NASHVILLE TORNADOES

MARCH 3, 2020

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EARLY ACCESS VIRTUAL RECONNAISSANCE REPORT (EARR)

Field Assessment Structural Team (FAST)

Leads: David Roueche, Auburn University & Richard Wood, Univ. of Nebraska Lincoln

Keith Cullum, Simpson Strong-Tie Brett Davis, Auburn University Mariantonieta Gutierrez Soto, Univ. of Kentucky Sajad Javadinasab Hormozabad, Univ. of Kentucky Yijun Liao, Univ. of Nebraska Lincoln	Frank Lombardo, Univ. of Illinois Urbana-Champaign Mohammad Moravej, Walker Consultants Stephanie Pilkington, Univ. of North Carolina, Charlotte David O. Prevatt, University of Florida

Virtual Assessment Structural Team (VAST)

Lead: Tracy Kijewski-Correa, University of Notre Dame; Contributing Author: Wilfrid Djima, Independant Consultant; Contributing Editor: Ian Robertson, University of Hawaii at Manoa

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). *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) and Social Science Extreme Events Research (SSEER), 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 ERROR 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).

Citing Images from this EARR

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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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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 also extends sincere gratitude to a number of state and local officials who aided FAST members in securing access to conduct assessments, including:

- Brian Hastings, Director, Alabama Emergency Management Agency
- Chris Johnson, Director, Middle Tennessee Regional Emergency Management Agency
- Brent Morse, Putnam County Emergency Management Agency
- Jamie Luffman, Chief, Mt. Juliet Fire Department

StEER further recognizes the efforts of Frank Lombardo's research team from the University of Illinois Urbana-Champaign, and particularly graduate students Justin Nevill, Antonio Zaldivar de Alba, Mia Renna and Daniel Rhee who provided valuable scout reconnaissance in advance of the arrival of StEER's FAST.

StEER further recognizes the technical expertise of Robbie Barnes, PhD, Auburn University, and Michael Vines, Structural Engineering & Inspections, LLC, related to the foundation construction practices observed by the FAST.

StEER further appreciates the responsiveness and support of the RAPID EF in meeting its equipment needs. 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: 1611820.

The sharing of videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

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EXECUTIVE SUMMARY

In the overnight and early morning hours of March 2-3, 2020, a series of tornadoes struck Tennessee and Kentucky. The seven tornadoes touching down in Tennessee caused 25 fatalities, 19 of which occurred within a two-mile stretch just west of Cookeville, TN. The deadly tornadoes struck on the one-year anniversary of the March 3rd, 2019 Beauregard-Smith Station, TN tornado which killed 23 people. This Early Access Reconnaissance Report (EARR) is StEER's second product in response to these tornadoes, overviewing the hazard characteristics, StEER's event response, preliminary findings based on the data and observations generated by its Field Assessment Structural Team (FAST), and recommendations for further study. This FAST consisted of researchers and practitioners with expertise in wind engineering, structural engineering, and community resilience to natural hazards. The FAST conducted Door-to-Door damage assessments coupled with unmanned aerial surveys for targeted clusters of buildings in Nashville, Mt. Juliet, Lebanon, Cookeville, and several rural communities, ultimately documenting the performance of nearly 1100 buildings and other structures. A broader perspective of impacts was documented by street view imagery (vehicle-mounted 360 degree panoramas) captured along nearly the entire track of the Nashville (EF 3) and Cookeville (EF 4) tornadoes.

The FAST repeatedly observed highly vulnerable structural details that were already identified in multiple previous post-tornado reports. These included schools with a lack of safe sheltering options, big box buildings with little load path redundancy suffering complete collapses with high life safety risk, and mobile and manufactured homes in which the anchorage is the first structural element to fail. **Most concerning from this tornado, FAST observed the majority of modern, code-compliant single-family home construction with glaring deficiencies in the load path to the foundation. Specifically, the majority of homes rested on unreinforced, and at times even ungrouted, concrete masonry block stem walls with little to no positive resistance to wind uplift forces.** This load path relies primarily upon the weight of the home to resist uplift forces and as a result, fails in a structurally brittle fashion leading to rapid and catastrophic collapses that compromise life safety.

For most of these, engineered solutions exist but for many reasons have simply not yet been adopted. Indeed, the current building code requirements lack any tornado-resilient criteria that could provide some capacity for houses to resist tornado loads. Research has established tornado-resilient design is economically feasible and need not exceed the criteria that are popular and widely used in Florida, yet there is one jurisdiction out of 89,000 in the US that has actually adopted tornado-resilient building design guides. This implies society has accepted the continuation of life loss and catastrophic structural damage over a large expanse of this country, annually. Retrofitting just a few houses or one or two schools would be insufficient to tangibly alter the deaths, injuries and building damage repeated in these tornado events. Instead, every exposed building should achieve a continuous load path, and all schools should include hardened rooms or corridors for adequate refuge. The realistic timeline to achieve this is measured in decades of consistently applying engineered details with known capacities.

To begin the important work of achieving such outcomes, StEER offers the following recommendations for further by study natural hazard engineering researchers:

- **Recommendation #1:** A rigorous assessment of disproportionate element strengths in the vertical load path of modern single-family homes is needed.
- **Recommendation #2:** Conduct tornado vulnerability and risk mitigation studies for existing schools in tornado-prone regions of the country, repeating recommendations made in numerous previous engineering studies.
- **Recommendation #3:** Continue to study and provide solutions for the poor performance of large volume low-rise buildings, particularly tilt-up precast concrete construction.
- **Recommendation #4:** Continue research and investment on methods for measuring or more reliably estimating wind speeds in tornadoes.
- **Recommendation #5:** Investigate the structural details of homes where fatalities and serious injuries occurred with support of local officials.

This event also underscored other topics beyond yet tangential to StEER's mandate that are worthy of further investigation by interdisciplinary teams:

- **Topic #1:** Improved exploration of the intersection of epidemiological and weather risks.
- **Topic #2:** Methods for quickly translating engineering reports to consumption by the general public for use in recovery for the current and future disasters.

Finally, note that all observations and findings provided in this EARR should be considered preliminary and are based on the limited scope of the FAST.

1.0 Introduction

According to the National Weather Service (NWS), ten tornadoes were spawned by a storm system that impacted Alabama, southeastern Missouri, western Kentucky, and West/Middle Tennessee on the night of March 2 through the early morning of March 3, 2020. Most notably among these was a strong tornado impacting Nashville, Mt. Juliet and Lebanon, with a path reminiscent of the city's 1998 Tornado (Fig. 1.1). These tornadoes were the worst experienced in Tennessee since the devastating tornadoes of April 27, 2011 moved across East Tennessee, and the Super Tuesday tornadoes on February 5-6, 2008 (NWS, 2020). Despite the wide extent of the storm system, this report focuses on the tornadoes impacting downtown Nashville and its wider metropolitan area, including Donelson, Mt. Juliet, Lebanon and Cookeville. These tornadoes are part of a highly active start to the 2020 season, with more than double the US average for tornadoes, not even counting the totals from March (Roach, 2020). Tragically, these tornadoes occurred on the one year anniversary of the March 3, 2019 tornado that killed 23 in Beauregard, AL (Roueche et al., 2019).

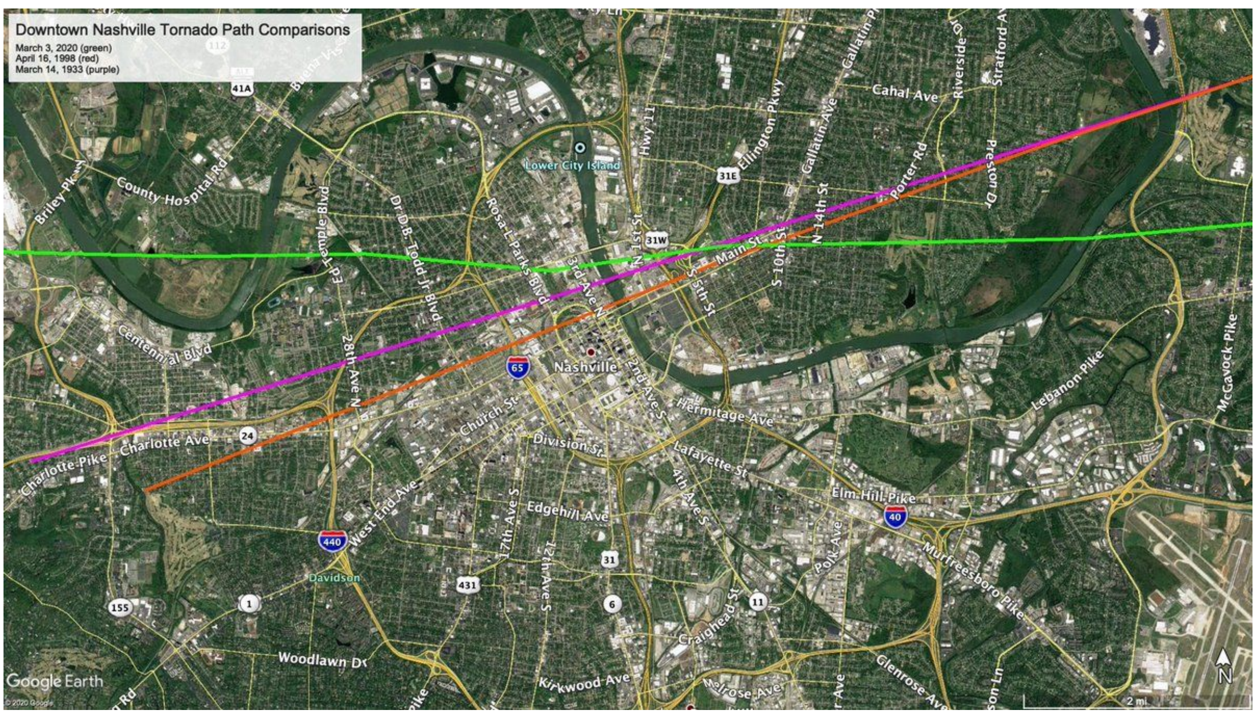


Figure 1.1. Preliminary path of the 2020 Nashville/Davidson County tornado (green) relative to an F3 tornado in 1998 (red) that killed one person and an estimated F3 tornado in 1933 (purple) that killed 15 persons (Grazulis, 1993). Source: Krissy Hurley, NWS Nashville

