichment and Quality Control
EARR	Early Access Reconnaissance Report
EF	Enhanced Fujita Scale used for Tornado rating; EF Equipment Facility (part of NHERI)
FAA	Federal Aviation Administration
FAST	Field Assessment Structural Team
FEMA	Federal Emergency Management Agency
GEER	Geotechnical Extreme Events Reconnaissance
IBC	International Building Code
ICC	International Code Council
IRC	International Residential Code
ISEEER	Interdisciplinary Science and Engineering Extreme Events Research
LiDAR	Light Detection and Ranging
NBC	National Building Code
NEER	Nearshore Extreme Event Reconnaissance
NHERI	Natural Hazards Engineering Research Infrastructure
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NWS	National Weather Service
PVRR	Preliminary Virtual Reconnaissance Report
RAPID	Type of NSF grant intended to support capture of perishable data Also refers to NHERI Experimental Facility (EF) renting equipment to capture perishable data
SPC	Storm Prediction Center
StEER	Structural Extreme Events Reconnaissance network
SUMMER	SUstainable Material Management Extreme Events Reconnaissance
UAV	Unmanned Aerial Vehicle
VAST	Virtual Assessment Structural Team

EXECUTIVE SUMMARY

In the late hours of 10 December and into the early hours of 11 December 2021, unseasonably warm air instigated an outbreak of at least 60 confirmed tornadoes across nine states. The outbreak included a family of damaging "Quad-State" tornadoes, with an EF4 tornado that was on the ground for over 160 miles causing devastating impacts to many small communities and in particular Mayfield, KY. This tornado outbreak is expected to be one of the largest and deadliest tornado events in US history.

Given the historic nature of this outbreak, StEER immediately issued a Level 3 response to this event, simultaneously activating its Virtual Assessment Structural Team (VAST) on 11 December, while, its Field Assessment Structural Team (FAST) was assembled to begin collecting perishable data in Mayfield and surrounding areas on 14 December. These efforts culminated in a single joint PVRR-EARR, a hybrid of StEER's standard Preliminary Virtual Reconnaissance Report (PVRR) and Early Access Reconnaissance Report (EARR):

- summarizing the genesis and hazard characteristics of these tornadoes,
- providing an overview of the regulatory environment in Kentucky,
- outlining StEER's field response and reconnaissance methodology,
- documenting the performance of a wide range of buildings and other infrastructure, and
- recommending topics worthy of continued study by the natural hazards engineering community and affiliated fields.

Importantly, this joint report underscores the need to design for tornadoes in high-exposure regions, a more realistic proposition given the recent release of ASCE 7-22 and its new tornado load provisions.

The FAST utilized rapid imagery capture methods to document accessible areas in Mayfield and other affected communities in Kentucky using street-level panoramic imaging, unmanned aerial vehicles, LiDAR scans of notable case studies, and forensic load path assessments using StEER's Fulcrum mobile app, with particular emphasis on structures where details of the load path were visible and "success stories". The timing of data collection allowed a number of sites in Mayfield to be documented before extensive demolition/debris removal, though some sites were still restricted due to recovery efforts. These data, available via StEER's Fulcrum and Mapillary platforms, can be particularly advantageous in supporting future investigations in the following topical areas:

Engineering investigations	Recommendations for further study
TOPIC 1: Performance of essential and critical facilities	The poor performance of many essential and critical facilities such as fire/police stations and nursing homes during this tornado outbreak highlights a desperate need to review, evaluate, and retrofit all essential and critical facilities in tornado prone areas.
TOPIC 2: Safe room performance	Successful performance of a number of storm shelters during this and other tornado events could assist in the promotion of storm shelters for superior protection during future tornadoes. Further, since two of the documented storm shelters were "home-built," the development of open-source designs and construction guidance compliant with ICC 500 standards in a suite of sizes, configurations, and price points can support

	personal-preparedness efforts.
TOPIC 3: Performance of critical infrastructure	Damage to critical infrastructure such as power distribution lines and water supply systems highlights the fact that design of these systems has not previously accounted for tornado wind speeds. The availability of tornado design guidance in ASCE 7-22 now allows investigation of its applicability to critical infrastructure systems and potential retrofit options.
TOPIC 4: Tilt-up structure performance	Large-volume warehouse and industrial buildings are frequently constructed using concrete tilt-up walls around the exterior of the building and braced by light steel roof systems. A study of the performance of tilt-up wall construction during this and prior high wind events could lead to improvements in the design of these structures.
TOPIC 5: Storage silo performance	Numerous grain silos experienced roof failure. Review of the uplift demand/capacity ratio of these structures, and improvements to roof-to-wall connection details could lead to improved performance of structures critical to local economy and food supply.
TOPIC 6: Recovery Model Development	Increased robustness of physical infrastructure can improve overall resilience by minimizing the initial damage that will later impact other aspects of community resilience. Future studies could quantify how the affected community recovers from this event through targeted longitudinal studies, integrating StEER data as baseline observations.
Policy and practice	**Recommendations for further study**
TOPIC I: Promoting Design for Tornadoes	The recent publication of new tornado load provisions in ASCE 7-22 is ideally timed for pre-emptive adoption by Kentucky and neighboring states for ensuing reconstruction efforts. These new provisions should also be applied to all new construction of not only Risk Category III (critical) and IV (essential) facilities in tornado-prone areas, but also to Risk Category II structures that play an important role in the economy, human safety, and resilience of the community.
TOPIC II: Preservation of life safety in tornadoes	This event underscores the need to design for a minimum level of tornadic winds for all structures with life safety implications, accompanied by in-building or in-community accessible sheltering for tornadoes that exceed the design-level event. In parallel, it is worth emphasizing the agency of designers and their building owner clients to opt for higher risk categories based on special circumstances for that structure, its unique significance to a community, or out of a commitment to preserving life safety in tornadoes.

TOPIC III: Public response to tornado warnings	Surveys of residents and workers in the areas subject to tornado warnings could provide valuable information about whether they received the warnings of nighttime tornadoes, and the immediate actions they took. Emphasis should also be placed on studying how owners/operators of commercial and institutional buildings respond to these warnings, given that they must weigh the impacts of disrupted operations against the life safety of their employees.
TOPIC IV: Promotion of storm shelters	Public awareness campaigns should promote retrofitting existing buildings with storm shelters or at minimum ensuring community storm shelters are constructed with sufficient capacity and geographic coverage to serve the immediate population. The successful integration of communal shelters into community culture is equally essential so residents are aware of when and how to access these life-saving resources.

Finally, all observations and findings provided in this report should be considered preliminary and are based on the limited scope of StEER's VAST and FAST investigations.

1.0 Introduction

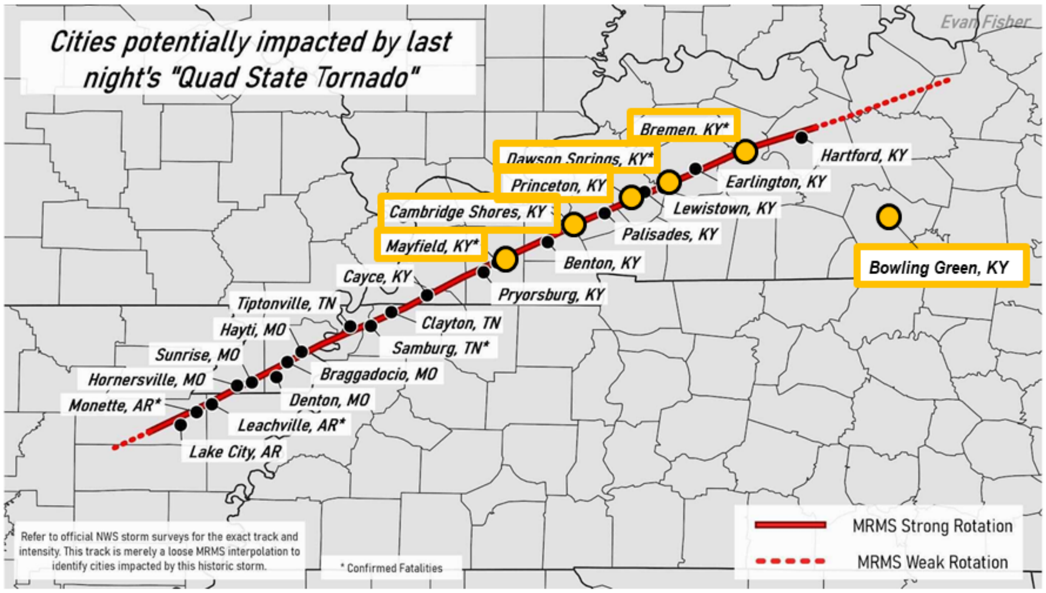
In the late hours of 10 December and into the early hours of 11 December 2021, unseasonably warm air instigated an outbreak of at least 60 confirmed tornadoes across nine states: Alabama, Arkansas, Indiana, Illinois, Kentucky, Mississippi, Missouri, Ohio and Tennessee (Shapiro, 2021), resulting in significant damage across numerous communities. Notable among these was a suspected long-track tornado with an estimated track of over 220 miles, termed the "Quad-State Tornado," cross-cutting Arkansas, Missouri, Tennessee and then Kentucky. However, subsequent analysis revealed this was actually a family of tornadoes that included an EF-4 on the ground for over 160 miles (Shapiro, 2021), the longest track on record in Kentucky's history. The Quad-State Tornadoes transected a number of communities (see line in Fig. 1.1) with devastating impacts to Mayfield, KY. While the National Weather Service is still in the early stages of evaluating this outbreak, preliminary evaluations suggest it will be among the worst in recorded history with respect to losses and the single deadliest December tornado outbreak in US history. Moreover, as December tornadoes are usually confined to the Gulf Coast region, outbreaks in areas this far north this late in the year are extremely rare (Finch, 2021).

1.1 Societal Impact

Viewed by Kentucky Governor Andy Beshear as the worst disaster in his state's history, the societal impact of the outbreak is far reaching, with state officials predicting that recovery will likely be measured in years, rather than months. Beyond the buildings directly damaged, major utility disruptions encompassed drinking water, wastewater service, natural gas and electricity (Finch, 2021). Damage to critical facilities like fire and police stations rendered first responders among those who required rescue. Damage to the Graves County Jail forced the evacuation of inmates from their cells. Meanwhile, schools in Mayfield and the surrounding areas have canceled classes for the remainder of the year. With heavy damage to the residential sector, preliminary loss estimates suggest that this outbreak is the costliest tornado event in US history, with a projected $18 billion in losses (Finch, 2021), inclusive of direct damage to homes, businesses and infrastructure as well as building contents, and indirect losses such as business disruption, lost wages, transportation disruption, displacement and rescue operations. Notably, these losses continue a staggering upward trend in weather-related disasters in the US, with nearly $100 billion in damages last year due to meteorological hazards (Uliano, 2021).

1.2 Loss of Life and Injuries

Nighttime tornadoes are twice as likely as their daytime counterparts to be deadly (Erdman, 2021). This life loss potential was further heightened as a number of higher-occupancy structures were directly impacted, including Monette Manor, a nursing home in northeast Arkansas where one person was killed and 20 others trapped under the debris from the facility's collapse (Reuters, 2021). Other notable high-occupancy structures whose failures resulted in injuries and fatalities include an Amazon Distribution Center in Edwardsville, IL and the Mayfield Consumer Products candle factory in Kentucky, both of which were operating fully at the time of impact to meet Christmas demands (Dawson and Vlamis, 2021; Romero et al., 2021).



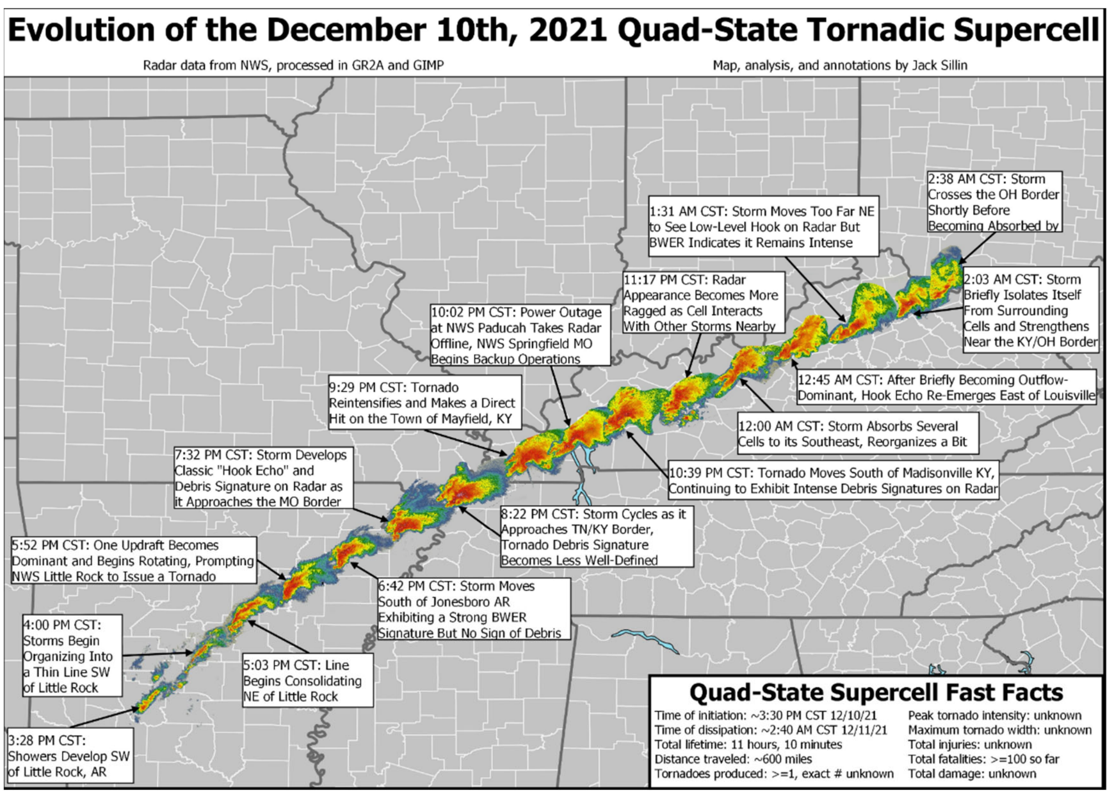


Figure 1.1. (top) Communities affected by Quad-State Tornadoes (source: Evan Fisher via Twitter) modified to include StEER data collection sites in yellow; (bottom) chronology of Quad-State Tornadoes' impacts (source: James Sillin via Twitter)

The severity of damage and its geographic extent led to over a week of search and rescue efforts, with the National Guard joining local officials in house-to-house searches and debris removal until all those who were reported missing were accounted for. While the death toll was feared to be much higher initially, the life loss from this nighttime outbreak was sizable at 93 persons, ranging in age from 2 months to 98 years of age (Shapiro, 2021). Table 1.1 summarizes (by state) the fatalities at the time this report was authored. Unfortunately, this outbreak coincided with a rise in the number of new coronavirus cases following the Thanksgiving holiday, which had already reduced healthcare capacity (particularly ICUs), complicating the management of severe injuries like chemical burns, long bone fractures and other crush-related injuries associated with the tornado outbreak.

Table 1.1. Projected Fatalities, by State (Source: Shapiro, 2021)

State	**Deaths**	**State**	**Deaths**
Arkansas	2	Missouri	2
Illinois	6	Tennessee	5
Kentucky	78	**Total**	**93**

1.3 Official Response

The National Weather Service (NWS) Storm Prediction Center (SPC) continuously monitored for severe weather potential several days before 10 December, issuing outlooks three days before the storms developed. On the morning of 10 December, the outlook was upgraded to Moderate Risk, alerting for "strong tornadoes" several hours before the worst thunderstorms formed. NWS watches continued throughout the day, issuing warnings (with lead times well above average) using standard NOAA/NWS channels (NWS, 2021a), though many were asleep by the time the risk was acute.