1.1 Societal Impact

Preliminary estimates suggest total damage and economic losses between $1.5 and $2 billion, inclusive of direct and indirect losses (Roach, 2020). Damage to the John C. Tune Airport alone was estimated at over $90 million, not counting the lost aircraft and personal property (Cooke, 2020). The storms caused widespread damage to both urban and rural buildings and infrastructure, resulting in power losses to tens of thousands of customers (Haworth & Shapiro, 2020), with nearly 5000 still without power on March 9 (Tennessean, 2020). Metro Nashville, Wilson County and Putnam County Schools were closed for the remainder of the week of March 2, 2020, while other heavily damaged schools (Mt. Juliet Christian Academy, West Wilson Middle School, and Stoner Creek Elementary, Donelson Christian Academy) will be closed for the remainder of the academic year, if not longer. Other disruptions were thankfully short-term, including a gas leak in Germantown requiring an evacuation (Brackett & Wesner Childs, 2020) and the closure of Interstate 40 in both directions between the heavily impacted areas of Mount Juliet and Lebanon for 12 hours (Illers, 2020).

As the tornadoes struck just hours before Super Tuesday voting in Nashville, some polling sites were impacted, with a number requiring generators. Fifteen polling sites in Nashville were shifted to alternate locations and hours for voting were adjusted in a number of locales (Shepard, 2020).

1.2 Loss of Life and Injuries

Building on StEER's initial report of injuries and fatalities (Roueche et al., 2020), as of March 12, 2020, officials have increased the death toll to 25, with 19 deaths in Putnam County, 3 in Wilson County, 2 in Davidson County and 1 in Benton County (AP, 2020). National Weather Service reports estimate 309 injuries (NWS, 2020). A breakdown of deaths and injuries by tornado are offered later in Table 2.1.

1.3 Official Response

Officials declared a State of Emergency in Tennessee soon after the tornadoes struck, activating an all-hands response from state emergency officials including activation of the State Emergency Operations Center (SEOC). The state also received an official visit from the President on March 6, 2020 (Dwyer, 2020). In addition to opening emergency shelters, initial efforts focused on clearing right of way, restoring utilities, and debris removal. This included restoring damaged traffic signals and signage (Davis, 2020). FEMA also activated disaster recovery centers, which were further expanded in Davidson County (Tennessean, 2020). In addition to benefit concerts by the music industry, a large number of free/discounted services, charitable funds, support services and opportunities to donate and volunteer have been launched (Do615, 2020). Tragically, recovery from the event was further compounded by the escalating threat of COVID-19, which triggered a wave of closures, travel bans, and stay-at-home orders across the nation in the weeks following the tornadoes (Ong, 2020).

1.4 Report Scope

The devastation caused by these tornadoes necessitated a swift response by the Structural Extreme Events Reconnaissance (StEER) network to assess impacts and advance knowledge surrounding mitigation of tornado-induced damage. Given the diversity of topologies exposed across urban, suburban, and rural settings, StEER sought to assemble a well-equipped Field

Assessment Structural Team (FAST) that could coordinate with a number of other aligned efforts from members of the Natural Hazards Engineering community. This Early Access Reconnaissance Report (EARR) is the second product for this event from StEER, following the Preliminary Virtual Reconnaissance Report (PVRR) (Roueche et al., 2020), and focuses on the mission and findings of the Field Assessment Structural Team (FAST) responding to this event.

2.0 Hazard Characteristics

As the PVRR already extensively documented the long-standing and powerful supercell that produced numerous tornadoes along the Interstate 40 corridor (Roueche et al., 2020), this section focuses on establishing characteristics of the tornadoes relevant to interpreting the observations made by the FAST. Damage surveys verified that this event produced 10 tornadoes in Tennessee, with 7 touching down in Middle Tennessee (see Fig. 2.1). As reported in the summary in Table 2.1, the event spawned EF-2 (north of Camden, TN), EF-3 (vicinity of Nashville and Lebanon, TN, hereafter termed the ***Nashville tornado***) and EF-4 (near Cookeville, TN, hereafter deemed the ***Cookeville tornado***) tornadoes that were extremely fast moving, with translational speeds of 50-70 mph (NWS, 2020). The paths of the EF-3 and EF-4 tornadoes are detailed in the following sections.

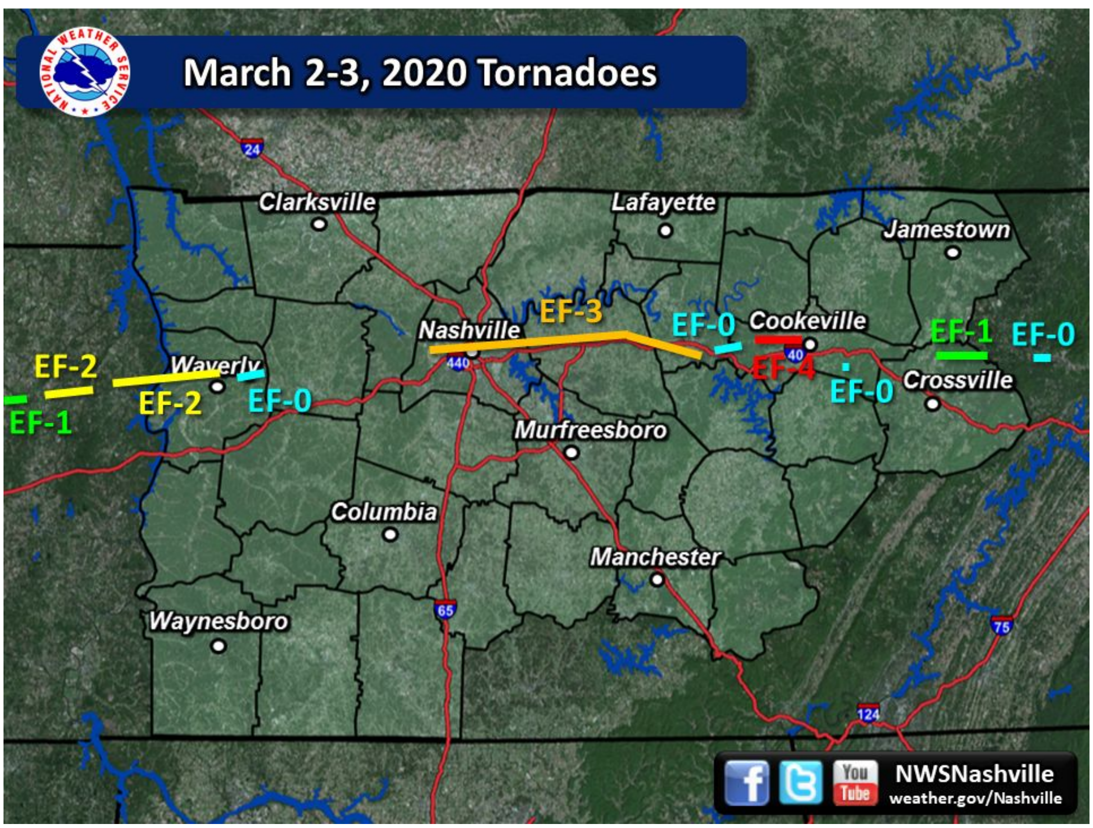


Figure 2.1. Tornado Outbreak Map showing the paths of March 2-3 tornadoes (NWS, 2020).

Table 2.1. Updated Summary of Tornadoes in Tennessee March 2-3, 2020 (NWS, 2020)

EF #	Name	County	Time (local)	Path Length (motion)	Est. Peak Winds	Max width	Injuries/ Deaths
March 2, 2020							
EF-2	Camden/ Waverly, TN	Benton Humphreys	11:05 PM - 11:31 PM	19.01 mi (TBD)	125 mph	250 yds	2/1
EF-0	McEwen, TN	Humphreys	11:42 PM - 11:48 PM	4.8 mi (TBD)	80 mph	50 yds	0/0
March 3, 2020							
EF-3	Nashville, TN	Davidson, Wilson, and Smith	12:32 AM - 1:35 AM	60.13 mi (East at 65 mph)	165 mph	800 yds	220/5
EF-0	Buffalo Valley, TN	Smith and Putnam	1:37 AM - 1:42 AM	5.98 mi (East at 71 mph)	75 mph	50 yds	0/0
EF-4	Cookeville, TN	Putnam	1:48 AM - 1:56 AM	8.29 mi (E at 63 mph)	175 mph	300 yds	87/19
EF-0	Goffton, TN	Putnam	2:05 AM - 2:06 AM	0.23 mi (E at 63 mph)	75 mph	25 yds	0/0
EF-1	Rinnie, TN	Cumberland	2:25 AM - TBD	10+ mi (TBD)	95 mph	200 yds	0/0

2.1 Cookeville Tornado (EF-4)

The most intense tornado in this outbreak was an EF-4 in Putnam County between Baxter and Cookeville. The EF-4 luckily dissipated before arriving in downtown Cookeville. This EF-4 was the deadliest single tornado in Tennessee (19 deaths) since the EF-3 Sumner/Trousdale/Macon County Tornado on February 5, 2008 (22 deaths) and was the worst Putnam County tornado on record (NWS, 2020). As reported by the National Weather Service (NWS, 2020):

> *The tornado began 2.5 miles NW of Baxter where it produced EF-0 damage for 2.7 miles as it crossed Gainesboro Highway. The tornado intensified to EF-1 and EF-2 intensity in the Prosperity Pointe subdivision just north of US 70N/Nashville Highway and further intensified to EF-3 as it crossed Bloomington Road and Clemmons Road, severely damaging several homes. The tornado then became violent for 0.8 miles as it entered the area around McBroom Chapel Road, where it reached EF-4 intensity, completely destroyed over a dozen homes, and caused numerous fatalities with the heaviest damage concentrated on Hensley drive. EF-4 damage continued eastward to Echo Valley Drive, where an apartment complex was completely destroyed. EF-2 and EF-3*

damage continued eastward for 2.0 miles, affecting homes along US 70N/W Broad Street, before rapidly coming to an end near N Franklin Avenue just west of Cookeville Regional Medical Center.