On the heels of Governor Beshear's State of Emergency Declaration, President Biden declared a major federal disaster in Kentucky on 12 December, as well as an emergency declaration for Tennessee and Illinois. National Guard, FEMA and the US Army Corps of Engineers joined local emergency management in the search, rescue and recovery efforts. An incident support base was established at Fort Campbell to deploy personnel and supplies, including generators, meals, water, cots, blankets, childcare kits, and pandemic shelter kits, with over 700 FEMA workers on-site to process claims (Finch, 2021). President Biden later visited Mayfield on 15 December, pledging that the federal government will cover "100% of the cost for the first 30 days for all the emergency work," amending the Kentucky disaster declaration to make additional federal funds available (Vazquez et al., 2021).

1.4 Report Scope

This tornado outbreak is expected to be one of the largest and deadliest tornado events in US history, with fatalities and monetary losses reiterating the need for greater progress in reducing the toll of damaging tornadoes on society. The long-duration nature of the tornado-producing thunderstorms, with two supercell thunderstorms each traveling well over 100 miles and spurring multiple tornadoes in unseasonably warm weather, raises important questions regarding the potential for an evolving hazard landscape in a changing climate (Uliano, 2021). **This joint report underscores the need to design for tornadoes in high-exposure regions as part of a**

national response to these trends, a more realistic proposition given the recent release of ASCE 7-22 and its inclusion of tornado load provisions.

StEER immediately issued a Level 3 response to this event, simultaneously activating its Virtual Assessment Structural Team (VAST) on 11 December 2021 to begin compiling information from the press, agency reports and social media. Meanwhile, StEER recruited members for its Field Assessment Structural Team (FAST) to begin collecting perishable data before debris was significantly disturbed while respecting the ongoing search for victims. Thus, StEER's primary product for this tornado outbreak will combine elements of the standard **Preliminary Virtual Reconnaissance Report (PVRR)** and **Early Access Reconnaissance Report (EARR)** into a single joint **PVRR-EARR**, which is intended to:

- summarize the genesis and hazard characteristics of these tornadoes,
- provide an overview of the regulatory environment in Kentucky,
- outline StEER's field response and reconnaissance methodology,
- document the performance of a wide range of buildings and other infrastructure, and
- recommend topics worthy of continued study by the natural hazards engineering community and affiliated fields.

This report is accompanied by a **Media Repository** compiling additional photographic accounts of damage across different building and infrastructure classes (also available in DesignSafe Project PRJ-3349). Finally, while damage was reported across multiple states and as the result of multiple tornadoes, the focus herein is on communities impacted in Kentucky, unless stated otherwise, as this state sustained the most significant damage in the outbreak and was the focus of the FAST's data-gathering efforts.

2.0 Hazard Characteristics

2.1 Severe Weather Forecast and Outlook

Convective outlooks, issued by the SPC (2021a), included a slight risk for severe weather in its Day 3 outlook starting 8 December 2021. This was later increased to an enhanced risk on 9 December with a greater than 10% chance for EF 2-5 tornadoes in Arkansas, Tennessee and Kentucky (Fig. 2.1). At approximately 10:30am CST on 10 December, the risk for that evening was increased to moderate[1].

The atmospheric conditions contributing to the events of 10 December were more typical of April or May than December. The weather in the Ohio Valley was relatively warm and humid. The formation of a low-pressure system allowed for warm, moist air from the Gulf of Mexico to push northward (Fig. 2.2). A very strong low-level jet moved through the region contributing to the environmental shear necessary to form rotating storms. The moisture, shear, and Convective Available Potential Energy (CAPE) values over 1000 J/kg ultimately led to an ideal setup for the formation of severe weather, including tornadoes. As the trough associated with the low-level jet strengthened, so did the associated low pressure system. The associated cold front (Fig. 2.3) would be primarily responsible for generating the storms' lift without a significant inhibiting inversion layer.

[1] Severe thunderstorm Risk Categories and associated probability of tornado development are defined by the Storm Prediction Center at https://www.spc.noaa.gov/misc/about.html

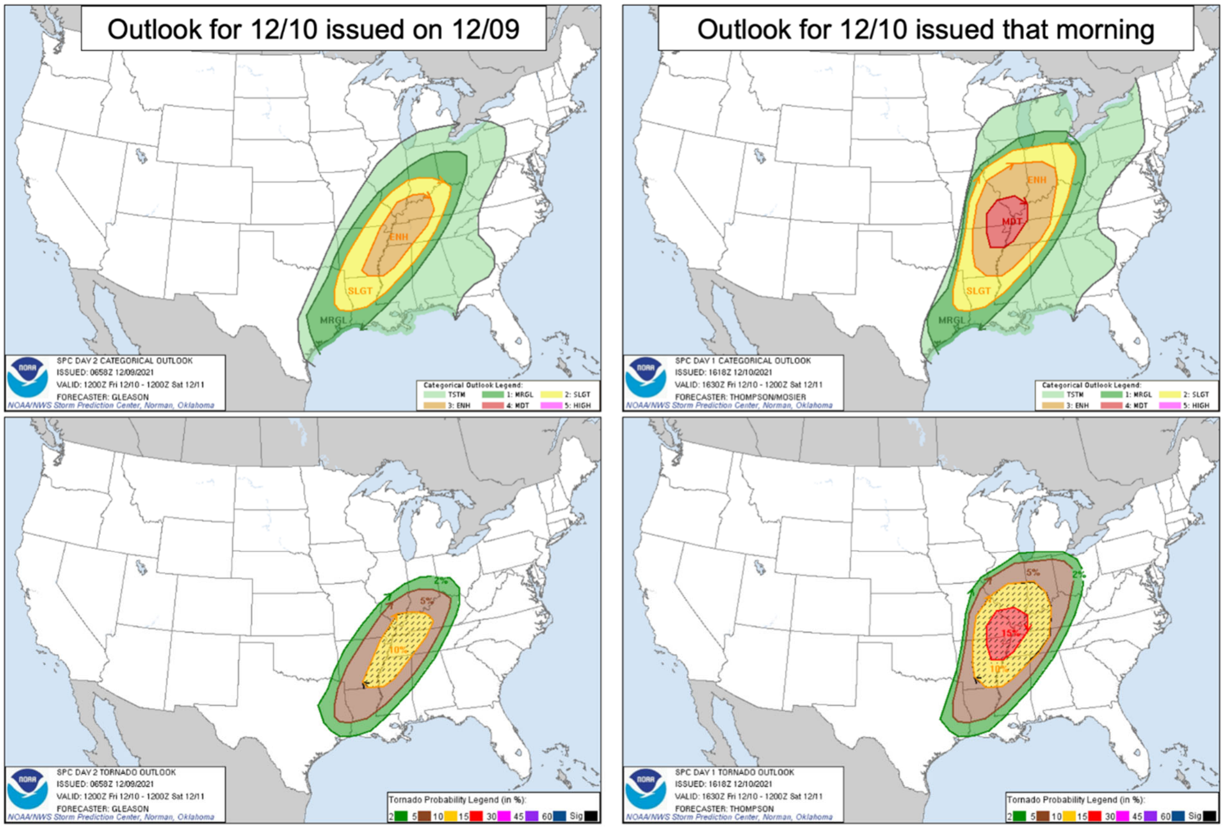


Figure 2.1. SPC-issued outlooks leading up to the events of December 10, 2021.

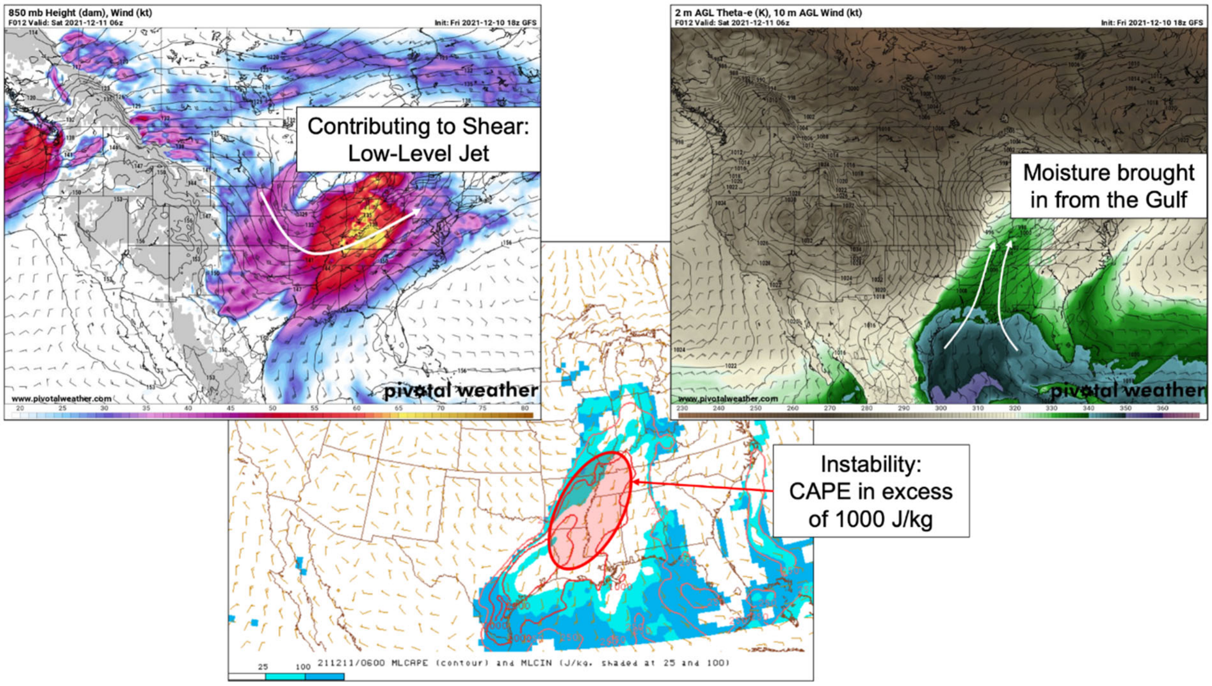


Figure 2.2. Atmospheric set-up leading into 10 December 2021 (via [Pivotal Weather]() and [SPC Mesoanalysis]()).

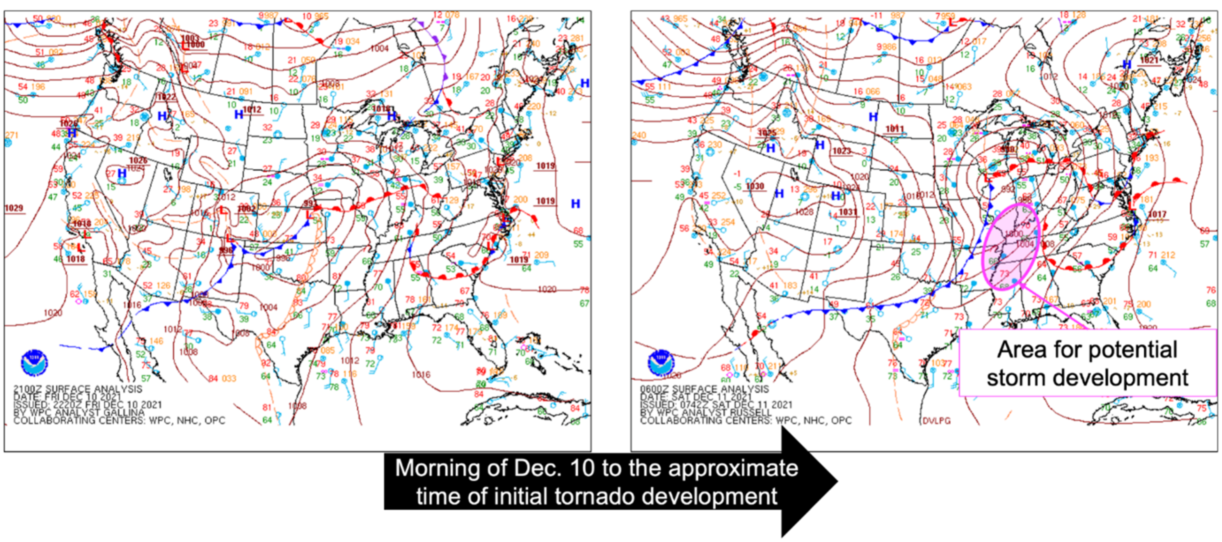


Figure 2.3. Formation of low-pressure system starting 10 December 2021 (from the Weather Prediction Center [Archive]()).

2.2 Severe Weather Occurrences

As anticipated from the atmospheric setup, severe weather scenarios initiated and Tornado Watches were issued covering nine states by 6:30pm CST (Fig. 2.4). Warnings were issued throughout the evening and overnight across eight states (Fig. 2.5), with one particular mesocyclone crossing four states (Fig. 1.1). As of 21 December 2021, the NWS had confirmed 66 tornadoes (Fig. 2.6), including two EF4 tornadoes with path lengths of 166 miles and 80 miles, respectively. A list of the tornadoes confirmed as of 21 December is provided in Appendix A. The majority of the events occurred overnight posing an enhanced risk to human life.

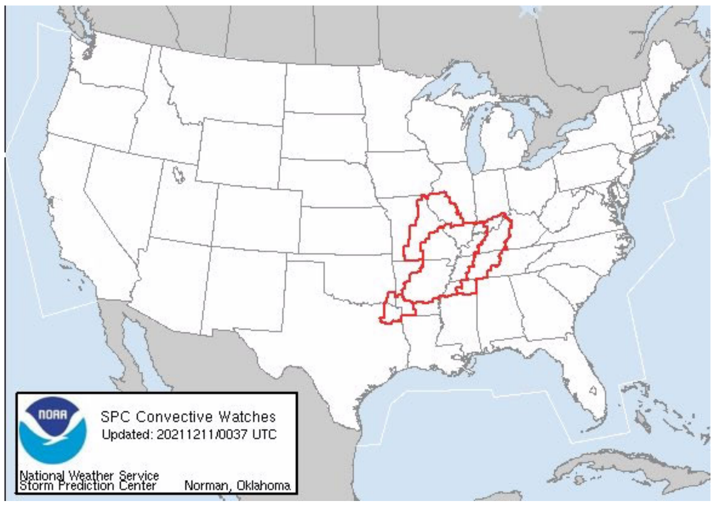


Figure 2.4. Tornado Watches issued as of approximately 6:30pm (CST) 10 December 2021 by the SPC.

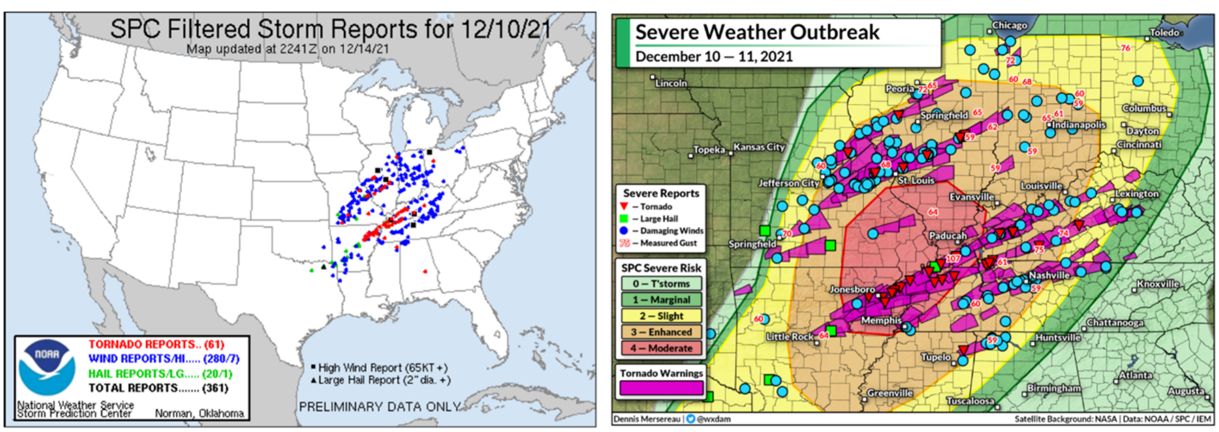


Figure 2.5. Storm Reports for 10 December from the SPC and overlapped with issued warnings and the convective outlook (DAMWeather).