2.2 Nashville Tornado (EF-3)

While less intense, another noteworthy tornado was the EF-3 that remained on the ground over 60 miles across the Nashville Metro area through Davidson, Wilson, and Smith counties, resulting in 5 fatalities and 220 injuries. This was the first tornado to strike the Nashville loop since February 13, 2000. This was the second longest known tornado path in the state of Tennessee (May 27, 1917 tornado reported a 80 mile path) and is the longest officially recorded since records initiated in 1950 (NWS, 2020). As reported by the National Weather Service (NWS, 2020):

> *The tornado began in far western Davidson County and rapidly intensified into EF-2 intensity as it tracked across John C. Tune Airport and into the North Nashville and Germantown areas. The tornado intensified further to EF-3 intensity as it tracked into East Nashville, with the most significant damage occurring in and around the Five Points neighborhood, where two fatalities occurred. EF-1 and EF-2 damage continued across the Cumberland River before the tornado strengthened again to EF-3 intensity in the Stanford Estates subdivision in Donelson. EF-2 damage was observed across Hermitage and the remainder of Davidson County. The tornado strengthened to EF-3 intensity for a third time upon entering Wilson County, with a 6-mile swath of EF-3 damage observed near the Mt. Juliet area, where three more fatalities occurred. EF-1 and EF-2 damage continued along a path that paralleled and occasionally crossed Interstate 40 south-southeast of Lebanon. Once the tornado moved into Smith County, it weakened some but was still causing significant tree and powerline damage, as well as damage to homes. Just south of Gordonsville, the tornado caused a mobile home to flip, along with destroying several barns and outbuildings. The tornado finally lifted just south of I-40 near Highway 141/Lancaster Highway*.

2.3 FAST Observations

Overall, the FAST observed damage over a relatively narrow tornado path in both the Davidson-Wilson-Smith Counties and Putnam County tornadoes in comparison to other major tornado disasters such as the 2011 Joplin, MO tornado or 2013 Moore, OK tornado. Specifically in the Davison-Wilson-Smith Counties tornado, variability in the tornado intensity over the length of the tornado appeared to be influenced by factors beyond the vulnerability and exposure of the built environment, suggesting the storm gained and lost intensity periodically throughout the track, as would be expected in a long-track event of this nature.

Related to the changes in intensity, FAST noted that the tornado track was also not always clearly defined. The expected damage gradation towards a defined center was often not obvious. For example, in the more dense, urban regions (e.g., Five Points, Germantown), the damage occurred over a relatively narrow swath (~200 m) with somewhat scattered damage within the swath (shown in Figure 2.2). The variety of structure typologies and vulnerabilities likely also played some role, and it is also possible that these obstacles served to modify the near-surface structure of the vortex itself. Significant obstacles to the flow have been shown to both alter the tornado path and cause significant increases/decreases in intensity depending on the relative position of the tornado and the obstacle (Satrio et al., 2020). The relatively narrow vortex, coupled with a moderately fast translation speed (estimated to be ~45 mph by radar), can lead to a skewed wind field which may also be a factor in some of the atypical damage patterns.

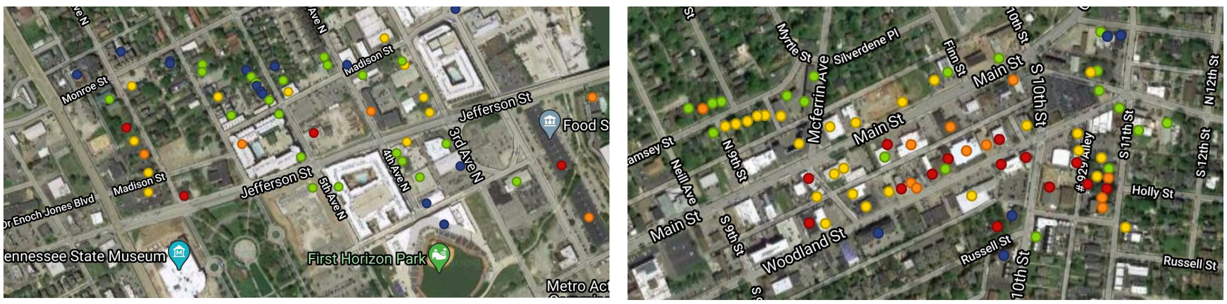


Figure 2.2. Scattered damage levels within a relatively narrow tornado damage path through Germantown (left) and Five Points (right).

3.0 StEER Response Strategy

StEER Activated its Virtual Assessment Structural Team (VAST) for the 3 March 2020 Nashville Tornadoes by mid-morning on March 3 to assemble information on the event from public sources and lead authorship of the Preliminary Virtual Reconnaissance Report (PVRR). Based on the initial assessments of damage in the PVRR (Roueche et al., 2020), StEER then formed its Field Assessment Structural Team (FAST) from available Level 3 and 4 StEER members with expertise in characterizing wind damage, as well as Level 2 members as FAST Trainees for this event.

The FAST began arriving and collecting data in the Nashville area on March 8, 2020. While the composition of the team fluctuated based on the availability of members, data collection continued until March 12, 2020. The surveyed geographies included multiple locales in the Nashville metro area. The FAST engaged a range of assessment technologies, as weather permitted, including door-to-door (D2D) damage assessments, unmanned aerial surveys (UAS), and streetview technology. See Section 5 for additional details.

The StEER response strategy centered on pre-identifying clusters of structures based on typology, occupancy, year of construction and reported damage level, focusing on buildings in Cookeville that were impacted by the Cookeville tornado (EF-4) and along the Nashville tornado (EF-3) track, including: West Nashville, Nashville's Germantown, East Nashville, Donelson, Mt. Juliet and Lebanon. Some additional investigations were conducted in rural Kentucky, SE of Bowling Green. In Tennessee, the targeted samples enabled the documentation of single/multi-family residential, commercial, industrial, and school buildings. The selected clusters included the known locations of fatalities, as well as areas where newer vintages of homes were damaged. Because the damage was tightly clustered around the tornado path, the team employed high density sampling. The deployment of the streetview camera enabled the team to rapidly gather data along the tornado path, beyond the sampled clusters, while UAS was selectively conducted in areas where D2D assessments were recorded to enable better characterization of damage to rooftops or across larger/less-accessible areas.

The assembled D2D assessment data, FAST Daily Summaries, and other publicly available information was then used to author this Early Access Reconnaissance Report (EARR), the second official publication released as part of StEER's event response. As a result of the significant coverage achieved by this FAST, as well as the evolving travel restrictions/social distancing encouraged to stem the progression of the COVID-19, StEER will not deploy a second FAST in response to this event.

Finally, it is important to note that detailed forensic investigations are generally not achievable within the scope and time limits of a FAST. Specific, hypothesis-driven research is outside of the scope of standard StEER missions, although data collected by StEER can be used for these purposes in some cases. To that end, the data collected by the FAST will be curated in DesignSafe under this unified project for re-use by the community following the completion of the Data Enhancement/Quality Control (DE/QC) protocol. Such follow-on investigations are certainly warranted to examine the performance of specific typologies or specific aspects of tornado-resistant design practices, as further discussed in Section 9.

4.0 Local Codes and Construction Practices

The current code in place in the Nashville metro, Davidson County, Wilson County, and Putnam County is the International Code Council's (ICC) 2012 International Building Code (IBC) and 2012 International Residential Code (IRC). As reported in the PVRR (Roueche et al., 2020), every jurisdiction in the state was required to have adopted the 2012 IBC/IRC by 2016, although some jurisdictions adopted sooner (see Table 4.1). Regarding wind loads, the 2012 IBC requires a minimum design wind speed of 115 mph (ultimate, gust velocity, used with 0.6 service load factor), while the 2012 IRC requires 90 mph (basic, gust velocity, used with 1.0 service load factor), but provides prescriptive requirements for most materials and connections.

Table 4.1. Known ICC code adoptions by jurisdiction based on publicly available ordinances.

Jurisdiction	IBC / IRC Edition					
	2000	**2003**	**2006**	**2009**	**2012**	**2018**
Nashville / Davidson County	June 2001 (BILL NO. BL2001-703)		Apr 2007 (BILL NO. BL2007-1390)		Aug 2015 (BILL NO. BL2015_1145)	
Wilson County			2008 (IBC only)	2010 (IRC only)	2016 (IBC only)	
Mt. Juliet					May 2012	Jan 2019
Lebanon		Apr 2010 (IRC only)	Apr 2010 (IBC only)		Adopted, but date unknown	Current, but adoption date unknown
Cookeville / Putnam County	Mar 2004(IBC only)		Aug 2009		Oct 2014	

5.0 Reconnaissance Methodology

The FAST for the Nashville Tornado worked in close collaboration with other StEER members who were conducting independent, ongoing research on tornado impacts. Members of these companion studies joined the FAST for select activities and exchanged information continuously the week of March 9, 2020. The primary StEER FAST was led by Richard Wood (University of Nebraska-Lincoln) and included Keith Cullum (Simpson Strong-Tie), Mariant Gutierrez Soto (University of Kentucky), Mohammad Moravej (Walker Consultants) and Stephanie Pilkington (University of North Carolina, Charlotte) and David O. Prevatt (University of Florida). Graduate students Sajad Javadinasab Hormozabad (University of Kentucky), Brett Davis (University of Auburn), and Yijun Liao (University of Nebraska-Lincoln) assisted their advisors and the StEER FAST. StEER Associate Directors David Roueche (Auburn University) and StEER Member Frank Lombardo (University of Illinois, Urbana-Champaign) worked interoperably as part of the StEER FAST and other independent investigations, along with a team of graduate students from the Lombardo group who served as scouts preceding the FAST's arrival in Nashville. Table 5.1 summarizes the individuals officially collecting StEER data for this mission during the week of March 9, as well as the geography targeted. On each of these days, both D2D damage assessments and UAS were conducted.

The team worked closely with Tennessee Emergency Management Agency (EMA) to secure access to sites, engaging local Emergency Operation Centers (EOCs) as necessary. In some cases, access to locations was denied by law enforcement or due to high densities of volunteers aiding with clean up. Weather conditions also limited data collection activities, particularly on March 10 and 12.

Table 5.1. FAST Daily Data Collection Activities

	Geography	**Team Members**
March 8, 2020	1) Rural Kentucky (Warren county, SE of Bowling Green) 2) Lebanon - extensive drone survey, D2D (Wood, Pilkington, Moravej) Mt. Juliet - 3 hours - D2D, drone survey (Wood, Pilkington)	R. Wood, S. Pilkington, M. Gutierrez Soto, S. Javadinasab Hormozabad, M. Moravej
March 9, 2020 (Team 1)	Cookeville / Putnam County 1) Charlton Square 2) Plunk Whitson Rd 3) Hensley Dr 4) McBroom Chapel Rd 5) Heald Ct and Willowbrook Dr 6) Echo Valley Dr 7) Mockingbird Hill Cir	D. Roueche, S. Pilkington, F. Lombardo
March 9, 2020 (Team 2)	1) Lebanon 2) Nashville 3) Mt Juliet	R. Wood, M. Gutierrez Soto, M. Moravej, S. Javadinasab Hormozabad, K. Cullum
March 10, 2020	1) Mt. Juliet: West Wilson MS, Stoner Creek MS 2) Donelson 3) Five Points Area 4) West Nashville 5) Lockeland Springs	R. Wood, M. Gutierrez Soto, M. Moravej, S. Javadinasab Hormozabad, K. Cullum, S. Pilkington, B. Davis
March 11, 2020	1) Mt. Juliet: West Wilson and Stoner Creek Schools 2) Germantown 3) John C Tune Airport 4) Lebanon 5) East Nashville: Barclay Drive 6) East Nashville: Lockeland Springs	R. Wood, M. Gutierrez Soto, M. Moravej, S. Javadinasab Hormozabad, K. Cullum, S. Pilkington, B. Davis, D. Roueche, D. Prevatt
March 12, 2020	1) East Nashville (Barclay Drive & Lockeland Springs) 2) West Nashville (Commercial	R. Wood,Y. Liao, M. Gutierrez Soto, D. Prevatt, K. Cullum

	facility east of the Tune airport) 3) near Waverly 4) North Nashville 5) Hermitage 6) Germantown	
March 13, 2020	1) Gibson and Carroll counties (rural areas) 2) Near Waverly (treefall area)	R. Wood,Y. Liao

5.1 Door to Door (D2D) Assessments

Variability in construction practices and performance were documented by D2D Damage Assessments and recorded using a Fulcrum mobile smartphone application: StEER Building - US (Windstorm) App, acquiring geotagged photos, recorded audio and other relevant metadata from the investigator's mobile device. Since the damage was highly concentrated along the tornado path, the FAST assessed every property (when feasible) working end-to-end along the identified transect or across the damage gradient (from destroyed structures and progressively outward to properties with minor to no damage). Emphasis was placed on documenting the structural performance of as many structures as possible in a short amount of time, while capturing the minimal depth of information needed for a useful assessment and supplementing with a few detailed case-studies within each cluster. As such, D2D assessors emphasized capturing high-quality photographs from all perspectives, as well as close-range images of any key forensic evidence to explain the performance along different points of the structural load path. FAST members used Fulcrum's embedded audio recording feature to describe the performance and relevant features not otherwise visible from supplemental data sources. As the FAST recorded primarily audio and photographic evidence, DE/QC protocols will subsequently be executed to populate the remaining fields in the StEER Building - US (Windstorm) App. A total of 1119 records were acquired by the FAST, and this Fulcrum data can be accessed immediately at StEER's Fulcrum Community page[1] (note again that these data have not yet been processed by the DE/QC protocol). Figures 5.1 and 5.2 illustrate the full geographic extent of D2D assessments, relative to the tornado tracks. The D2D data collected by the FAST will be made available on DesignSafe under this project (PRJ-2723) after completing the DE/QC Process.

In the process of conducting D2D assessments, FAST members also gathered forensic evidence of hazard intensity, e.g., tree fall patterns, using a separate Fulcrum mobile smartphone application (StEER Hazard Indicator). A total of 43 records documenting evidence

[1] Make sure the layer stack in the upper right of the map has the StEER Building - US (Windstorm) App checked. Those new to visiting the site should be fine, but those who have used this URL in the past to view prior data from hurricanes Irma, Michael, etc. may need to take an additional step: After enabling this layer, returning users may need to hit refresh and clear the cache on their browser to view.

of wind field intensity were collected, as visualized in Figure 5.3. An additional 16 records of damage to non-building structures, such as power infrastructure, were collected in the StEER Non-Building (Windstorm) Fulcrum App. The locations of these records are summarized in Figure 5.4.

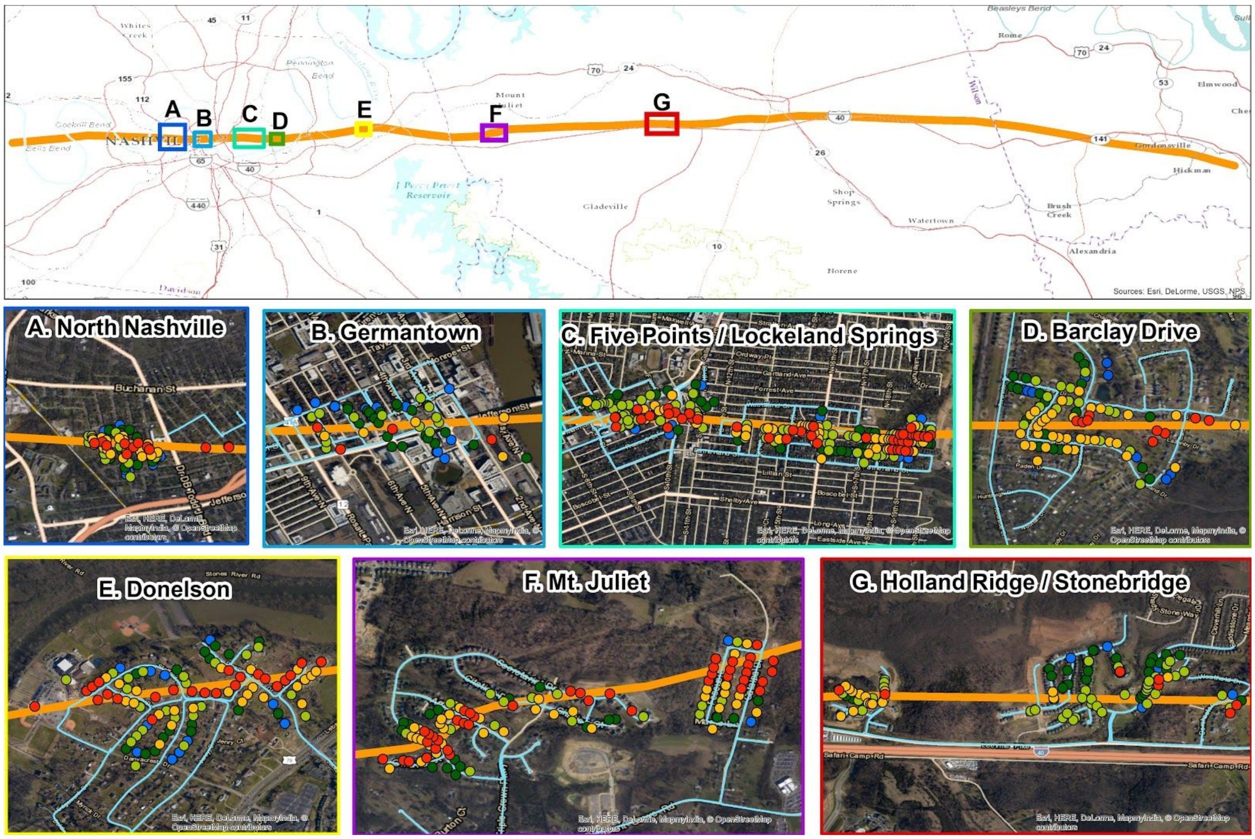


Figure 5.1. StEER FAST D2D assessments in response to the Nashville tornado in key geographic regions relative to the tornado centerline. Blue lines in the detail plots indicate routes captured with streetview imagery.

Figure 5.2. StEER FAST D2D assessments in response to the Nashville tornado in key geographic regions relative to the tornado centerline. Blue lines in the detail plots indicate routes captured with streetview imagery.

Figure 5.3. StEER FAST non-building assessments (N = 16).