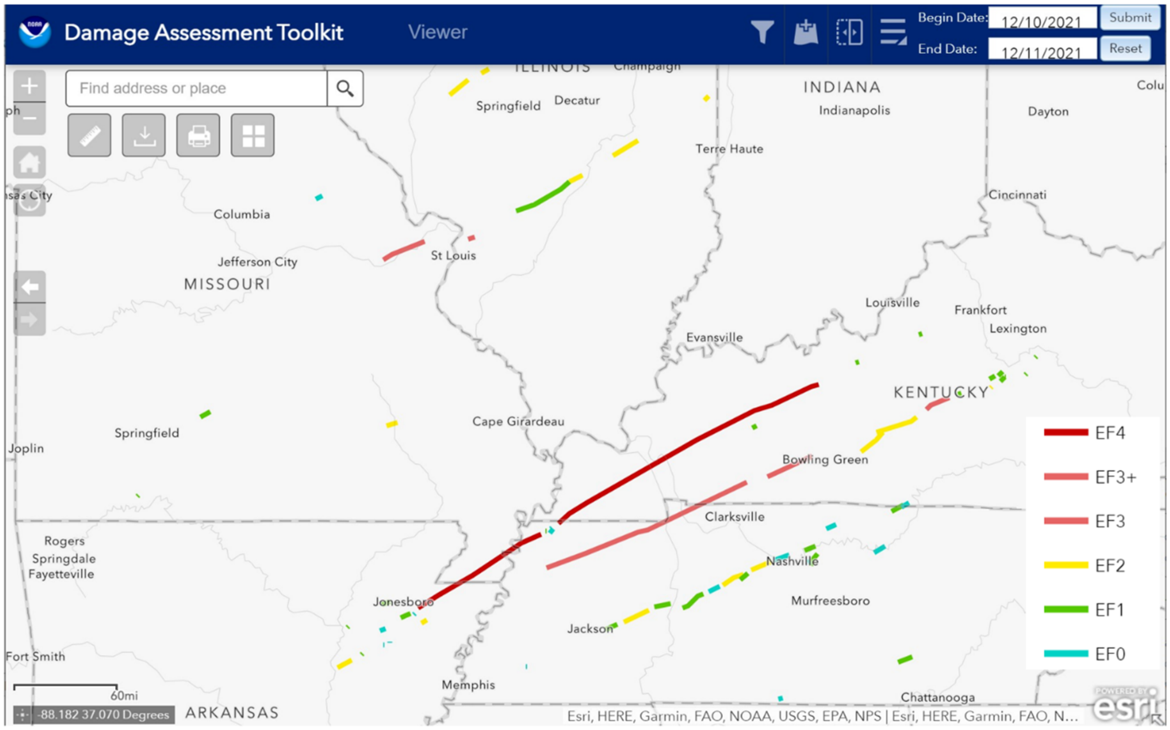


Figure 2.6. Preliminary tornado tracks identified by the various NWS offices, as reported in the NWS Damage Assessment Toolkit.

Notable in this outbreak was the so-called "Quad-State Tornado," which originated in Arkansas just after 8pm (CST) (NWS, 2021b) and traveled northeastward passing through Arkansas, Missouri, and Tennessee before reaching Kentucky (SPC, 2021b). NWS surveys later determined that the tornado briefly lifted in northwestern Tennessee, resulting in two separate long-track EF4 tornadoes. Figure 2.7 shows a radar image as this cell approached Mayfield, KY. A strong rotation signature and an apparent debris ball are present, which typically indicate a strong tornado on the ground.

This storm system continued overnight, bringing more warnings and tornadoes into Tennessee, Indiana, and further into Kentucky. At approximately 3:00am CST, the Nashville, TN area had multiple tornado warnings and apparent rotation signatures (Fig. 2.8).

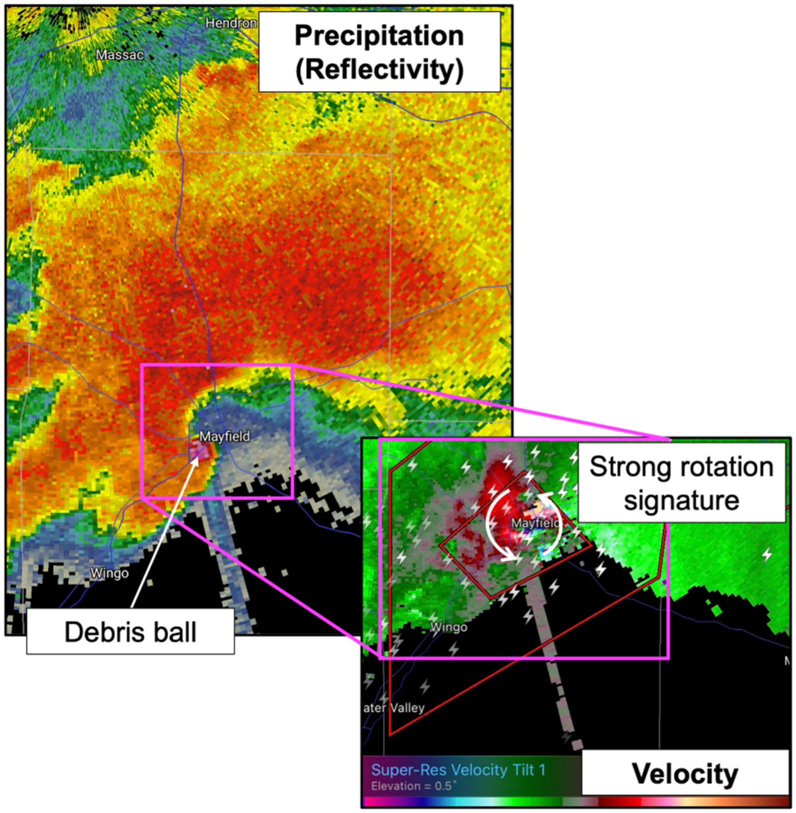


Figure 2.7. Radar image of the Mayfield tornado from 10 December 2021 (Screen captured from the RadarScope smartphone app).

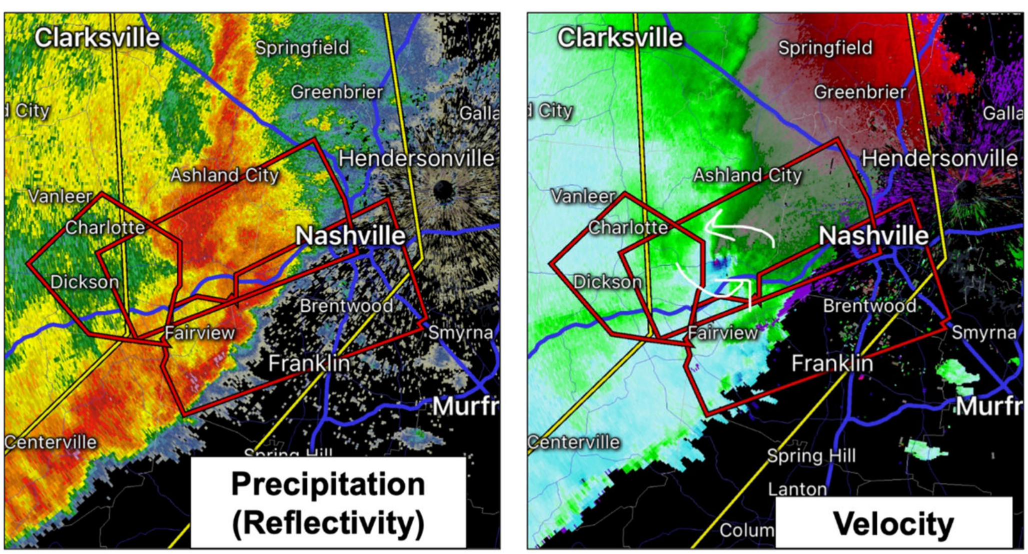


Figure 2.8. Radar image of tornado warnings approaching Nashville, TN at 3:00am CST on December 11, 2021 (Screen captured from the RadarScope smartphone app).

3.0 Local Codes and Construction Practices

The impacts of tornado outbreaks on society are not dictated entirely by the hazard, but also by society's level of preparedness, from early warning systems and sheltering protocols to well-prepared emergency response, which all are ultimately necessary based upon the performance of the built environment and the decisions made (or not) to harden lifelines and adopt risk-consistent construction well before storms arrive. This section examines the decisions that ultimately guided construction practices in Kentucky. This discussion rightfully acknowledges the historical neglect of tornadoes in building codes and standards.

Although this outbreak focused much attention on the powerful EF-4 tornadoes in the sequence, of the 66 tornadoes confirmed by the NWS in this outbreak, only 10 had damage categorized as EF3 (N=6) or EF4 (N=4) strength. In fact, research affirms that tornado losses are more often driven by EF0-EF2 tornadoes with estimated peak 3-second gust wind speeds of 135 mph or less. These EF0-EF2 tornadoes occur much more frequently than more powerful EF3-EF5 tornadoes. Moreover, even when EF3+ tornadoes strike, a minority of the tornado's path is actually exposed to wind speeds exceeding 135 mph (Levitan, 2021). Thus, most structures built to meet the wind demands in coastal counties per ASCE 7-10 conceivably could have the capacity to withstand typical tornado winds without suffering catastrophic failure. *Proven strategies exist to mitigate the majority of tornado losses in the US* (FEMA, 2010).

3.1 Kentucky's Regulatory Environment

The evolution of building codes for structures within the Commonwealth of Kentucky over the past 40 years is summarized in Table 3.1. Before 1980, various editions of the National Building Code were enforced by local jurisdictions, but there was no statewide building code mandate. Discussion to improve the regulation of the building industry initiated around 1974 and resulted in the formation of the Division of Building Enforcement in 1980, as part of the Kentucky Department of Housing, Buildings and Construction (Furnish, 2009).

The first statewide building code – the Kentucky Building Code (KBC) – was adopted in 1980, based on the 7th edition of the Basic Building Code published in 1978 by the Building Officials and Code Administrators (BOCA). Between 1980 and 1996, seven subsequent editions of the KBC were adopted based on various editions of the BOCA Basic Building Code and BOCA National Building Code (NBC).

In 2002, the basis for the 8th edition of the KBC transitioned for the first time to the International Building Code (IBC) published in 2000 by the International Code Council (ICC). In that same year Kentucky also published the Kentucky Residential Code (KRC), which was based on the 2000 International Residential Code (IRC). Since that time, KBC and KRC have continued to adopt ICC model code editions. The current Kentucky Building Code (2018), first edition, is based upon IBC 2015 and was adopted on 1 January 2019. The previous edition was based on the 2012 IBC/IRC and was effective from 1 January 2014 until 31 December 2018.

Note that the KBC and KRC apply to new buildings; the International Existing Building Code (IEBC) is referenced and applies to existing buildings. The IEBC indicates that changes or upgrades to existing buildings are not required to comply with the current code unless there is a change of occupancy, addition, significant repair or renovation.

The transition from using locally-enforced BOCA model building codes to the statewide adoption of IRC/IBC codes was a significant step towards consistency in enforcement and in improving wind-resistant design. Because the ICC codes rely upon the minimum design load provisions of respective editions of ASCE 7, once adopted it assures uptake of state-of-the-art knowledge when determining wind loads. Unfortunately, ASCE 7 historically had only limited impact in tornado-prone regions since it focused exclusively on straight line (non-tornadic) winds.

Table 3.1. Building code history for Kentucky, as compiled by the FLASH InspectToProtect tool.

Code Edition	Years in Effect
1978-1981 Basic Building Codes	1980 - 1985
1984 Basic National Building Code	1985-1987
1987-1996 National Building Codes	1988 - 2001
2000 IRC / IBC	2002 - 2007
2006 IRC / IBC	2007 - 2013
2012 IRC / IBC	2014 - 2018
2015 IRC / IBC	2019 - present

3.2 Storm Shelter Regulations

Around 2012, storm shelter regulations became part of the KBC, requiring that storm shelters meet the quality and performance standards of the ICC 500 standard (ICC, 2020). This standard specifies a design wind speed of 250 mph. Note that at this point KBC did not mandate storm shelters, but rather regulated their design for those who voluntarily employed them. Later in 2015, a KBC provision mandated storm shelters for all schools with occupancies of 50 or more persons, though it is unlikely that most residents would have access to such shelters on short notice.

3.3 Design Wind Speeds

Design Wind Speeds are derived from respective versions of the ASCE 7 standard, whose adoption in Kentucky became somewhat more regulated over time under the ICC process. The current 3-second gust basic design wind speed in Kentucky is 115 mph for ordinary buildings, homes, and businesses (based on ASCE 7-10), used with a 1.0 load factor for strength design and a 0.6 factor for allowable stress design. For large buildings having occupancies of 300 persons or more and critical facilities (Risk Category III), and for essential and hazardous facilities (Category IV), the 3-second gust basic design wind speed is 120 mph. Prior to the adoption of ASCE 7-10, the state of Kentucky, like most states outside of hurricane-prone regions, had a 90 mph design wind speed (per ASCE 7-05) with a 1.6 load factor for strength design and 1.0 load factor for allowable stress design. In terms of wind pressures on a structure, ASCE 7-05 and ASCE 7-10 produce effectively the same result.

To put these values in perspective, an EF4 tornado would conservatively produce wind loads that are approximately twice the design wind loads specified by ASCE 7-10. Moreover, the vast majority of existing structures were built in Kentucky before it adopted ICC model codes (and thus drew its loading provisions from ASCE 7).

3.4 The History of ASCE Tornado Design Provisions - Paradigm Shift

It is coincidental timing that in the same month of this outbreak, ASCE 7-22 was published with its first-ever guidance on tornadic winds (published as ASCE 7-22 in December 2021)[2]. Although

[2] Introduction to the new Tornado Loads Chapter 32: https://www.youtube.com/watch?v=XvjcW1y7x94.

ASCE 7-22's new Chapter 32 on Tornado Loads requires checking if tornado loads govern only if the building/structure is Risk Category III and IV buildings/structures in tornado-prone regions, building owners and designers should recognize that these are *minimum standards* and thus provisions can voluntarily be extended to all buildings, including the Risk Category II buildings such as single and multi-family residential structures that sustained some of the most significant damage during these tornadoes.

However, prior to this edition of the standard, building codes and design load standards had remained silent about design for tornado loads, with ASCE 7 acknowledging that "tornadoes have not been considered in developing the basic wind-speed distributions." This position was justified in ASCE 7-10 Commentary Clause C26.5.4: "It is recognized that tornadic wind speeds have a significantly lower probability of occurrence at a point than the probability for basic wind speeds. In addition, it is found that in approximately one-half of the recorded tornadoes, gust speeds are less than the gust speeds associated with basic wind speeds." This position was reinforced by the comparatively low annual fatality rate for tornadoes: 3.0 per 100,000 persons in 1974, dropping to 0.8 by 2020 -- 1-2 orders of magnitude smaller than other leading causes of death in the US such has homicide, suicide and cancer. Improvements in weather forecasting and sheltering guidance can be credited with the reduced fatality rates.

In 2011, when nearly 260 persons were killed in just two tornado outbreaks (Tuscaloosa, April, and Joplin in May) and the annual cost of damage from severe storms approached $200 billion, the public began to question the life-safety philosophy of building codes that would allow large swaths of communities to be destroyed by moderately strong winds (120-140 mph). Since then, exposure in tornado-prone regions has increased, including rapid growth of single-family housing neighborhoods in the southeastern US. So, while the fatality rate from tornadoes reduced annually, the nominal cost of damage to buildings steadily rose (NOAA, 2021). According to Aon (2021), U.S. losses in severe storms have totaled at least $10 billion each year since 2008, placing the insurance industry in a particularly perilous position. This has placed renewed emphasis on reducing the number of billion-dollar weather and climate related disasters in the US, adopting a building code performance standard that is inclusive of both human safety and rational (cost effective) loss reduction.

4.0 StEER Response Strategy

StEER activated its VAST for the Midwest Tornado on 11 December 2021, which worked to assemble information on the event from public sources, while StEER simultaneously formed a specialized regional FAST. The VAST was charged primarily with collecting early intelligence on the tornadoes and their impacts that would (1) inform a hybrid PVRR-EARR and (2) feed priority targets to the FAST once deployed.