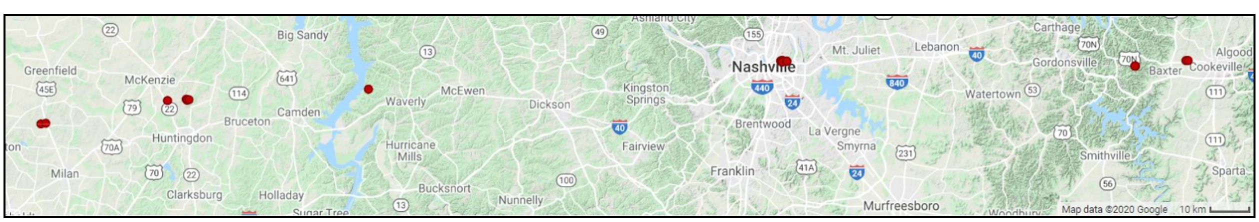


Figure 5.4. StEER FAST hazard indicator assessments (N = 43).

5.2 Unmanned Aerial Surveys

The Unmanned Aerial Systems (UASs) engaged in this deployment included one DJI Mavic Pro 2 (Operator: R. Wood) and one DJI Mavic Platinum (Operator: D. Roueche). The UASs were used primarily to capture high-resolution nadir or oblique (off-nadir) photographs in a predefined pattern, front and side overlap as reported in Appendix A, from which orthomosaics and 3D models can be generated using Structure-from-motion (SfM) photogrammetry methods (see Appendix A). Appendix A includes estimated flight altitudes in respect to the resulting ground sampling distance (GSD). In a few sites, gridded flight patterns were either not able to be used or could not be completed. This was generally due to time constraints, rainy conditions, or loss of daylight. As an alternative, UAS was at times used to acquire high resolution aerial photographs from key angles and elevations in order to provide a birds-eye view of the post-storm condition. The data collected by UAS will be processed into orthomosaics, digital surface models (DSMs), and densified point clouds that will be made available on DesignSafe under this project (PRJ-2723) along with the individual images.

5.3 Streetview Imaging

A subset of the team (Davis and Roueche) gathered high-level impressions of damage using an NCTech iStar Pulsar+ streetview Camera, recording spot observations of representative performance using the Fulcrum App, and identifying areas for follow-up assessment based on damage and accessibility. This subteam covered a broad area consisting of the entire Cookeville tornado path and the vast majority of the Nashville tornado path (missing specific roads primarily due to power pole replacement along certain streets). The subteam drove all accessible roads that were within the tornado path, capturing the full gradient of damage wherever possible. 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 focal length of 2.6. GNSS-tracking via a U-BLOX Neo M8N receiver geotagged each image location with ~2.5 m accuracy. Frames were captured every four meters along the routes driven, capturing near-continuous coverage of exterior building performance. The team cataloged just over 100 miles of imagery between the two tornado paths with over 160,000 individual photographs. The images collected from the system will be stitched together into seamless 360 degree panoramas that will be made available on DesignSafe under this project (PRJ-2723) and are also now available publicly via the Google Streetview platform to enable valuable pre-post comparisons (see Fig. 5.5).

Figure 5.5. Streetview imagery captured by FAST (bottom) compared to pre-tornado Streetview (top). Both views are available through Google Maps (Lat: 36.176658; Long: -85.590073).

6.0 Observed Performance of Buildings

The FAST conducted 1098 D2D assessments in Tennessee and Kentucky in response to the March 3rd tornadoes, including 258 destroyed buildings, 207 with severe damage, 244 with moderate, 272 with minor, and 114 with no visible damage, resulting in a relatively diverse data set in terms of damage. These data, supplemented by the UAV data, streetview data, and available aerial imagery, are used to summarize key observations from FAST in the sections below. Observations are separated by building typology, as construction practices from region to region were not noticeably different. Unless otherwise noted, all photos contained in the following subsections were taken by FAST members or supporting personnel and full-resolutions and supplementary photos and data are available through the StEER Fulcrum Community. The data as presented should be assumed to be in its raw form, without having undergone the full StEER Data Enrichment and Quality Control (DE/QC) process. The sections below do not include an assessment of storm shelters or safe rooms as the team did not encounter any during their assessments.

6.1 Site-built Single-Family Residential Buildings

Observations regarding the performance of site-built single-family residential (SFR) buildings are further organized by era of construction. Regional differences appeared to be minor relative to temporal differences.

6.1.1. Pre-1950s SFR

Pre-1950s construction was mostly encountered in portions of Nashville, near downtown, including West Nashville, East Nashville, and Germantown. These homes were primarily single-story, wood-frame homes constructed from sawn lumber, resting on unreinforced masonry piers and stem walls. The wall and roof substrate was typically composed of dimensional wood planks with a variety of cladding elements installed overtop. The vertical load paths in these homes to resist wind were negligible, with roofs attached to walls with toe-nails, and no positive connection between the walls and foundation. However, the use of 1X (1 inch or less in thickness) wood planks instead of sheathing does increase the weight of these homes, and the use of diagonal wood planks as substrate in the walls and/or roofs provides reasonable lateral stiffness (Prevatt & Roueche, 2015). A few homes of this era were constructed with unreinforced masonry block walls. In these homes, a 1X wood top plate was nailed to the top course of CMU block and roof joists toe-nailed to the top plate. Performance of these homes was not noticeably different than adjacent wood-frame homes. Figures 6.1.1 exemplifies the performance of homes in this era.

Figure 6.1.1. (left) 2-story hollow CMU residential structure with horizontal 1X wood planks for roof sheathing in Lockeland Springs; (right) single-story wood-frame home (constructed in 1945) in the Osage/North Fisk neighborhood in north Nashville with wood rafters and plywood sheathing.

6.1.2. 1950-1990 SFR

Communities with 1950-1980s construction included Donelson (1960s) (Figs. 6.1.2-3), Hermitage (Figure 6.1.4), Barclay Drive (Figure 6.1.5), and isolated structures elsewhere. These homes were primarily constructed with light wood-frame walls and 2X (i.e., sawn lumber 1.5 inches in width with varying depths) wood roof trusses (site-built or pre-engineered) toe-nailed to the wall top plates. Walls were typically sheathed with insulation boards (e.g., Thermo-Ply) with some homes having 1X let-in bracing[2] at corners. Wood connections relied upon fasteners only - no straps were observed outside of occasional joist hangers. The majority of roofs were gabled. Hilly topography dictated style of mostly 1 story wood frame with brick veneer over 1 story CMU garage/walkout. CMU was generally hollow (with a few exceptions where the top course only was grouted). The sill plate was typically anchored to the CMU wall with concrete nails or (in at least one case) with framing nails. Floor joists were generally toe-nailed to the sill plate. FAST also observed the collapse of a few 2nd story backyard decks (Figure 6.1.3). There was minimal (if any) attachment at the base of each post and often the deck ledger was anchored into the brick veneer only.

[2] Let-in bracing consists of a diagonal 1X board extending diagonally from the top plate to the bottom plate of a wall segment. Steel straps can also be used in-lieu of the wood board. See 2012 IRC Table R602.10.4

Figure 6.1.2. Typical construction and common failures in Donelson, with (left) a roof entirely removed, and (right) partial collapse of a wood-frame wall.

Figure 6.1.3. Several decks in Donelson that collapsed were fastened only to the brick veneer at the 2nd floor level.

Figure 6.1.4. Single-story gable-roofed structure destroyed in Hermitage. Single-wythe brick facade on wood stud wall with Celotex wall sheathing. Home built in 1980. Photo taken March 12.

Figure 6.1.5. Typical 1980's construction in Barclay subdivision, with wood rafters, non-structural wall sheathing, and unreinforced masonry stem wall foundations with walk-out basements. Damage may have been enhanced by topographic features, with heaviest damage colocated with a valley that ran East-West through the area.

6.1.3. 1991-2005 SFR (pre-IRC)

Communities with 1990-2005s construction included Triple Crown in Mt. Juliet (excluding the northern portion of Secretariat Dr.). These homes were primarily constructed with light wood-frame walls and stick framed wood roofs toe-nailed to the wall top plates. No connectors were observed beyond the occasional hanger and the sill plate anchorage outlined below. Walls were typically sheathed with OSB and styrofoam insulation boards. Sill plates were often attached with anchor straps installed into an ungrouted CMU block stem wall, comprised primarily of stretcher blocks (Fig. 6.1.6, left). These blocks create a small void at the head joint and typically every 3rd void (equating to 48-inch on-center spacing) was grouted and an anchor strap was installed. Floor joists were generally toe-nailed to the sill plate and wall framing above was nailed to the floor system using one or two nails at every stud bay or every other stud bay (16- or 32-inches on-center) (Figure 6.1.6, right). Occasional gable end and tall wall collapses were observed with hinge failures occurring at the intersection of the gable frame bottom plate and lower wall frame top plate (Figure 6.1.7).

Figure 6.1.6. Common failures in Triple Crown subdivision with (left) foundation anchor straps installed into primarily ungrouted CMU block stem wall and (right) nailed sill plate attachment to floor system (two nails at 16-inches on-center).

Figure 6.1.7. Gable end (left) and tall wall (right) failures occurring at the intersection of upper gable frame bottom plate and lower wall frame top plate, where sheathing is not overlapped and no lateral support is present.

6.1.4. Post-2005 SFR (IRC)

The exact adoption data varied slightly by community, but this section details homes that were nominally constructed to a version of the International Residential Code. Communities included are Charlton Square and Hensley Dr. in Cookeville, the Triple Crown neighborhood in Mt. Juliet, and the Holland Ridge and Stonebridge neighborhoods in Lebanon. Key observations from these neighborhoods included the following:

- Load paths typically consisted of (1) unreinforced masonry stem wall foundations, (2) wood sill plates anchored to a single grouted cell with a j-bolt, (3) sawn lumber or wood I-beam floor joists, (4) wood-frame stud walls nailed to plywood flooring, (5) engineered wood wall sheathing, (6) wood trusses or rafters connected to walls with a metal tie or fully-threaded screw, and (7) wood roof sheathing with ring-shanked or smooth-shank nails at 6:12 spacing (6 inches at edges, 12 inches at interior wood members).
- Foundations were consistently 2x8 sill plate atop unreinforced masonry stem wall, anchored with ½"x7" j-bolts approximately 6 ft on center. However j-bolts were usually installed in a single-grouted cell in the best of cases. Worst case, the j-bolts were jammed into empty blocks, bricks, or between the brick cladding and CMU stem wall. Floor joists were toe-nailed to the sill plate. Wall bottom plates were simply nailed into flooring fastened to floor joists and sheathing often did not overlap with the sill plate. **Considering these neighboring connections, the anchor bolt has a disproportionately high capacity relative to the surrounding elements of the load path, rendering it mostly useless at enhancing the wind resistance of the structure overall**.

- Discontinuities in the vertical load path were often exacerbated by wall sheathing installation practices. The FAST noted many cases of wall sheathing not overlapping both top plates, not continuous across story joints, and not extending continuously from the stud walls over the floor joists to the sill plate. Such practices can greatly aid in providing a continuous load path, but were inconsistently used in homes observed by FAST.
- Hurricane ties were generally present at roof-to-wall connections, but there was no additional resistance through other straps or hardware. There was also some evidence that hurricane ties/threaded fasteners were incorrectly installed based on observations of debris from failed homes, such as fully threaded screws only engaging the upper top plate instead of both top plates.
- The FAST observed no noticeable improvement in performance overall with the new builds (2012 IRC) vs old builds (pre-2012 IRC), but rarely were there new and old in close proximity to each other and to tornado center. The Triple Crown subdivision (Mt. Juliet) was one of the exceptions and no significant differences in performance were observed.
- Garage door failures were frequently observed and often led to collapse of garage walls, exploiting weaknesses in the load path described above.
- One neighborhood of homes in Holland Ridge subdivision (Lebanon), built between 2019 and 2020, used open cell foam in walls and roofs, metal ties at roof-to-wall connections, and a continuous concrete footing with anchors at approximately 6 ft on center. One home suffered complete loss of the roof structure leading to an impact failure in the roof of the adjoining home, but other homes suffered only a few sheathing panels lost at most, with the majority only suffering cladding damage. The exact tornado path through the area was difficult to discern and this area will continue to be studied.

Related to the foundation anchorage, it is worth repeating the language in the 2012 IRC, Section R401.2, which states:

> *Foundation construction shall be capable of accommodating all loads according to Section R301 and of transmitting the resulting loads to the supporting soil.*

It is unclear how this can be achieved with the foundation construction details the FAST observed in these modern single-family homes. Yet at the same time, review of the prescriptive code requirements, and discussion with local foundation engineers familiar with regional practices, confirmed that the anchorage connections observed (specifically j-bolts embedded in a single grouted cell or head joint) nominally meet code requirements when considering the dead loads of the structure. However, such connections lead to brittle failures during above design wind events, providing little to no plastic capacity beyond initial failure and ultimately cause rapid and catastrophic collapses that compromise life safety. It is StEER's opinion that such glaring deficiencies in specific elements of the load path are inexcusable and should have no place in future construction. The following photos and graphics highlight some of the observations noted above:

Figure 6.1.8. Bottom and top views of the typical sill plate to masonry stem wall connection. Here the sill plate is fastened to the stem wall with a j-bolt embedded in the head joint between adjacent empty CMU blocks.

Figure 6.1.9. Observed roof-to-wall connections in newest homes, including (left) a hurricane strap, (middle) an incorrectly installed fully-threaded truss screw (0.15 in x 6 in; insufficient embedment in the wall double top plates) in the Hensley Dr. neighborhood, and (right) fully-threaded truss screw used in a raised heel truss.

Figure 6.1.10. Garage wall failures were commonly observed, typically due to failure of garage doors, positive internal pressurization of the garage, and separation of walls at story joints, where discontinuities in the vertical load path exist.

Figure 6.1.11. Anchorage failures were widespread, even when the majority of the home remained intact. This home slid approximately 50 ft off its foundation, and lofted over bushes. Red box indicates the original location of the home. The anchorage system present was the same as described previously - unreinforced masonry stem wall.

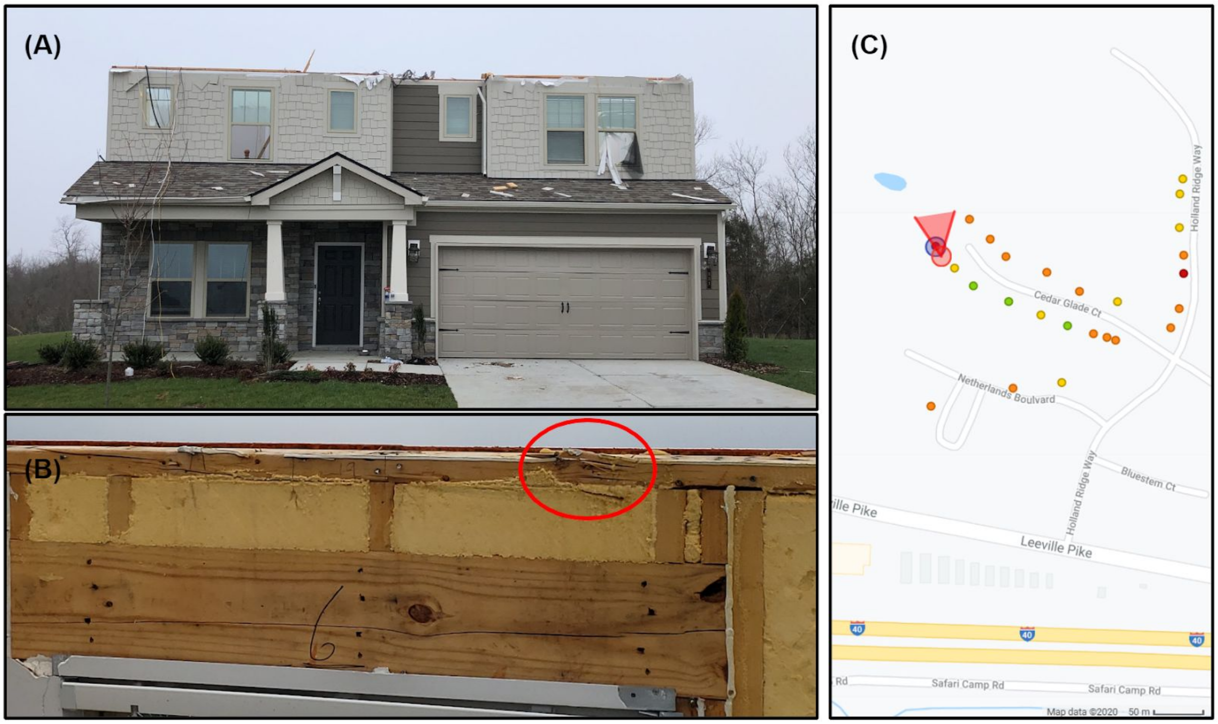


Figure 6.1.12. (a) New construction of single-family residential building structure in Lebanon with entire roof failure; (b) although hurricane straps were used to fasten the roof trusses to the walls (located on the inside of the wall), the lower nails of the hurricane strap barely caught the lower of the two top plates (highlighted by red oval), while the wall sheathing was stapled only to the lower top plate. The vertical load path at this connection therefore relied upon the withdrawal capacity of the nails connecting the upper and lower top plates to transfer loads to the walls.

In some North Nashville neighborhoods, many older homes were being demolished with new "tall and skinny" homes constructed in their place. These new structures were often situated with two homes on a single lot and can be 2- to 3-stories in height, sometimes with an additional rooftop patio, and have a very narrow (side-to-side) and deep (front-to-back) footprint. Area and prototypical structure were identified in a local news article (link). Failure of three of these structures (Fig. 6.1.13) showed the lower level had collapsed while the upper level remained relatively intact, similar to a soft-story failure. Since these were lateral failures and the upper levels and roofs were primarily intact, it was difficult to identify roof sheathing and fastening, or presence of any roof-to-wall connections. Although these structures appeared to be continuously sheathed with OSB, the combination of narrow side-to-side width and large openings along these directions - doors and window(s) - resulted in limited space for lateral bracing. Additionally, the foundation anchorage was consistent with that observed in other areas, such that anchor bolts or strap anchors were typically spaced at 48 in. on-center embedded into the CMU, and only those cells in the top course were grouted. Wall bottom plate-to-floor connections consisted of one or two 16d common nails at each stud bay.

Figure 6.1.13. (left) Collapse of lower level in newly built “tall and skinny” home in North Nashville on 14th Ave.; (right) pictured is the 2nd floor with the left-hand 1st story wall laying flat. Single grouted blocks in the top course of the stem wall were still attached to the sill plate.

6.2 Multi-Family Residential Buildings

Observations regarding the performance of multi-family residential (MFR) buildings are organized by type: townhomes (2-stories or less) and apartments (>10 units and >2 stories). Most apartment buildings were located in Germantown and Five Points and were constructed more recently. Townhomes were located in various neighborhoods and had a wider age range. These buildings were primarily inaccessible for detailed inspection of connections and continuous load paths.

6.2.1. Townhomes (≤ 2-stories)

Townhomes observed for this event were primarily wood frame structures, with some instances of brick veneer exterior. Townhomes in Cookeville (near the EF-4 tornado path) were primarily single-story with four to five units and likely built prior to 2000. The residential structures shown in Figure 6.2.1 were of similar build (wood frame with brick exterior). The structure in Figure 6.2.1b sustained a complete loss of roof and a punctured wall. The single family residential structures neighboring this structure were marked as destroyed. The structure in Figure 6.2.1a sustained minor damage while the neighboring structures sustained minor to moderate damage. The damage to this structure was focused on the end unit.