The FAST strategy centered on swiftly deploying regional StEER members to collect rapid assessment data using street-level panoramic imaging technologies, Unmanned Aerial Vehicles (UAV), Light Detection and Ranging (LiDAR) scans, and door-to-door (D2D) forensic engineering assessments in Kentucky. All team members were located within drivable distance from the impacted sites and all arrived in Calvert City, the selected base of operations, less than 72 hours after the tornadoes touched down. In total, the FAST consisted of team members, including David Roueche and Jordan Nakayama (Auburn University), Mohammad Alam (University of Notre Dame), Andrew Lyda (NHERI RAPID EF at the University of Washington), and Mariant Gutierrez Soto, Rebecca Napolitano, Muhammad Saleem, and Saanchi Kaushal (Penn State University), who coordinated with a team led by Frank Lombardo (University of Illinois Urbana-Champaign) working on complementary investigations in the region. Teams conducted full-day assessments on 14-15 December. Additional data was collected on the morning of 16 December before inclement weather prevented further data collection efforts.

The FAST prioritized the following objectives: (1) street-level panoramic image collection throughout key impacted municipalities in Kentucky, specifically Mayfield, Cambridge Shores, Buena Vista, Princeton, Dawson Springs, Bremen, and Bowling Green (see Fig. 1.1a); (2) UAV imaging in downtown Mayfield (dense collection of engineered and non-engineered structures) and Buena Vista (potential topographic effects) suitable for generating 3D models using Structure from Motion (SfM) techniques; (3) D2D throughout Mayfield; and (4) detailed case studies of important structures, including the collapsed water tower in Mayfield, the University of Kentucky Grain and Forage Center of Excellence in Princeton, the East Marshall fire station, and several residential structures. Each of these objectives were associated with the long-track tornadoes passing through Kentucky. Deployments to sites of interest in other states were considered, but were ultimately not activated due to rapid cleanup (e.g., the Amazon facility in Edwardsville, IL), lack of proximity to the regional response teams, and timing restrictions due to inclement weather that approached on 16 December.

Table 4.1 summarizes the geographies surveyed by the FAST. Note that data collection was impacted on 14 December 2021 (road access, issues with the streetview hardware, and difficulty securing FAA approval for UAV flights), 15 December 2021 (no-fly zone imposed by the Presidential visit), and 16 December 2021 (inclement weather). These issues impacted the pace, but not quality, of data collection.

Table 4.1. Geographic Coverage of FAST

14 December 2021	<u>Mayfield, KY</u> ● Street-level panoramas in downtown Mayfield and surrounding areas ● UAV panoramas of downtown Mayfield, forensic assessment of buildings downtown (FNB Bank, Fire station, Hargrove and Foster) ● LiDAR scan of Mayfield water tower ● D2D assessments of structures surrounding water towers, multi-family residential buildings near Mayfield Health and Rehabilitation Center, and northeast Mayfield single and multi-family residential buildings <u>Princeton, KY</u> ● Street-level panoramas and forensic assessment of targeted sites, including University of Kentucky Agriculture Center of Excellence <u>Dawson Springs, KY</u> ● Street-level panoramas of entire town
15 December 2021	<u>Mayfield, KY</u> ● Street-level panoramas around Candle factory ● UAV panoramas over Mayfield, extending from downtown and to the west ● D2D assessment along W Walnut St., S 9th St., S 10th St., W Water St., N and S 8th St., W South St., W North St. and W Broadway <u>Cambridge Shores/Buena Vista, KY</u> ● Street-level panoramas in Cambridge Shores & Buena Vista ● UAV imaging and D2D assessments in Buena Vista

	East Marshal Fire Station and Water Tower, KY ● Forensic assessment and LiDAR scan of Marshall County Fire Station ● LiDAR scan of adjacent standing water tower Princeton, KY ● Street-level panoramas and D2D assessment of Princeton residential community ● LiDAR scan of University of Kentucky Agriculture Center of Excellence
16 December 2021	Bremen, KY ● Street-level panoramas and targeted D2D Bowling Green, KY ● Street-level panoramas

5.0 Reconnaissance Methodology

The following subsections provide details of the data collected by the FAST during the mission sequencing described in Section 4.

5.1 Street-Level Panoramic Imaging

The FAST employed two NCTech iStar Pulsar+ streetview cameras (one provided by the RAPID Facility and one by Auburn University) and a Labpano Pilot One. The NCTech Pulsar used in this investigation consists of four cameras mounted together to gather a 360 x 145 degree field of view. Each camera has a resolution of 12.3 MP, sensor size of 3042x4062, and uses fisheye lenses with fixed focus and aperture size of f/2.6. GNSS-tracking via a U-BLOX Neo M8N receiver geotagged each image location with ~2.5 m accuracy. Frames were captured at 30 frames/second along the routes driven, capturing near-continuous coverage of exterior building performance. The Labpano Pilot One was deployed in a limited capacity in Bremen, KY on 16 December as weather conditions prevented the use of the Pulsar. The Labpano Pilot One uses four Sony CMOS 12 MP sensors and F2.28 aspherical, optical fisheye lenses to capture 7680x3840 pixel (30 MP) panoramas at up to 24 frames/second. While the resolution of the Pilot One is about half that of the Pulsar, the Pilot One is waterproof, which allows it to collect data even in adverse weather conditions. See Appendix B for driving routes used in data collection (see Table B.1).

5.2 Unmanned Aerial Vehicles

UAV deployments were limited because of FAA flight restrictions associated with search and rescue efforts in Mayfield on 14 December and the president's visit to Mayfield on 15 December. Despite these logistical challenges, FAA approval was obtained for a small window of time from the afternoon of the 14th to the morning of the 15th that allowed several flights to be completed in Mayfield and in Cambridge Shores/Buena Vista. The Mayfield imagery was captured using a double-grid flight pattern flown by a DJI Phantom 4 RTK at an altitude of 230 ft, covering the collapsed water tower and extending into the downtown regions. The imagery captured was later processed into a 3D point cloud using SfM techniques. Five panoramic images were also captured in downtown Mayfield by a DJI Mavic 2 at altitudes of ~ 100 ft above ground level and processed into a virtual tour. In Cambridge Shores/Buena Vista, a DJI Mavic 2 was used to capture a double-grid flight pattern suitable for construction of a 3D point cloud. See Appendix B for additional details of UAV flights (Table B.2).

5.3 Door-to-Door (D2D) Performance Assessments

D2D performance assessments were conducted throughout Mayfield and for select case studies in Buena Vista, Princeton, and Bremen. These employed StEER's Fulcrum smartphone application: *StEER Building - US (Windstorm) App*, acquiring geotagged photos, recorded audio and other relevant metadata. A total of 154 D2D assessments were completed. Case studies included the collapsed Mayfield water tower, the Mayfield fire station, the Mayfield Health and Rehabilitation Center, the East Marshall County Fire Station, buildings on the campus of the University of Kentucky Grain and Forage Center of Excellence, and multiple single- and multi-family residences. This Fulcrum data is open access and can be viewed at StEER's website. StEER members can also access the full data dashboard to further interrogate this data by logging in at FulcrumApp.com with their credentials. Note that these data have not yet been processed by the StEER Data Enrichment and Quality Control (DEQC) protocol.

5.4 LiDAR Scans

Terrestrial LiDAR was deployed on a limited basis for case studies of the Mayfield water tower (7 scans), the East Marshall County Fire Station (6 scans), the East Marshall County water tower (3 scans), and the main building of the University of Kentucky Grain and Forage Center of Excellence (20 scans). Site locations are summarized in Appendix B (see Table B.3). All LiDAR scans were completed using a Leica RTC360, which captures both High-Dynamic Range (HDR) imagery and 3D point clouds, captured using medium scanning resolution (6 mm point density at 10 m from scanner).

5.5 Other Ground-Based Imagery

Several Android, iPhone and DSLR cameras were used to shoot imagery with locations logged via the internal GPS system when available. These representative photographs were captured outside of Fulcrum and used to augment the FAST Daily Summaries and provide higher resolution photographs for case study structures. The geotagged photos will be made available on DesignSafe under project PRJ-3349.

6.0 Damage to Buildings

The following sections overview the performance of buildings during the tornadoes occurring on 10 December, 2021 and overnight into the early hours of 11 December, 2021. This is not intended to be exhaustive, but rather to emphasize those building classes/occupancies most commonly impacted and/or showing uniquely relevant damage or superior performance. Within each subsection, a synopsis of performance reported through publicly-available sources is first presented (e.g., 6.1.1), followed by observations from the StEER FAST (e.g., 6.1.2). Interested readers can access the accompanying Media Repository in DesignSafe Project PRJ-3349, which includes additional visual evidence organized by occupancy.

FAST conducted D2D assessments of 153 residential, institutional and commercial buildings in the Kentucky communities of Mayfield, Cambridge Shores, Princeton, Dawson Springs, and Bremen (see locations in yellow in Fig. 1.1a). Assessments were concentrated in clusters within the areas of the tornado path with highest damage, focusing on instances where damage revealed visible details of the structural load path, while also highlighting success stories (buildings with less damage than surrounding buildings). Street-level panoramas were relied upon to capture the exterior performance of structures in the periphery of the tornado path, where the structural load path could not be observed. Destroyed structures included residential, institutional and commercial buildings, both engineered and prescriptively-designed, of timber, steel, concrete and masonry in both single-story and multi-story configurations. The resultant distribution of damage ratings was assigned using definitions described in the StEER FAST Handbook (Kijewski-Correa et al., 2019), and provided in Table 6.1. The undamaged structures in Table 6.1 are located in Mayfield and included a multi-family, single-story masonry building surrounded by damaged buildings, as well as a single-story, masonry commercial building near the edge of the tornado path. While peak wind speeds from NWS will be assigned to each record as part of StEER's Data Enrichment and Quality Control (DEQC) process, each building's location relative to the estimated tornado path can be a proxy for the severity of winds on site.

Table 6.1. Distribution of damage ratings in FAST D2D Assessments

Undamaged	Minor Damage	Moderate Damage	Severe Damage	Destroyed	Total Surveyed
2	24	28	28	71	**153**

Notably, the destruction of buildings observed along the track of the Quad-State tornadoes was, in many ways, on a par with the worst damage witnessed by the authors after prior tornadoes, including the very deadly 2011 tornadoes (Tuscaloosa EF4 and Joplin EF5). A telling sign in this outbreak is the condition of vegetation surrounding buildings, with the FAST noting splintering of tree trunks at mid-height and stripping of branches from the trunk, all reminiscent of the landmark 2011 tornadoes.

Within the survey of what may be construed as catastrophic damage particularly among single-family residential structures, there are notable "success stories" in performance. As such, the subsections that follow highlight typical damage, as well as success stories. Not included in this section are two high-profile case studies: the Amazon Distribution Center in Edwardsville, IL and the Mayfield Consumer Products candle factory. These case studies are mass casualty events that require more in-depth investigation. There was limited information available in the media concerning the specifics of these structures, and the Amazon facility could not be surveyed by the FAST due to the swift clean up; the candle factory was only rapid-imaged using street-level panoramas since access was restricted by local officials.

6.1 Single-Family Residential Buildings

6.1.1 Synopsis of Reported Performance

Residential construction was among the most severely impacted building classes in this event, with over 1,000 homes destroyed across Kentucky (Center for Disaster Philanthropy, 2021). Some of the most heavily impacted regions (Mayfield, Cambridge Shores, and Bowling Green) consist of homes with a median year-built of 1948-1979, while homes in areas just outside of Bowling Green have a median year built of 1976-2005 (per U.S. Census, 2021). For example, Figure 6.1.1 shows a neighborhood of relatively new homes in Bowling Green, where the damage gradient indicates proximity to strongest winds. As of 23 December 2021, this tornado has been classified as an EF-3 (NWS, 2021c). Figure 6.1.2 provides an aerial perspective on the damage to residences in Buena Vista.

Figure 6.1.1. EF-3 tornado track through Bowling Green highlighting damage gradient to either side of the track (source: CNN news Clinton Lewis)

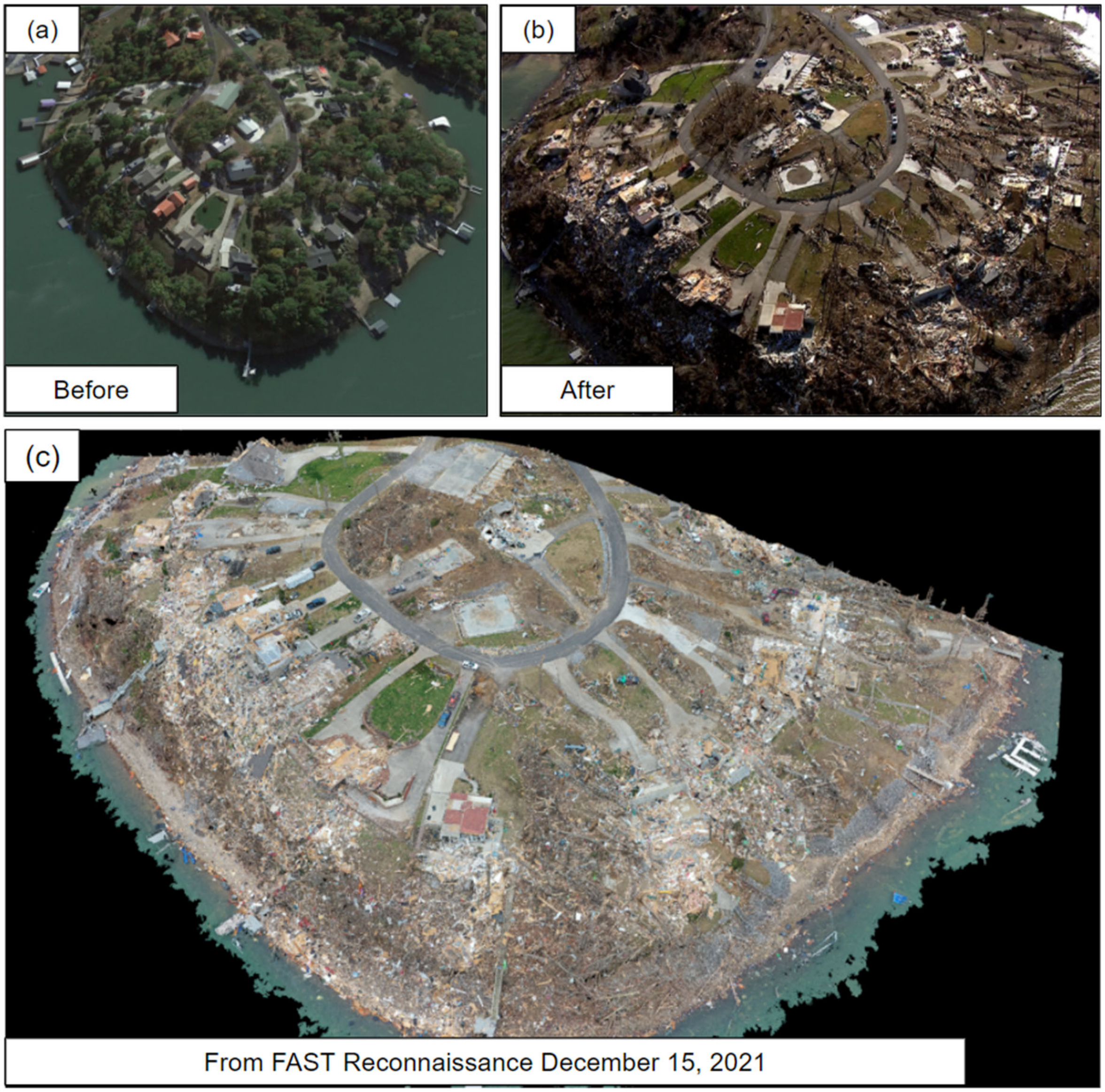


Figure 6.1.2. Buena Vista aerials (a) before the 10 December tornado (via Google Earth); (b) afterward (Scott Eckhardt via Twitter); (c) 3D densified point cloud of Buena Vista created from UAV images captured by the FAST.

6.1.2 FAST Field Observations

In Mayfield, Princeton, Dawson Springs, and Bremen, the FAST noted that the majority of the homes were older building stock with little to no wind uplift load path. Figures 6.1.3-6.1.4 offer representative images of FAST-observed performance of single family residences in Princeton and Mayfield. Most homes were wood-frame, constructed atop unreinforced masonry piers and stem walls, with wood platforms forming the substructure.

Figure 6.1.3. Representative residential damage and debris found in Mayfield, KY, including (a) varying damage levels, from no visible damage to complete collapse, evident in a cluster of wood-frame homes in close proximity to each other; (b) loss of the roof structure and windows blown out in a two-story home with a large pile of debris in front of it; and (c) debris piles in front a row of homes that suffered primarily building envelope damage. (Images acquired by the FAST).

Figure 6.1.4. Representative damage to single-family homes in Princeton, KY along (a) Dogwood Ln (Lat: 37.0808, Long: -87.8984), and (b) Country Club Ln (Lat: 37.0781, Long: -87.9052), showing wood-frame structures with roof structure failures and subsequent wall collapses. (Images acquired by the FAST).

FAST documented many roof-to-wall and wall-to-foundation connection failures (Fig. 6.1.5) of residential structures in the targeted locations (see locations in yellow in Fig. 1.1a). Most roof-to-wall connections, where they could be observed, consisted of (3) 16d (0.165-inch diameter by 3.5-inch long) toe-nails from the roof truss/rafter to the wall top plate. The wall-to-foundation connection failures were structurally the result of an inadequate connection either of the sill plate to the masonry stem wall or of the bottom plate of the stud walls to the subfloor. Anchor bolts were observed in slab-on-grade construction, but were not found in any homes constructed on masonry stem walls, nor was there any evidence of grout-filled cells in the concrete masonry units. As a result, the majority of homes towards the center of the tornado path suffered structural damage, including loss of the roof structure, wall collapse, or shifting off the foundation. One success story however, shown in Figure 6.1.6, was an exception to this trend. This home was built in 2001 and, unlike surrounding homes, used metal straps that wrapped around the roof trusses and secured them to the wood stud wall (Fig. 6.1.7). Foundation anchorage could not be observed due to the lack of damage. Although the home was surrounded by other homes and structures that suffered severe roof structure damage and even collapse (including an adjacent collapsed water tower), this home only suffered damage to the building envelope, with ~50% of the roof cover removed, multiple windows blown out, and wind-borne debris impacts to the walls. The collapsed water tower and severe structural damage to the buildings surrounding this home suggest that the enhanced load path used in this home was key to its comparatively successful performance, but further analysis is needed to reveal whether any other factors (e.g., micrometeorological) played a part.

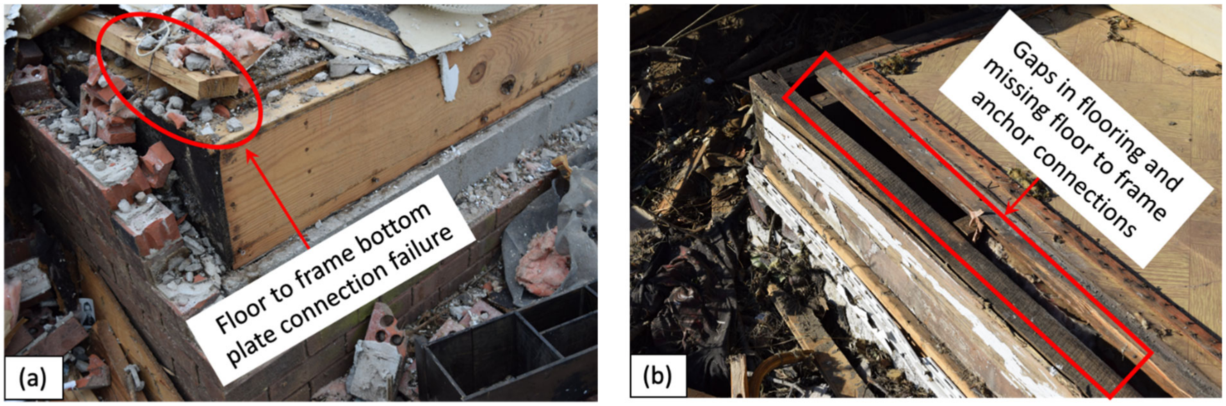


Figure 6.1.5. Common wall-to-foundation connection failures; (a) removal of the bottom plate from subfloor and wall studs from bottom plate in a Princeton home due to reliance on nailed connections in withdrawal; (b) removal of the bottom plate and stud walls from the wood-frame floor platform in a downtown Mayfield home due to reliance on nailed connections. (Images acquired by the FAST).

Figure 6.1.6. Single-family residence with building envelope damage 200 ft down-path of the collapsed water tower in Mayfield. The home had been constructed with hurricane straps that wrapped over the top of the wood trusses and connected them to the wood-frame walls. (Images acquired by the FAST).

Figure 6.1.7. Steel strap wrapping around a truss to secure it to the wood-frame wall in a home adjacent to the collapsed water tower in Mayfield, KY. (Photo taken by the FAST).

6.2 Multi-Family Residential Buildings

6.2.1 Synopsis of Reported Performance

There are several reports of severe damage or complete destruction of multi-family structures. For example, a two-story apartment building in Dawson Springs completely collapsed, but was lacking any substantial anchorage to the foundation (Tim Marshall via Facebook). Other multi-family structures suffered almost complete removal of their roof structures, exposing the top floor occupants and their contents to extensive damage and potential injuries.

Figure 6.2.1 illustrates another multi-family residential example, the Cardinal Motel in Bowling Green, which was built in the 1960s and includes apartments (Autry, 2021). This hotel was impacted by the EF-3 tornado (NWS, 2021c) and sustained roof damage, including the loss of its lobby entry carport, and blown out windows and doors.

Figure 6.2.1. Before and after imagery of the Cardinal Motel located in Bowling Green following EF-3 impact (Sources: Google Street View at 1310 U.S. 31 W Bypass, Bowling Green, KY 42101 (Lat: 36.9813, Long: -86.4424) and Twitter Gunnar Word, AFP)

6.2.2 FAST Field Observations

The FAST documented the performance of several multi-family residential buildings in Mayfield (Fig. 6.2.2), including the Windhaven Apartments and Mayfield Manor Apartments (both in the northeast area of Mayfield), and Mayfield Garden Apartments (southwest area of Mayfield). Damage varied considerably within these different communities including loss of roof shingles, roof structure failure, and collapse of exterior walls, as illustrated by the damage ratings, assigned by FAST in Figure 6.2.3, overlaid atop post-event aerial imagery (3-inch ground sample distance) provided by the Florida State University Center for Robot-Assisted Search and Rescue. Figure 6.2.4 shows the locations of the apartments relative to the other D2D assessments and the approximate tornado centerline through Mayfield, which is the preliminary NWS estimate modified slightly to better match the damage patterns visible in the FSU aerials.

Within the Windhaven Apartment complex, an undamaged building was surrounded by other damaged buildings, some of which lost their entire roof structure. Each of these buildings were single story, rectangular wood-frame structures with gable roofs and brick masonry cladding. The FAST noted the buildings were constructed with 2x4 Spruce-Pine Fir stud walls (16-inch stud spacing), anchored to the slab foundation with ½-inch anchor bolts, nuts, and washers (anchor bolt spacing could not be observed). Roofs consisted of 2x4 metal-plated wood trusses (Southern Yellow Pine) anchored to the walls with hurricane clips and 6d nails, although the clips only had three nail holes and multiple clips were observed with missing nails. Further, the clips only attached to the upper of the double top plates in the stud walls, and wall sheathing only lapped the lower of the double top plates, resulting in the failure plane between the upper and lower top plates (Fig. 6.2.5). Attention to detail, training and inspection are needed to eliminate these weaknesses in the load path even when anchor bolts and metal clips/straps are present.

The Mayfield Manor Apartments, which were constructed with light steel framing performed well as a whole. One building in the complex, shown in Figure 6.2.6, was destroyed (roof uplifted and several exterior walls collapsed). However, buildings in the same apartment complex across the street (approximately the same distance to the tornado center as the damaged building -- see Fig. 6.2.3 and Fig. 6.2.4), and presumably with the same construction, performed well structurally. Presuming these buildings all had the same load path and detailing, the causal factors may be non-structural, with site features suggestive of the role of tree falls or debris from adjacent damaged buildings, and warrants further analysis.

Figure 6.2.2. Examples of damage to multi-family residential structures in Mayfield: (a) Windhaven Apartments (two-story units) (Lat: 36.7447, Long: -88.6297), (b) Windhaven Apartments (one-story units), (c) Tree impact on the Mayfield Garden Apartments (Lat: 36.7350, -88.6436). (All images acquired by the FAST).

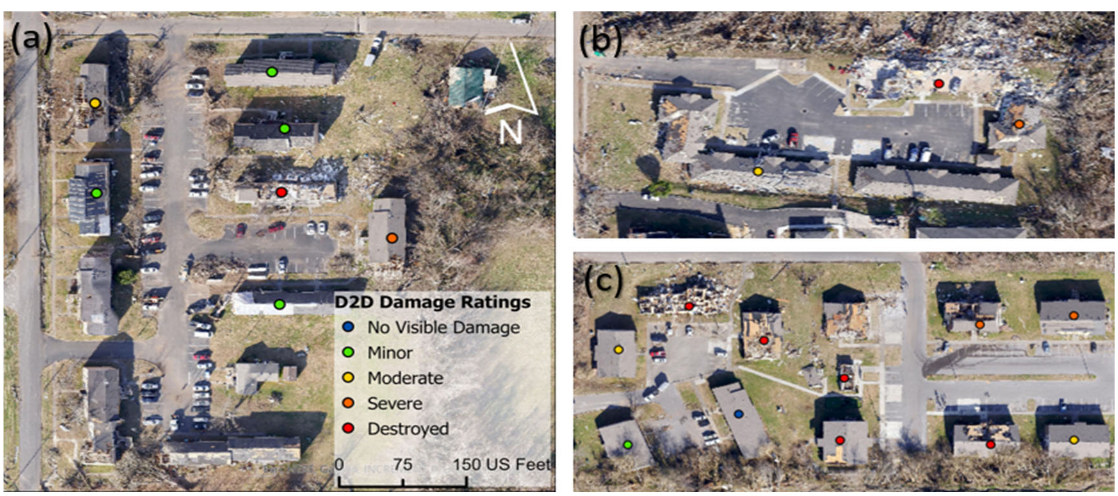


Figure 6.2.3. Variability in performance of multi-family residential buildings captured by FAST D2D assessments in Mayfield overlaid atop post-tornado imagery sourced from the Florida State University Center for Robot-Assisted Search and Rescue: (a) Mayfield Garden Apartments (Lat: 36.7350, -88.6436), (b) Windhaven Apartments (Lat: 36.7447, Long: -88.6297), and (c) Mayfield Manor Apartments (Lat: 36.7463, -88.6329).

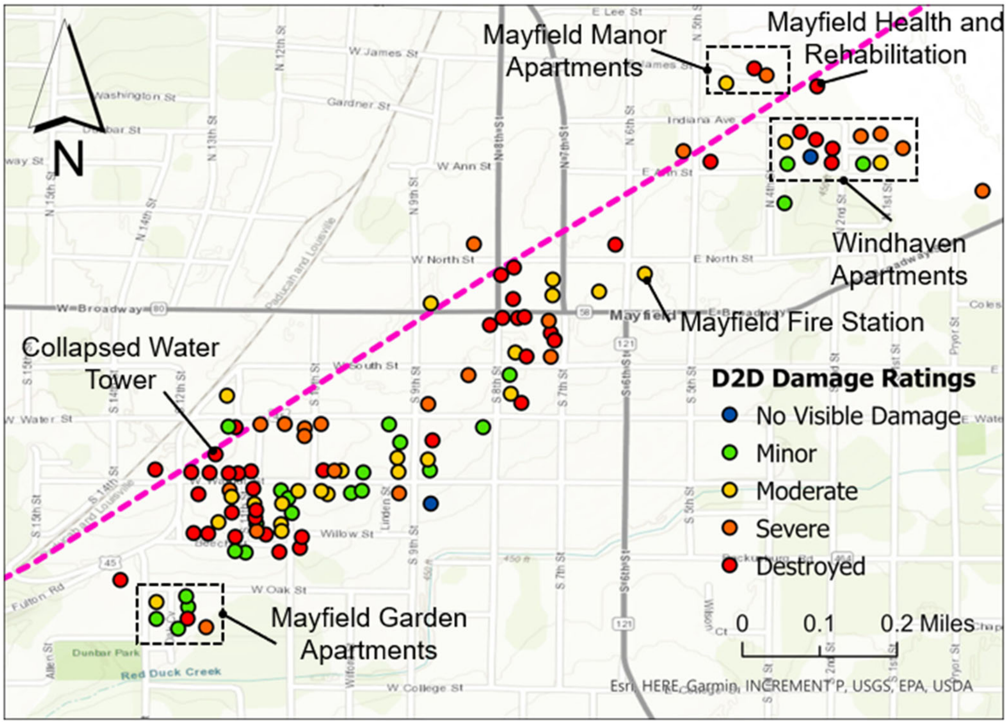


Figure 6.2.4. Assessed apartment complex locations within Mayfield relative to an approximate tornado track centerline (pink dashed line) and select points of interest.

Figure 6.2.5. Roof-to-wall failure occurring via separation of the upper and lower top plates of the stud wall of a unit at the Windhaven Apartment complex (Lat: 36.7452, Long: -88.6313). Removal of the upper of the two top plates was observed around the perimeter of the structure (Image acquired by the FAST).

Figure 6.2.6. Collapse of a cold-formed steel framed unit at the Mayfield Manor Apartments in Mayfield, KY (All images acquired by the FAST).

6.3 Commercial & Institutional Buildings

6.3.1 Synopsis of Reported Performance

The Mayfield Downtown Commercial District was added to the National Register of Historical Places in 1984 and expanded to include additional buildings in 1996. A number of historical load bearing masonry commercial and institutional buildings in this district were significantly damaged in the tornado, as documented in the Media Repository in DesignSafe (PRJ-3349) and the photo essay by Simms (2021). Notable among these for their institutional value to the community are the Mayfield Electric and Water Systems building constructed in 1955 (Fig. 6.3.1), the Mayfield US Post Office (Fig. 6.3.2), and the Graves County Court building constructed in 1888 (Fig. 6.3.3), all three of which were listed on the National Register of Historic Places. Notably, the original square section of the Post Office was constructed in 1910 as a one-story building with a clay-tile truncated hip roof. In the 1960s, the two additional wings were added with flat built-up roofs[3]. The majority of the 1910's masonry building remained intact, with damage concentrated in the 1960s additions.

[3] https://npgallery.nps.gov/GetAsset/0b4a0412-7137-404b-9399-62acd04d01b5

Figure 6.3.1. Before and after images of the Mayfield Electric and Water Systems building (Lat: 36.7419, Long: -88.6329) on East Broadway, Mayfield (source: Lexington Herald Leader).

Figure 6.3.2. Before and after images of the Post Office (Lat: 36.741, Long: -88.6383) on West Broadway in Mayfield (source: Lexington Herald Leader). Note complete loss of all visible fenestration.

Figure 6.3.3. Damage to the 133-year-old Graves County Courthouse (Lat: 36.7413, Long: -88.6352) building (a) before, (b) after damage, and (c) aerial view of destroyed tower (source: CNN and NY Times).

6.3.2 FAST Field Observations

FAST assessed the performance of multiple institutional and commercial structures, particularly within Mayfield. In general, wind-resistant detailing was lacking in these structures. No brick ties were evident in several buildings with brick cladding loss (e.g., Figure 6.3.4). Unreinforced concrete masonry walls, both load bearing and infill, collapsed in multiple structures (Fig. 6.3.5b). While hurricane ties were used to secure the wood trusses of the FNB bank to its top plate, separation was again observed at the interface between the upper and lower top plates even when the hurricane ties held (Fig. 6.3.6). More detailed analysis of these structures is warranted, using the data collected by the FAST.

Figure 6.3.4 St. Joseph Catholic School at 702 W Broadway (Lat: 36.7411, Long: -88.6442), Mayfield with failure (or lack) of brick veneer ties to the backup CMU (Photo taken by the FAST).

Figure 6.3.5. Examples of failure modes in commercial structures located at 715 E Broadway (Lat: 36.7442, Long:-88.6278) in Mayfield (All images acquired by the FAST).

Figure 6.3.6. Roof-to-wall connection failures at the FNB bank (Lat: 36.7419, Long: -88.6350) in downtown Mayfield (Photo taken via UAV by the FAST).