(a) (b)

Figure 6.2.1. Multi-family residences in Cookeville that appeared to be (a) on the edge of tornado path with minor damage and (b) directly in tornado path, where roof structure was destroyed. Photos taken March 9, 2020.

Increased damage to end units appeared consistent with townhomes in the Five Points neighborhood (Nashville Tornado) as well. Two of three structures in a townhome grouping are shown in Figure 6.2.2, where again damage appeared worse on the outer end unit(s). The relatively minor damage to the center structure (Fig. 6.2.2b) suggests the close proximity of the other townhome structures may have shielded it in this case, but more analysis is needed. Structures were of relatively newer construction than those in Cookeville and two-story instead of single-story. While the Cookeville townhomes consisted of primarily roof-related damage, the Five Points townhomes had more damage focused on the windows. These differences could be attributed to a combination of the tornado severity and proximity to path, year built, and/or two-story versus one-story structures. Debris surrounding the Five Points townhomes did not contain any evidence of hurricane ties for connecting wood roof trusses to wood wall framing.

Figure 6.2.2. Cluster of townhome structures where (a) eastern exterior structure sustained moderate damage and (b) northern interior structure sustained minor damage. Photos taken March 10, 2020. Photo with map available on Fulcrum App.

6.2.2. Apartments (>10 units)

Apartment buildings of greater than 2 stories and greater than 10 units were primarily located in the Five Points and Germantown neighborhoods of Nashville, with some in Hermitage as well. The apartments in Five Points and Germantown were all relatively new (less than 12 years old). The most common damage to these structures was punctured windows and/or glazing failure as shown in Figure 6.2.3. Many windows had neither tempered or laminated glass, which poses a particularly high danger to occupants within the room, as the glass will break into large pieces liable to cause serious cuts and injury.

The most severe damage to these structures occurred at the upper levels as illustrated in Figures 6.2.3 through 6.2.4. Additionally, stark differences in damage were observed based on the side of the building being viewed. Figure 6.2.4 shows an apartment complex in Five Points that appeared to have minor damage when approaching from Main St.; however, the north side of the structure showed exposed wood-roof trusses and a completely collapsed exterior wall for one of the units on the top floor. These differences suggest the tornado tracked just to the north of this structure.

Figure 6.2.3. Typical residential structure in Germantown (Apartments >10 units). Damage primarily to windows and roofing/ top floor.

Figure 6.2.4. Four-story apartment building located in Five Points neighborhood. Photos taken the week of March 10, 2020.

An apartment complex (approximately 10-12 years old) in Germantown sustained more severe damage. This 3-story L-shaped apartment building suffered 100% glazing failure on the windward wall, and roof loss in several places, initiated at locations having roof overhangs (Figs. 6.2.5a and b). The wind uplift on the roof structure was exacerbated by internal pressurization caused by fracture of window glazing. Evidence of hurricane ties was documented with this structure as well (Fig. 6.2.7c). This structure had more significant window failure than other multi-family structures, which were documented as minor to moderate damage.

(a) (b) (c)

Figure 6.2.5. Documented (a) roof failure, (b) initiated at overhang, with (c) evidence of metal ties in a 3-story apartment building in Germantown.

A wood-framed, three-story, apartment complex in Hermitage, with overhang balconies, showed similar failures initiated at the balconies on the top floor (Fig. 6.2-6). The majority of structures in this large complex did not show severe damage; however, most trees were downed in the area. Damage was also focused at center breezeway, which likely experienced increased wind speeds, leading to partial roofing failure

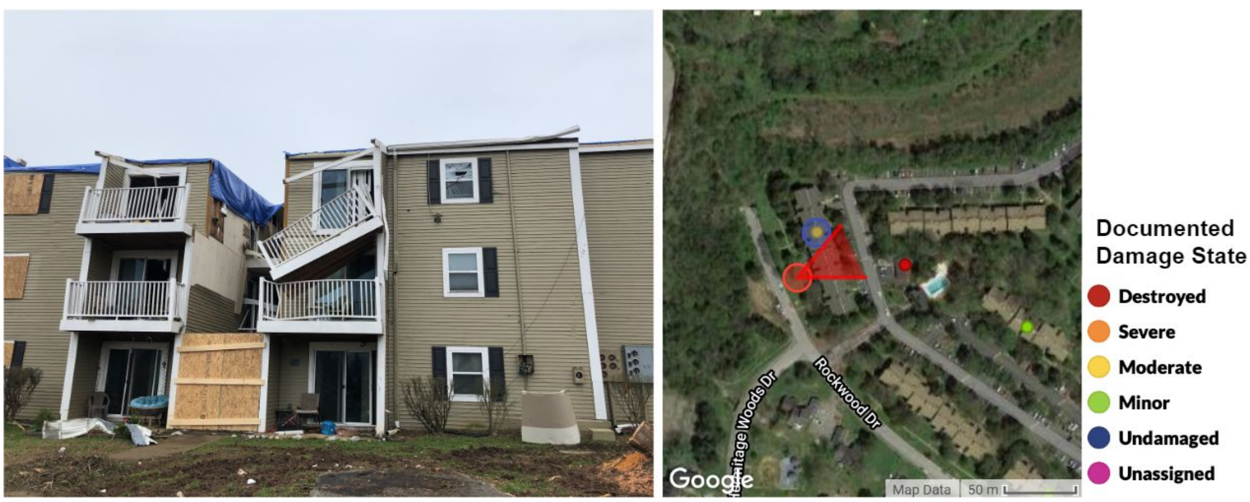


Figure 6.2.6. Balcony failure observed in a three-story apartment complex at Hermitage. Photo taken March 12, 2020.

A collection of two-story townhomes near Lebanon were recently constructed, with some still under construction, when impacted by the tornado. Townhome units at the framing stage in construction sustained the most damage, with the completed units generally performing well; however, the leeward wall on two units of a completed building did blow out (Fig. 6.2.7) due to the leeward wall suction pressures in combination with positive internal pressure. The roof structure, connected to the walls with hurricane ties at each truss, was not damaged. One or two roof sheathing panels were removed at the northwest gable end. A few roof shingles were blown off. The roof damage was typical for other buildings in the area.

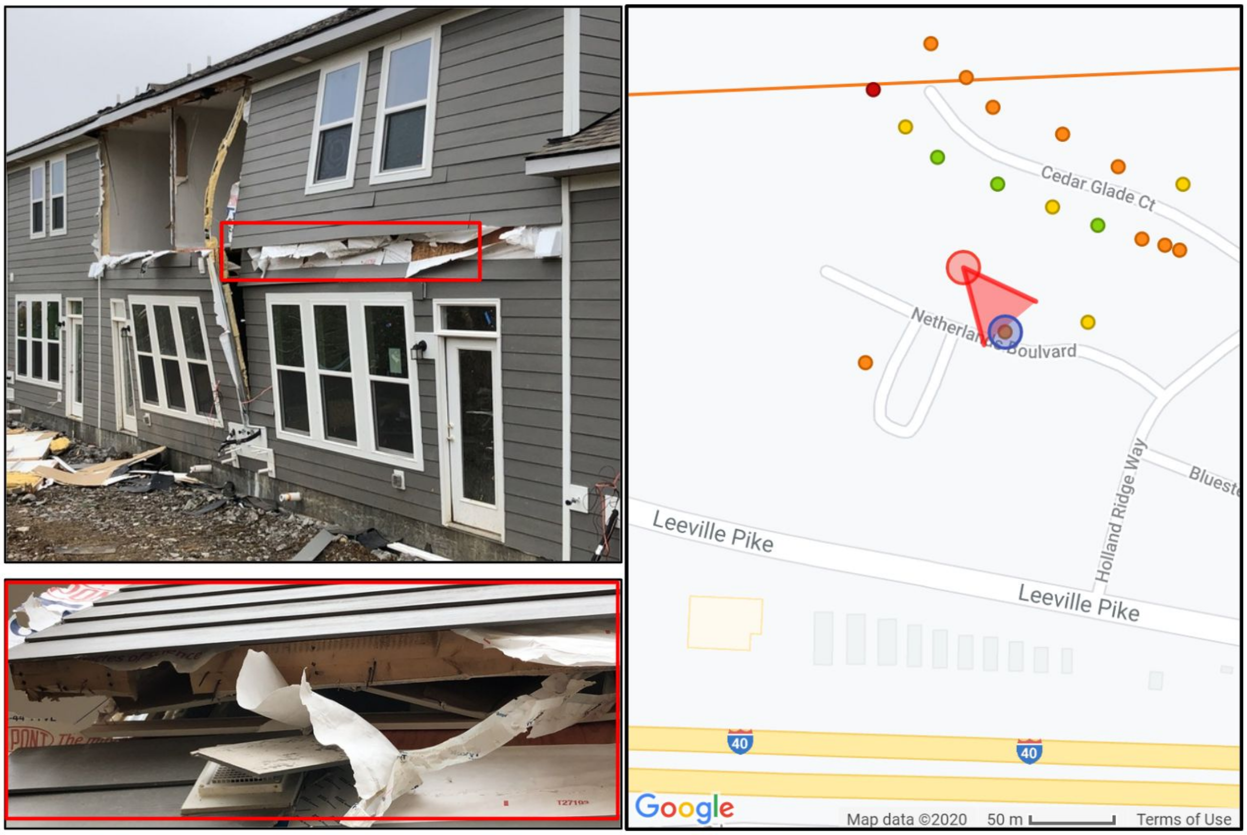


Figure 6.2.7. A multi-family complex near Lebanon constructed in 2019/2020 with blowout of the leeward wall. Connection between floors relied upon the shear capacity of nails into the bottom plate of the upper story. Sheathing was not continuous across the story joint. Open cell spray foam insulation was used in the walls and roof. The orange line in the right figure shows the NWS-estimated tornado centerline.