Multiple buildings on the campus of the University of Kentucky (UK) Research and Education center in Princeton were damaged, the most notable being the Grain and Forage Center of Excellence. This multi-story combination of steel frame and concrete masonry unit (CMU) block building was originally constructed in the 1980's, but underwent a significant expansion in September 2019, including the addition of several new wings and a two-story multipurpose space with large equipment access (20,000 square feet) (see designer site and construction photos). Located directly in the path of the tornado, this building was destroyed, with the roof and exterior walls in all but two wings severely damaged or collapsed (see aerial view in Fig. 6.3.7). One of the newly added corner buildings survived. This may be attributed to the adoption of modern codes and structural separation of the new addition from other existing buildings (see Fig 6.3.8b). However, the other new additions at the opposite side of the existing building suffered severe damage or collapse. A sharp wind speed gradient was likely present across the width of the building, evidenced by the standing trees and light poles on the left side of the image, aligned with the still standing new wing of the building. Detailed investigation will be needed to ascertain the factors behind better performance of this new addition compared to its collapsed neighbors and StEER LiDAR scans can assist in this regard. Figures 6.3.9-10 provide a closer view of damage and collapse of the industrial roof trusses of the structure, respectively.

Figure 6.3.7. Looking west at the University of Kentucky Grain and Forage Center of Excellence (Lat: 37.1007, Long: -87.8536) in Princeton, KY (source: UK website).

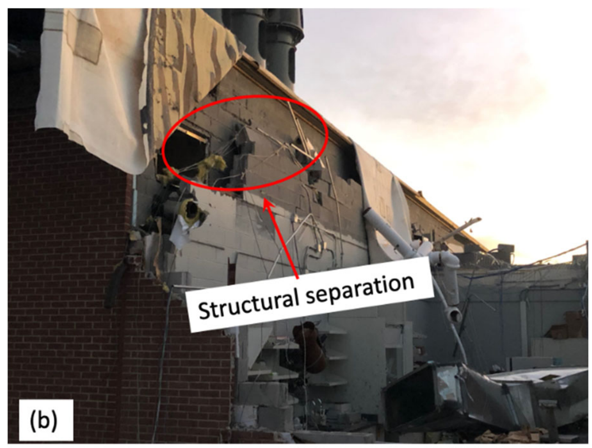


Figure 6.3.8. (a) Undamaged new addition (Lat: 37.1003, Long: -87.8530), which is the left-most building in Figure 6.3.7, and (b) structural separation of the new addition from the collapsed existing structure of the University of Kentucky Grain and Forage Center of Excellence in Princeton (Images acquired by the FAST).

Figure 6.3.9. A closer view of destruction in the Grain and Forage Center of Excellence at the University of Kentucky Research and Education Center (Source: KATIE PRATT, The Paducah Sun).

Figure 6.3.10. Collapse of light metal industrial roof trusses of UK Research and Education Center in Princeton, new building (Image acquired by the FAST).

6.4 Critical Facilities

6.4.1 Synopsis of Reported Performance

A number of critical and essential facilities were severely damaged by the tornadoes, including multiple fire stations (specifically in Trumann, AR, Samburg, TN, Fulton, KY, Mayfield, KY and Gilbertsville, KY), a court house in Mayfield, KY, and nursing homes in Monette, AR and Mayfield, KY. The performance of the court house in Mayfield has already been described in Section 6.3, and the performance of fire stations in Mayfield and Gilbertsville and the nursing home in Mayfield were documented by the FAST as discussed in Section 6.4.2.

The Monette Manor nursing home, a 90-bed nursing home in Monette, AR (Fig. 6.4.1), was a particularly notable critical facility with significant potential for injury and life loss. The building, with a reported 1973 "life safety code" (see Arkansas Department of Human Services), suffered complete roof structure loss and partial wall collapse. While the majority of residents survived (one fatality occurred, along with five reported injuries), with many sheltering in the facility's hallways (Washington Post, 2021), the occupants' high vulnerability and limited mobility underscore the need to consider retrofitting such existing facilities with storm shelters, as any inclusion of storm shelter requirements in current or future building codes would apply only to new construction.

Figure 6.4.1. Before and after imagery of the 90-bed Monette Manor nursing home in Monette, AR (Location: 669 Hwy 139 North, Monette, AR 72447 (Lat 35.9008, Long: -90.3421)), Sources: Google maps (left, top), Brian Emfinger / LSM (right, top), Eileen AJ Connelly from NY Post (left, bottom) The Commercial Appeal via USA TODAY NETWORK (right, bottom).

Among the numerous fire stations damaged by the tornadoes, the Cayce Volunteer Fire Department building in Fulton County is a classic example of a complete collapse (Fig. 6.4.2). Not only is the structure destroyed, but the firefighting equipment is unavailable for post-event search and rescue. This level of poor performance of an essential facility should not be tolerated by any community, particularly now that improved design standards are available for tornado design (ASCE 7-22, 2021). All such essential facilities damaged during this event should be required to rebuild or retrofit to the new Tornado Design requirements of Chapter 32 of ASCE 7-22, even if this new standard has not yet been adopted as part of their local building code, as discussed further in Section 8.

Figure 6.4.2. Damage to Cayce Volunteer Fire Department building (Lat: 36.5551, Long: -89.0326) in Fulton County, rendering emergency equipment inoperable (source: FirefighterCloseCalls.com).

6.4.2 FAST Field Observations

FAST documented in detail the performance of two fire stations: Mayfield Fire Department Station 1 in Mayfield and East Marshall District Station 1 in Gilbertsville. The Mayfield fire station lost its wood-framed roof structure, had all windows and doors blown out on the west elevation, and one door blown out on the east elevation. The roof structure consisted of 2x8 Southern Pine trusses, anchored to the wood-frame walls with hurricane ties (Fig. 6.4.3). While the roof trusses were blown off the building to the north of the building footprint, an interior flat roof structure, supported by steel beams and interior columns, still remained in place, visible from the interior of the structure. The police station located just south of this damaged fire station survived with minimal visible damage, but details of the structural load path were not observable by the FAST.

Figure 6.4.3. Mayfield Fire Department Station 1 at the corner of E. North Street and N. 6th Street in Mayfield (Lat: 36.7424, Long: -88.6342). (Top) Pre-tornado view of the building from Google Streetview; (Bottom Left) post-tornado view of the structure taken by the FAST and (Bottom Right) details of the hurricane clips used to tie the roof structure to the walls captured by the FAST.

The East Marshall District Station 1, in Gilbertsville, was a light steel framed building that lost all its roof cladding and had some of its exterior walls blown out (Fig. 6.4.4). No evidence of buckling or other permanent deformations was observed in the rigid steel frames or purlins, but multiple LiDAR scans were taken of the facility for further analysis. The standing seam metal roof was attached to the Z-purlins using flexible metal ties of some kind, but details could not be discerned while on-site. The fire station had an emergency generator next to the main structure, which remained intact, though it is unknown whether it was used.

Figure 6.4.4. East Marshall District Station 1 (Lat: 36.9232, Long: -88.2476). (a) Exterior doors were blown in and all roof cladding uplifted; (b) LiDAR scans were collected inside and outside the building; (c) roof panels were attached to the roof structure through flexible ties that were fastened to the top flange of the z-purlins. Failure occurred at the connection between the flexible tie and the roof panel. All images acquired by the FAST.

Figure 6.4.5 shows the before and after image of Mayfield Health and Rehabilitation Center located at Indiana Ave in Mayfield, which opened in 1978. It is one of the three nursing homes serving Mayfield. The other two nursing homes were not in the tornado path. The 'X' -shaped one-story structure of Mayfield Health and Rehabilitation Center is composed of a CMU block load bearing wall with brick cladding and light steel roof truss system. It has no basement. The structure experienced severe damage to its four wings (see Fig. 6.4.5), resulting from loss of roofs and exterior walls due to wind and falling trees. The center junction of the four wings, where the nurses station was located, experienced minor damage. The majority of the residents sheltered within this central location and all of the 74 residents survived (Musgrave, 2021). Figures 6.4.6-7 show the observed component-level damage (walls, roofs, falling ceiling) to one of these wings.

Figure 6.4.5. Damage to the Mayfield Health and Rehabilitation Center (Lat: 36.7459, -88.6309) in Mayfield, KY. (Shared by Manny Perotin from the GIC Grey Skies platform).

Figure 6.4.6. Damage to one wing of the Mayfield Health and Rehabilitation Center (Image acquired by the FAST).

(a)

(b)

Figure 6.4.7. A closer view of damage to the Mayfield Health and Rehabilitation Center: (a) loss of roof and exterior CMU wall with brick cladding, and (b) falling roof ceiling panels and other debris. (Sources: (a) acquired by the FAST, (b) from Mayfield Health and Rehabilitation Center Facebook page).

6.5 Religious Institutions

6.5.1 Synopsis of Reported Performance

Reports suggest the most severe damage to religious institutions was documented in Mayfield. As an illustrative example, the masonry churches on South 9th St. and West Broadway in Mayfield exhibit varying damage levels (Fig. 6.5.1), which may have been a result of their respective distances from the tornado path. The dome structure and the roof of the first Christian church had collapsed (Fig. 6.5.1b), while the first Presbyterian church completely collapsed (Fig. 6.5.1d). One fortunate aspect of nighttime tornadoes is the fact that large assembly buildings like these were not in use.

Figure 6.5.1. Damage to churches in Mayfield: (a) First Christian Church on South 9th Street (Lat: 36.74086, Long: -88.6389) before and (b) after tornado, and (c) historic First Presbyterian Church (Lat: 36.7420, Long: -88.6389) on West Broadway before and (d) after tornado (source: Kentucky.com).

6.5.2 FAST Field Observations

The FAST acquired on-site imagery at a third church, the First United Methodist Church, in Mayfield. The main sanctuary of this historic structure was constructed in 1919. Walls consisted of multiple wythes of brick masonry, while the roof structure consisted of timber rafters. The church suffered the loss of its roof structure over the majority of the building, along with the collapse of the exterior walls of the main sanctuary. The church appears to have a basement, but whether it was affected by the above-ground damage or would have been a safe shelter option had the church been occupied is unknown.

Figure 6.5.2. Damage to First United Methodist Church (Lat: 36.7399, Long: -88.6366) in Mayfield, KY. Images acquired by the FAST.

6.6 Safe Rooms

Because of the lack of tornado design for most existing buildings in the US, storm shelters are encouraged as a refuge during tornado warnings. A number of storm shelters appear to have survived in spite of the building around them being completely demolished. Figure 6.6.1 shows three examples of successful shelter performance, all of which were visited by the FAST. The underground shelter (Fig. 6.6.1c) was commercial, but the manufacturer could not be identified. The two above-ground shelters (Figs. 6.6.1a-b) were both "home-built" but performed well. The residential shelter (Fig 6.6.1a) was constructed with CMU with unknown reinforcement to form the walls, while an approximately 4-inch concrete slab formed the roof. The shelter within the attorney's office (Fig. 6.6.1b) appeared to be constructed with reinforced concrete shear walls, while also using an approximately 4-inch concrete roof slab. In these two above ground shelters, the FAST could not evaluate the details of the structural design for ICC 500 compliance, but the door hardware was confirmed to not meet the requirements[4]. A 24-gauge wood-edge steel door complying with ASTM E330 (+/- 70.5 psf static air pressure resistance) and frame was used in the shelter shown in Figure 6.6.1a (Fig. 6.6.2). No deadbolt was present - only a typical interior door knob. The above-ground shelter shown in Figure 6.6.1b used a steel door and frame of some kind, but no labeling was visible to indicate ASTM compliance, and again, only an interior door knob was used with no deadbolt (Fig. 6.6.3). Both the shelters in residences were occupied during the tornado outbreak; with the underground shelter (Fig. 6.6.1c) occupied by nine persons and two pets, and the above-ground shelter (Fig. 6.6.1a) occupied by at least one of the home's residents. Whether the shelter in the attorney's office was used during the tornado is unknown.

Performance of these and other storm shelters during this and other tornado events could assist in the promotion of storm shelters for superior protection during future tornadoes. Further, since two of the documented storm shelters were "home-built," the development of open-source designs and construction guidance compliant with ICC 500 standards in a suite of sizes, configurations and price points can support self-recovery efforts.

[4]Requirements for door hardware used in safe rooms and storm shelters are summarized in FEMA (2021).

Figure 6.6.1. (a) Homeowner shows surviving home-built “safe room” at 44 Perry Lane, Bremen, KY (Lat: 37.3729, Long: -87.2200) after the 10 December Tornado outbreak. This safe room was constructed after a tornado destroyed this same home in 1988 (source: Twitter), (b) a safe room in Hargrove & Foster, an attorneys’ office building at Mayfield, KY (Lat: 36.7429, -88.6347) (source: FAST UAV), and (c) a pre-fab underground shelter, which safely housed 8 people and 2 dogs during the tornado at Berman, KY (exact location unknown) (source: WHAS11 News).

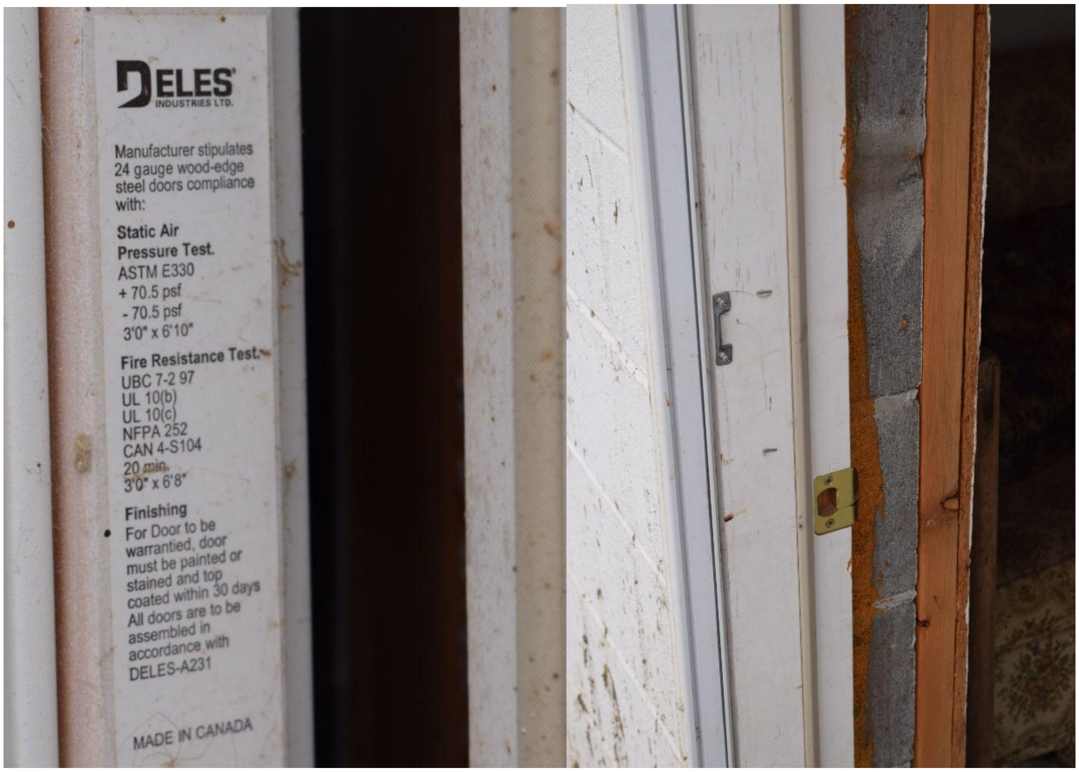


Figure 6.6.2. Door and hardware for the "home-built" shelter in Bremen shown in Figure 6.6.1(a) (Photos acquired by the FAST).

Figure 6.6.3. Door hardware for safe room in attorney's office building shown in Figure 6.6.1(b) (Photos acquired by the FAST).

7.0 Damage to Infrastructure

7.1 Power and Telecommunications Infrastructure

The New York Times (2021) compiled data from PowerOutage.us and reported that approximately 200,000 customers were without power as of 9 am on 11 December across the impacted states shown in Figure 7.1.1. The damage to Mayfield was particularly extensive and rebuilding the electric-power network infrastructure is anticipated to take weeks to months according to Kentucky Emergency Management Director Michael Dossett (Powell, 2021). As of 24 December, approximately 979 customers are still without power, with 82% of the city re-energized (Mayfield Electric and Water Systems).

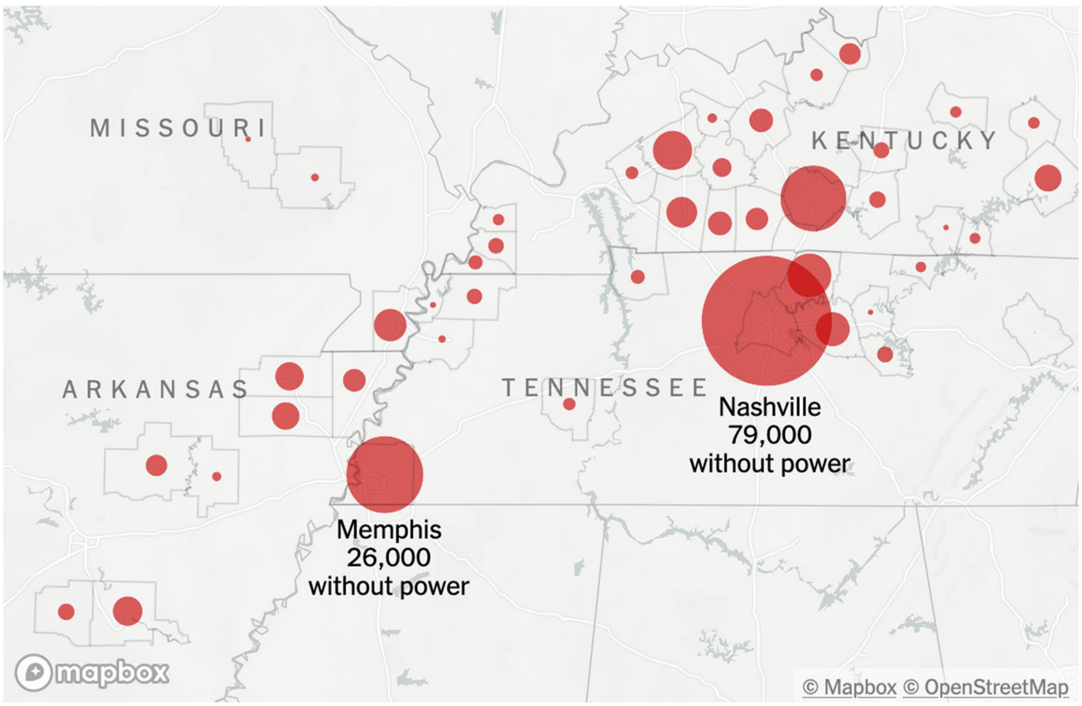


Figure 7.1.1. Power outages reported as of 9am on 11 December 2021 across the states affected by tornado outbreak. Size of circles proportional to the number of affected customers in each outlined jurisdiction (Source: NY Times).

7.2 Water Infrastructure

The water infrastructure in Mayfield was significantly impacted following the 10 December tornado outbreak. An electric substation that powered pumps was severely damaged and forced to run on emergency generators to supply low-pressure water to residents (Fuller, 2021). A boil water order (lifted on 17 December) was issued while repairs were made to the substation as well as the wastewater treatment plant. As of 21 December the Hickory water district was still under a boil water advisory (Mayfield Electric and Water Systems).

A 500,000-gallon water tower on 12th Street in Mayfield was completely destroyed by the tornado (Fig. 7.2.1). Images from the FAST reconnaissance (Fig. 7.2.1 c-d) reveal that not only were supports completely removed from the footings, but the concrete footings themselves were partially lifted out of the ground. This water tower underwent $374,000 in renovations during Fall of 2016 (Mayfield Electric & Water Systems News).The FAST documented that the eight main support columns of the water tower were constructed from ½-inch thick steel, each welded to a 1.5-inch thick steel base plate that was anchored to a concrete footing with (2) ~1.18-inch diameter steel rods (~1.36-inch thread diameter) shown in Figure 7.2.2. The cause of the failure, beyond simply experiencing high wind speeds, is not obvious at this point. No evidence of large mass debris impacts to the columns was observed, or deep corrosion or other maintenance issues that would suggest a premature failure. The debris was shifted to the southeast from the original footprint of the water tower but lies in a southwest to northeast orientation. Further analysis is needed to inform possible collapse scenarios. Seven LiDAR scans and additional field measurements collected on site will support additional investigations to determine the collapse sequence.

Figure 7.2.1. (a) Water tower in Mayfield (Lat: 36.7389, Long:-88.6425): (a) before and (b) after 10 December tornado (source: Chris Jackson on Twitter) with a closer evaluation of footings during the FAST assessment (c & d).

Figure 7.2.2. Shearing of one anchoring rod and pullout of another at one of the eight support footings for the Mayfield water tower (Image acquired by the FAST).

A second water tower was inspected in Marshall County, in the Cambridge Shores area (GPS 36.9240, -88.2474). The tower did not collapse but did have a large dent (diameter ~3.5 m) near the top of the water tank. No obvious large debris object was noted nearby. Measurements taken on site suggested the structural details of this water tower were the same or at least very similar to the Mayfield water tower. Three LiDAR scans were taken at this undamaged tower for comparison to the collapsed tower.

7.3 Agricultural Infrastructure

A number of grain silos in Kentucky were impacted by windborne debris and/or sustained damage through loss of metal sheeting as shown in Figure 7.3.1. Total destruction of accessory steel structures and grain elevators was observed. In Monette, AR, severe damage to farm structures was also observed, including the full removal of roofs. Collapse of masonry walls and bent steel roof trusses were observed (Ryan Quarles via Twitter).

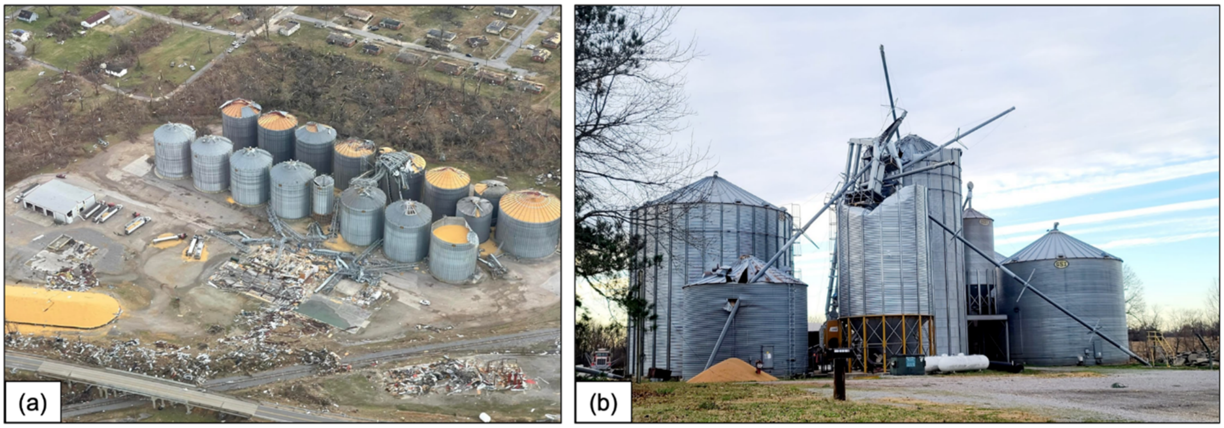


Figure 7.3.1. (a) Aerial view of damage to grain silos (NAPSG Crowdsourcing) (Lat: 36.7339, Long: -88.6477) and (b) damage caused by grain elevator collapse (NAPSG Crowdsourcing) in Fulton County.

8.0 Recommendations for Further Study

The FAST utilized rapid imagery capture methods to document accessible areas in Mayfield and other affected communities in Kentucky, including street-level panoramic imaging, UAV deployments, LiDAR scans of notable case studies, and forensic load path assessments, with particular emphasis on structures where details of the load path were visible. The timing of data collection allowed a number of sites in Mayfield to be documented before extensive demolition/debris removal, though some sites were still restricted due to recovery efforts. The panoramas will be particularly valuable to inform additional investigations and forensically reconstruct the tornadoes' tracks through multiple communities. This may identify additional "success stories" as well as case studies suitable for on-site assessment. Furthermore, StEER focused mainly on structural damage in select communities in Kentucky, leaving opportunities to assess the impacts of this outbreak in other areas/states. Future studies could also collect information on the recovery, reuse, recycling, and repurposing of materials salvaged from the sites. These studies could be in conjunction with NSF's SUMMEER and further enhance NHERI collaborations.

In addition to the re-use of StEER's data and/or extension of StEER's data collection efforts to other regions, the authors' preliminary review of data crowdsourced from public sources and observations by FAST members have led to the following recommendations for continued study:

- **TOPIC 1: Performance of essential and critical facilities**
  The poor performance of many essential and critical facilities such as fire/police stations and nursing homes during this tornado outbreak highlights a desperate need to review, evaluate and retrofit all essential and critical facilities in tornado-prone areas. With the newly available Tornado Loads Chapter 32 in ASCE 7-22, these buildings can be strengthened to meet or exceed the latest engineering guidance for tornado design. Research into cost-effective retrofitting options to meet the demands articulated in ASCE 7-22 will be vital to achieving improved performance of these facilities during future tornadoes and other high wind events, thereby enhancing the resilience of these communities. Increasing local agency to set performance standards (and ensuring the research is available to support decision-making related to these performance levels) is

critical, ensuring minimum standards are met while giving the local community the opportunity to define their preferred performance levels when armed with a clear understanding of the achievable performance levels and the direct and indirect impacts associated with them.

- **TOPIC 2: Safe Room performance**
  At least three safe rooms have been identified by FAST in buildings destroyed by the tornadoes. Two of these safe rooms were known to be occupied at the time of the tornadoes, likely saving lives and preventing injury to the occupants. The two above-ground shelters did not meet requirements of the ICC 500 Standard for the Design and Construction of Storm Shelters due to improper door hardware, but still performed successfully despite being struck by strong tornadoes. Performance of these and other storm shelters during this and other tornado events could assist in the promotion of storm shelters for superior protection during future tornadoes. Further, since two of the documented storm shelters were "home built," the development of open-source designs and construction guidance compliant with ICC 500 standards in a suite of sizes, configurations and price points can support self-recovery efforts.
- **TOPIC 3: Performance of critical infrastructure**
  The collapse of a water tower in Mayfield along with loss of power to water pumps led to a diminished water supply after the tornadoes; natural gas supply was also disrupted. Failure of other critical infrastructure such as power distribution systems is to be expected because these have not traditionally been designed for the higher wind speeds anticipated during tornadoes. Now that tornado loading and design guidance is available in ASCE 7-22, it would be valuable to study the applicability of these design provisions to critical infrastructure systems, determining potential retrofit options, with the view to improving community resilience.
- **TOPIC 4: Tilt-up structure performance**
  While not detailed in this report due to a lack of direct observations by the FAST, damage to large-volume warehouses and industrial buildings was reported. In many cases these are constructed using exterior precast concrete tilt-up walls with steel interior gravity columns supporting a light steel roof system. Such systems have little redundancy, enhancing the vulnerability to progressive collapses. Damage to the roof framing and/or its connection to the tilt-up panels due to wind uplift pressures combined with interior pressurization results in loss of lateral bracing for the tilt-up panels, leading to their out-of-plane collapse. Similar failures were observed to tilt-up structures in Hurricane Michael (2018) (Berman et al. 2020), and the 2020 Nashville, TN tornadoes, also documented by StEER (Wood et al., 2020). Anyone seeking shelter adjacent to these concrete panels are in grave danger. A synthesis of past performance of similar tilt-up wall construction during high wind events could lead to improvements in the design of these structures to enhance their capacity and ability to arrest disproportionate collapse.
- **TOPIC 5: Storage silo performance**
  Numerous grain silos experienced roof failure, presumably due to wind uplift, during these tornadoes. If the silos are full, the walls generally remain intact. However, empty silos often experience wall failure after losing their roof. Review of the uplift demand/capacity ratio and the roof-to-wall connection details of these structures could lead to improved design provisions to enhance future performance. Note that StEER was not able to forensically evaluate grain silos across the affected states, so additional data collection is required to fully document their performance and inform such an investigation.
- **TOPIC 6: Recovery Model Development**

Frameworks have been recently developed for measuring the resilience of the physical infrastructure. Within community resilience, increased robustness of physical infrastructure minimizes the initial damage that will later impact other interdependencies. Future studies could quantify how the affected communities recover from this event through targeted longitudinal studies, integrating StEER data as baseline observations to develop and/or calibrate recovery models for tornado outbreaks.

The following topics may not require additional engineering investigations, but represent areas of policy and practice concurrent with natural hazards engineering that are worthy of further investigation:

- **TOPIC I: Promoting Design for Tornadoes**
  The US can build upon the successful reduction of tornado fatality rates achieved by improved forecasting by similarly adopting improved technological capabilities in hazard engineering. From the demand side, this means creating political pressure to shorten the multi-year lag between new ASCE 7 standards and their adoption via ICC codes so that the improved knowledge in ASCE 7-22 (including Chapter 32 on Tornado Loads) benefits communities immediately. From the capacity side, this means promoting stricter fastener and load path requirements (proven effective in coastal areas at a very modest additional cost) in tornado-prone regions. Kentucky and neighboring states can use this event to build momentum as early adopters of ASCE 7-22's tornado standards, which has been a politically-challenging prospect (Flavelle, 2021). Identification of (i) the most appropriate policy mechanisms to mandate these changes or (ii) means to create the market conditions that would incentivize and reward voluntary investment in code-plus construction will be critical to reverse the mounting losses in these disasters across residential, commercial, and institutional buildings. Doing so swiftly is essential if "build back better" is to be achieved in the subsequent reconstruction efforts.
- **TOPIC II: Preservation of Life Safety in Tornadoes**
  The definition of Risk Categories in ASCE 7 and IBC is derived primarily from a structure's use, the number of persons it shelters, and assumptions regarding its contribution to community functioning. Collapse/severe damage to nursing homes, critical facilities, and warehouses/factories all posed life safety risks that warrant not only consideration of evacuation and sheltering protocols (Topic III) but also their design requirements. This event underscores that if there is a reasonable probability that lives will be lost in a structure, it should be designed to withstand a minimum level of tornadic winds from a life safety performance perspective and accompanied by in-building or in-community accessible sheltering (Topic IV) for tornadoes that exceed the design-level event, consistent with a dual-objective tornado design philosophy (van de Lindt et al., 2013).

  In the meantime, it is worth advocating not only for voluntary adoption of ASCE 7-22's Chapter 32 (Topic I), but also a more conservative risk category selection in the reconstruction (and future design in tornado-exposed regions). This advocacy should emphasize the agency of designers and their building owner clients to opt for higher risk categories based on special circumstances for that structure, its unique significance to a community, or out of a commitment to preserving life safety in tornadoes. For example, unless they store or handle hazardous materials, warehouses and factories are considered by ASCE 7 and IBC as Risk Category II (RCII) for structural design purposes. They would therefore be exempt from the requirements of the new ASCE 7-22 Chapter 32 on Tornado Loads, which is only required for RCIII (high occupancy and critical) and

RCIV (essential) buildings. However, when these RCII facilities are operating 24 hours a day, 7 days a week, there is a significant increase in the potential for loss of life or injury due to structural failure during tornadoes. The engineering definition of a warehouse, storage facility, or factory has not changed to account for recent shifts to a 24/7 consumer culture. Even facilities like nursing homes, depending on the number of occupants and degree of “assistance” required for their residents may be categorized as RCII buildings. However, these residents’ limited capacity for the stresses of pre-emptive evacuation and their fragile health warrants RCIII designations with on-site storm shelters, regardless of the number of residents.

- **TOPIC III: Public response to tornado warnings**
  Surveys of residents and workers in the affected areas can provide valuable information about the actions they took immediately upon hearing watches/warnings/sirens. Of particular interest is how warnings projecting nighttime tornadoes are deployed and heeded. Emphasis should be placed both on how individual households receive and respond to such warnings, as well as owner/operators of commercial and institutional buildings, who must weigh the impacts of disrupted operations with life safety. An opportunity is presented here to explore personal safety questions regarding the likelihood of a resident or worker being impacted during a tornado outbreak. An engineering/social science collaboration could delineate whether being at home or at work at the time of impact would influence how community members respond. The Natural Hazards Center’s Tornado Ready Quick Response Research program could be leveraged for such partnerships. Given the heightened attention to worker safety and evacuation/sheltering guidance in this outbreak (Ankel, 2021; Hampton, 2021), this event can be used to mandate a review of sheltering and evacuation protocols that consider not just when tornadoes are an imminent threat (sirens) but also modifying operations of businesses, institutions and large assembly buildings like churches preemptively when tornado outlooks project high levels of risk (watches to warnings). This warrants development of appropriate public education and advocacy campaigns.
- **TOPIC IV: Promotion of storm shelters**
  While preserving life safety under tornadic winds should be a minimum performance expectation (as argued under Topic II), extending design for tornadoes across building classes will still affect only new construction (unless there is the unlikely sweeping mandate to retrofit existing structures). Thus a parallel line of inquiry could explore how public awareness campaigns can be launched to promote retrofitting existing buildings with storm shelters (including RC II structures), as part of the recovery effort, or at minimum ensuring community storm shelters are constructed with sufficient capacity and geographic coverage to serve the immediate population. However, construction is not enough. The successful integration of communal shelters into the fabric of communities is equally essential, as highlighted in recent experience with other hazards like tsunamis, and thus warrants a study of how similar programs could be developed in tornado-affected communities so residents are aware of when and how to access these life-saving resources.

While these and other research topics are worthy of additional study, due to StEER’s mandate and the timing of clean-up relative to the approaching holidays, StEER does not anticipate deploying additional on-site FAST teams. The timing of this FAST was too soon to access some areas restricted by local authorities. Thus, StEER is eager to coordinate with other teams who decide to deploy, using RAPID funding or other funding sources, and strongly encourages them to make use of StEER’s archived data and where appropriate, share/coordinate their plans with StEER.

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Appendix A: Summary of Confirmed Tornadoes

Based on data compiled by the NWS as of 12/21/2021.

City	County	State	EF Rating	Est Max Wind Speed (MPH)	Path Length (Miles)
Mayfield & Dawson Springs	Fulton to Breckinridge	KY	EF4	190	165.7
Bowling Green	Warren to Edmonson	KY	EF3	165	30
Gordonsville, Hadley	Logan, Warren	KY	EF3	140	28
Saloma, Bradfordville	Marion, Taylor	KY	EF3	145	14.7
Rock Hill, Horse Cave	Edmonson, Barren, Hart	KY	EF2	130	16.6
Horse Cave, Summersville	Hart, Green	KY	EF2	125	24
Junction City	Boyle	KY	EF2	135	0.63
South Bowling Green	Warren	KY	EF2	115	6.1
MT Washington	Spencer	KY	EF1	95	1.5
Danville	Boyle	KY	EF1	110	3.63
Bradfordsville	Eastern Marion	KY	EF1	100	1.9

Chrisman Lane	Boyle	KY	EF1	93	0.61
Bryantsville	Boyle, Gerrard	KY	EF1	94	2.93
Hedgeville	Boyle, Gerrard	KY	EF1	110	1.93
Richmond	Madison	KY	EF1	90	--
Kirksville	Madison	KY	EF1		--
--	Hardin	KY	EF1		--
--	Garrard	KY	EF1		--
Defiance	Saint Charles	MO	EF3	165	21
Ellington	Reynolds	MO	EF2	130	6.3
Wellsville	Montgomery	MO	EF0	80	4.3
Niangua	Webster to Wright	MO	EF1	90	6.3
Branson West	Stone	MO	EF1	90	0.67
Edwardsville	Madison	IL	EF3	150	3.65
Ramsey, Herrick	Fayette, Shelby	IL	EF2	118	41.4
Virginia	Cass	IL	EF2	125	12.8

Windsor, Gays, Mattoon	Shelby, Moultrie, Coles	IL	EF2	125	15.8
Atterberry	Menard	IL	EF2	120	4.6
Chrisman	Edgar	IL	EF2	115	--
Cedar Lake to Crown Point	Lake	IN	EF0	80	4.8
Bay to Samburg	Craighead to Obion	AR, TN	EF4	170	80.3
Trumann	Poinsett	AR	EF2	130	--
Augusta to Overcup	Woodruff to Conway	AR	EF2	135	--
Diaz	Jackson	AR	EF1	100	--
Cary	Craighead	AR	EF1	100	--
Beedeville	Jackson	AR	EF1	110	--
Bay	Craighead	AR	EF0	65	--
7 ENE Fisher	Poinsett	AR	EF0	80	--
4 ESE Fisher	Poinsett	AR	EF0	80	--
Weiner	Poinsett	AR	EF0	65	--
Weldon	Jackson	AR	EF-Unknown		--

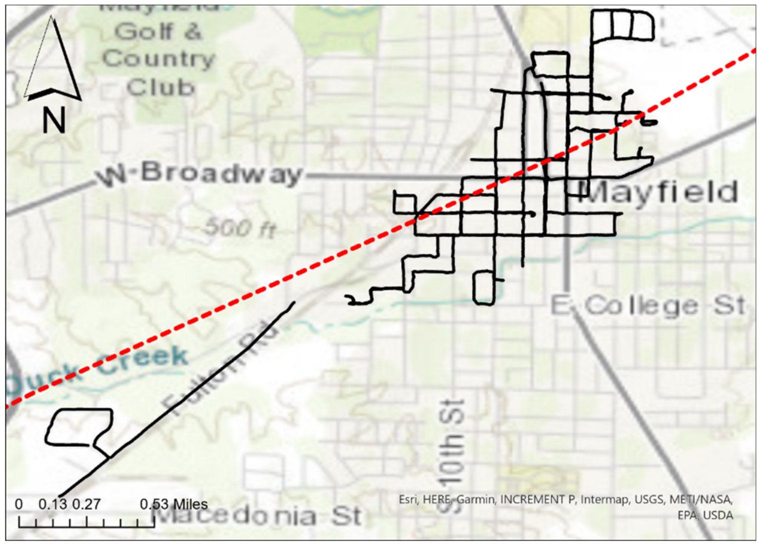
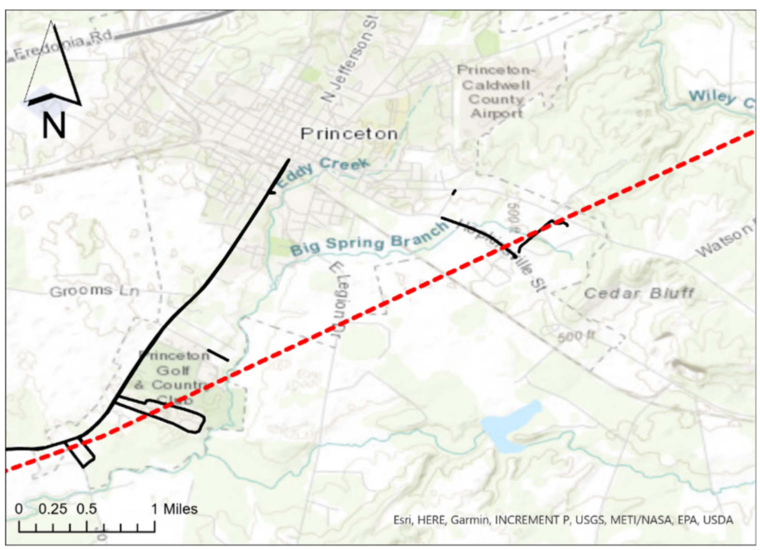
Newbern to Elkton	Dyer, TN to Todd, KY	TN, KY	EF3	160	122.7
Dickson to Burns	Dickson	TN	EF2	135	--
White Bluff to Pegram	Dickson to Cheatham	TN	EF2	125	--
Lexington	Henderson	TN	EF2	135	--
Samburg	Obion	TN	EF1	90	--
Jackson	Madison	TN	EF1	100	--
Holladay	Benton, Decatur	TN	EF1	90	--
Burns to White Bluff	Dickson	TN	EF1	110	--
Lobelville	Perry	TN	EF1	100	--
Hendersonville	Sumner	TN	EF1	95	--
Mount Juliet	Wilson	TN	EF1	105	--
Hermitage Springs to Hestand	Clay, TN to Monroe, KY	TN, KY	EF1	105	--
Coalmont	Grundy	TN	EF1	90	--
NW of Centerville to SW of Dickson	Hickman to Dickson	TN	EF0	85	--

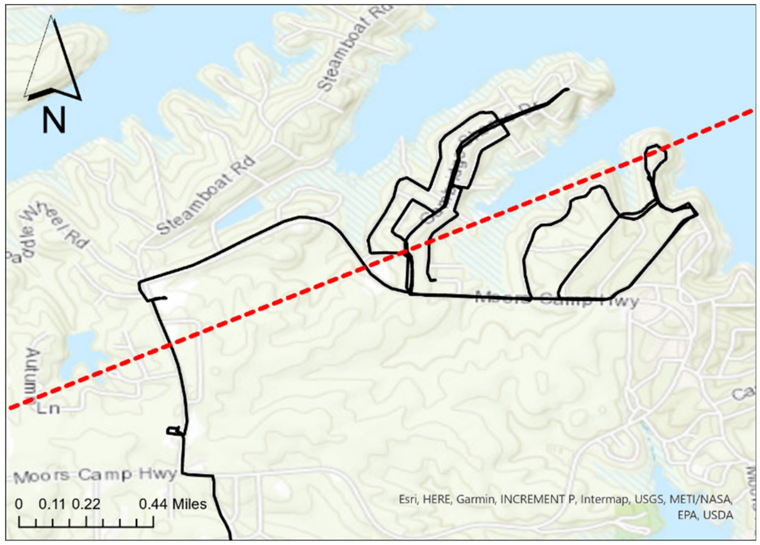
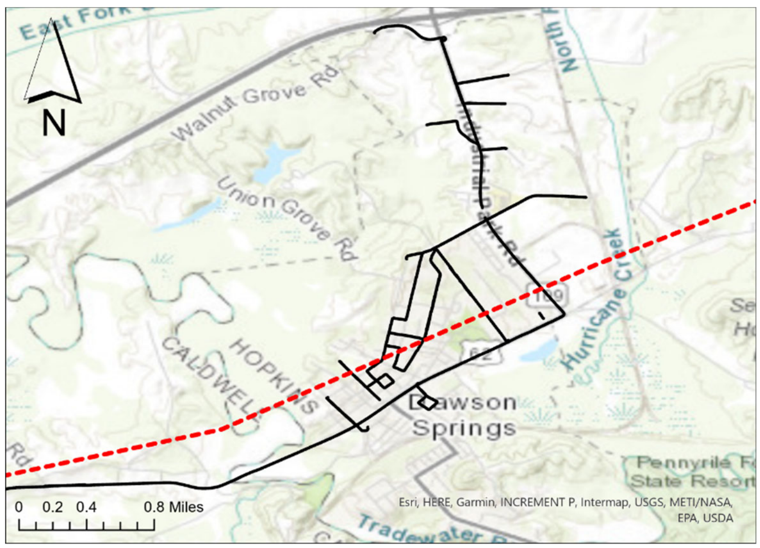
Union City	Obion	TN	EF0	70	--
Hornbeak	Obion	TN	EF0	80	--
NE of Pegram to NNW of Nashville	Cheatham to Davidson	TN	EF0	85	--
Green Hill	Wilson	TN	EF0	85	--
Bethpage	Sumner	TN	EF0	85	--
Carthage	Smith	TN	EF0	80	--
Elkton	Giles	TN	EF0	70	--
Emerald Mountain	Elmore	AL	EF0	70	--
Irwinton	Wilkinson	GA	EF0	70	--
Ada	Hardin	OH	EF1	110	--
Marietta	Prentiss	MS	EF1	95	--

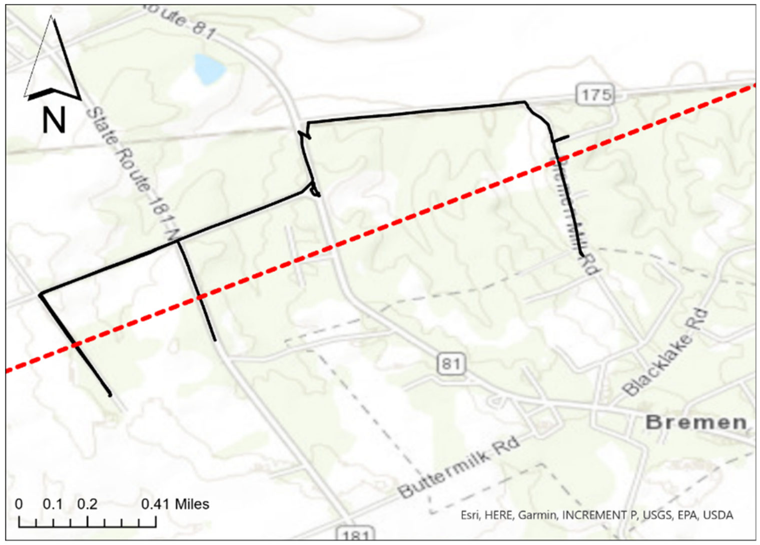
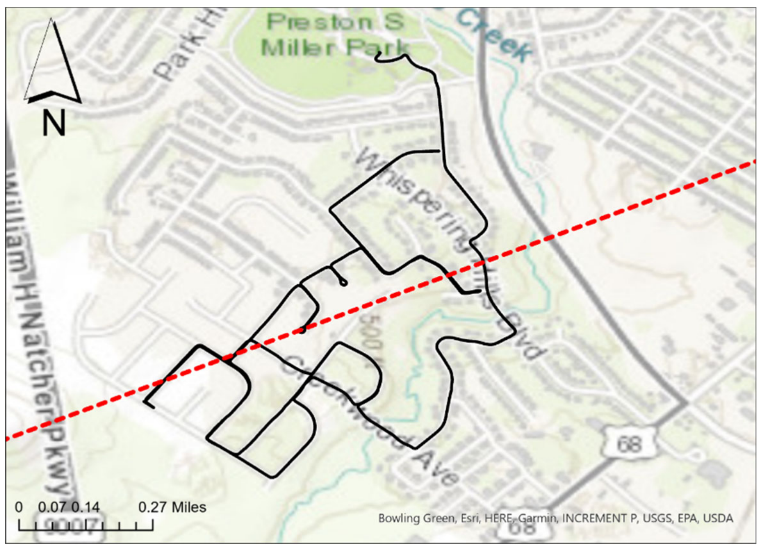
Appendix B. Geospatial Details of Data Collection

B.1. Street-Level Panorama Routes

Table B.1. Summary of routes driven in FAST street-level panorama collection (approximate tornado track indicated by red dashed line).

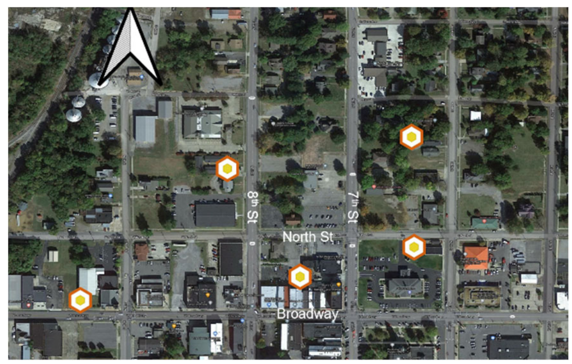
Location	Map of area covered
Mayfield, KY	
Princeton, KY	

Buena Vista / Cambridge Shores, KY	
Dawson Springs, KY	

Bremen, KY	
Bowling Green, KY	

B.2. Properties of UAV Flights

Table B.2. Summary of FAST UAV flights

Flight Type	Number of Photos	GPS	Map
Double-grid	1243	Mayfield, KY (36.740085, -88.639750)	
Panoramas	5	Mayfield, KY (36.740085, -88.639750)	
Double-grid	727	Buena Vista, KY (36.936, -88.224)	

B.3. LiDAR Scan Locations

Table B.3. Site locations of FAST LiDAR scans.

Structure	City	County	Latitude	Longitude	Building Damage State	Number of Scans
Water tower	Mayfield	Graves	36.738907	-88.64243	Destroyed	7
Fire Station	Cambridge Shores	Marshall	36.923022	-88.24779	Destroyed	6
Water tower	Cambridge Shores	Marshall	36.923979	-88.24748	Minor	3
UK Grain and Forage Center of Excellence	Princeton	Caldwell	37.100704	-87.85353	Destroyed	20