6.3 Mobile/Manufactured Homes

Relatively few mobile/manufactured homes (MMH) were in the path of the tornadoes. The FAST documented the performance of 20 MMH, which included seven in the Camden tornado, eight in the Nashville tornado, and five in the Cookeville tornado. Performance was noticeably conditioned on distance from the center of the tornado and orientation. Sliding of the MMH off the concrete piers, with only minor damage otherwise, was noted in five of the homes. One home had the home and debris completely swept away. Roof structure failure was noted in two homes. Where visible, anchorage systems were traditional tie-down straps and ground anchors with various spacing and anchor types. Figure 6.3.1 exemplifies the sliding behavior of two MMH in Wilson County. Interestingly, the two homes were pushed away from the tornado centerline based on the NWS estimated track (orange line). Tie-down straps were not visible, although one cross-drive anchor was noted in one home.

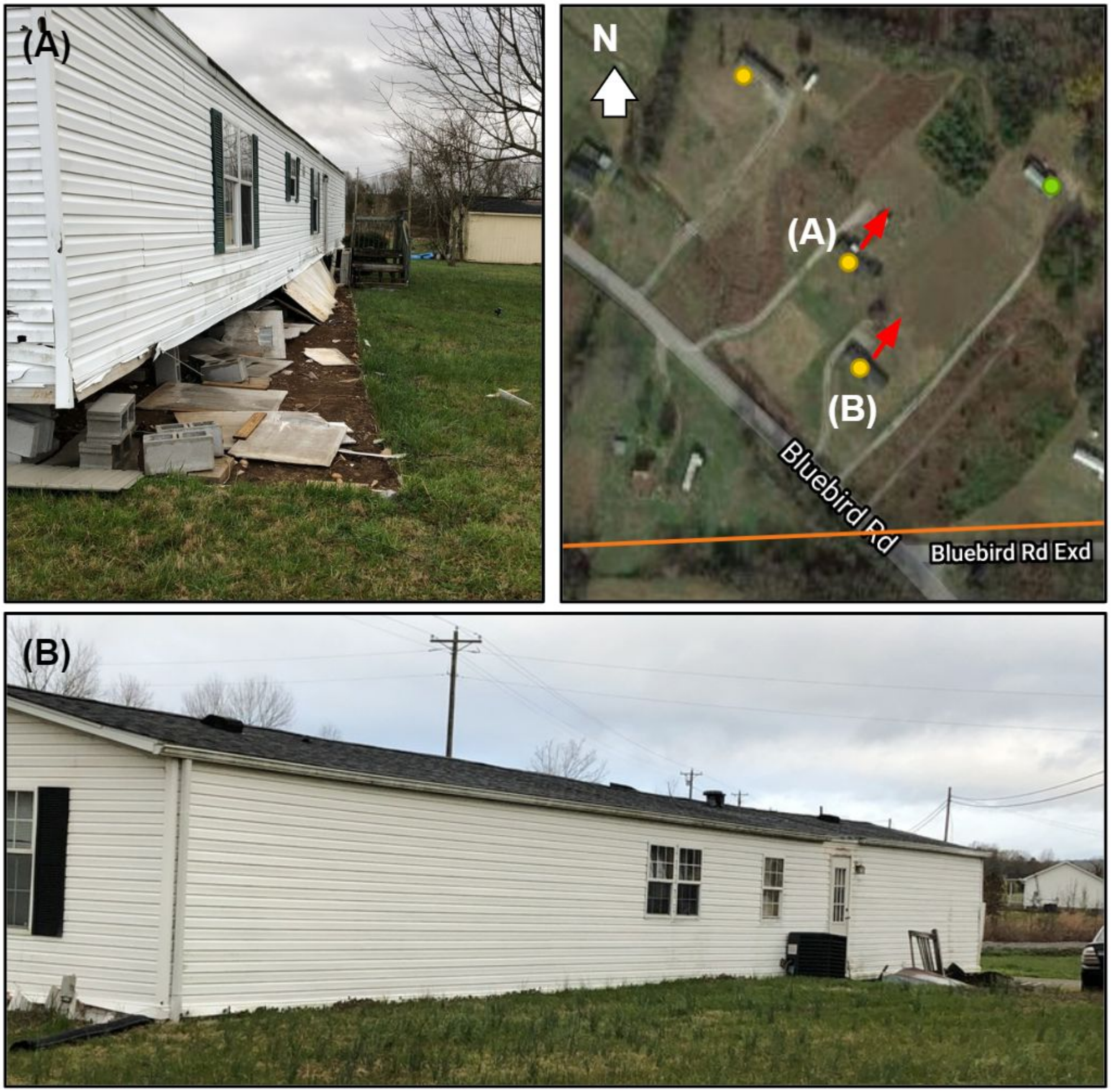


Figure 6.3.1. Typical sliding behavior observed in MMH, demonstrating that the anchorage system is often the weakest link in the structural load path.

6.4 Commercial Buildings

A relatively high density of commercial buildings were impacted in Nashville and surrounding communities. The FAST D2D assessments and UAS deployments primarily sampled from warehouses and other industrial buildings in and around the John C. Tune airport (west of Nashville), a mix of retail and professional buildings in Germantown and Five Points in Nashville, an industrial complex in Hermitage (just east of Nashville), and a large industrial complex just west of Lebanon. The following subsections provide preliminary observations for Retail and Small Professional Buildings and separately for large-footprint buildings such as Warehouses and Industrial buildings.

6.4.1 Retail and Office Buildings

The smaller professional and retail buildings were mostly older structures (pre-2000 construction) consisting of a mix of CMU and wood-frame construction, with some older construction consisting of multi-wythe brick masonry walls and wood rafters. In general, the light retail and professional buildings did not exhibit any signs of wind-resistant construction above local code requirements, which was not unexpected. Some CMU buildings had evidence of grouting and reinforcement in the bond beam, but in combination with lightly reinforced or reinforced walls. Bond beams and top sill plates still existed in place at several of the collapsed walls of the commercial buildings, demonstrating the lack of a continuous vertical load path from the bond beam down through the walls to the foundation. In general the structural load paths, particularly in the older buildings, were not well defined, and often evidenced a number of repairs and adjustments to the structure and architecture over the years. Figures 6.4.1 through 6.4.3 show several examples of the performance of these buildings.

Figure 6.4.1. Damage to two adjoining buildings in the Five Points area of Nashville demonstrating the typical variability in performance observed in retail and office buildings. (a) a destroyed brick and concrete masonry block building with some steel framing members (built in 1950). Minimal reinforcement visible in the rubble, primarily existing in the bond beam; (b) a brick and concrete masonry block building with moderate damage to the roof cover (built in 1970).

Figure 6.4.2. Additional failures noted in the Five Points area of Nashville: (a) Remnants of the bond beam and the wood top plate at a restaurant building originally constructed in 1935 with masonry block exterior walls, wood rafters, and cold-form steel interior walls; (b) Failure of prestressed concrete beams used in a small warehouse building constructed in 1962.

Figure 6.4.3. Destroyed office space in Germantown. Structure was built in 1910 and consisted of solid brick wythe walls (4 units thick) and heavy timber roof members.

6.4.2 Warehouse and Industrial Buildings

FAST sampled three primary clusters of large-volume warehouse and industrial buildings, the first just west of the John C. Tune airport west of Nashville, a second just north of I-40 in east Mt. Juliet, and a third approximately 1 mile west of the second. Structural systems in each of these consisted of tilt-up precast concrete systems or steel-frame metal buildings with unreinforced masonry in-fill. As highlighted in prior post-tornado reports, these structures generally did not perform well relative to surrounding structures, although further analysis incorporating the location of each building relative to the tornado centerline is needed to better contextualize their performance. Figure 6.4.4 summarizes the performance of commercial and industrial buildings in the industrial complex just west of John C. Tune Airport.

Figure 6.4.4. Cluster of damaged, large-volume industrial buildings west of the John C. Tune Airport sampled by FAST. Damage ranged from structural collapse of multiple bays (e.g., Building A) to moderate loss of metal roofing panels and insulation. Structural systems were steel-frame buildings with primarily CMU in-fill walls, steel roof joists or purlins, and corrugated metal deck.

Between Mt. Juliet and Lebanon, a large cluster of large-volume, tilt-up precast concrete buildings experienced damage varying between the uplift of roof deck and collapse of some roof joists to complete destruction of the building with all walls collapsed (Figure 6.4.5). It was not within the FAST objectives to conduct a detailed forensic assessment of the buildings, but team members did note failure of the welded connection between the steel girder trusses and the wall embed plates in the precast wall panels that may have been a failure initiation point. The destruction gives further evidence that these structural systems are very low along the spectrum of safe sheltering options in a tornado (preliminary evidence suggests at least one fatality occurred in one of these buildings), and businesses that utilize these structures must prepare well in advance of tornado impacts and have a plan for safe sheltering options for their employees.

FAST also sampled a cluster of industrial buildings off Eastgate Blvd. just east of the cluster shown in Figure 6.4.5. These buildings utilized a variety of structural systems and were constructed mostly in the early 2000s. Performance was mixed with several experiencing near complete collapse and others experiencing primarily loss of roof cladding without major structural collapses. A distinct damage gradient was not obvious, with the collapses appearing somewhat random throughout the cluster, necessitating further analysis.

Figure 6.4.5. Damage to a cluster of modern industrial buildings between Mt. Juliet and Lebanon. All buildings were tilt-up precast concrete construction with steel roof joists and joist girders. FAST captured aerial imagery via UAV of this cluster to develop densified point clouds to facilitate measurements and further analysis. A residential cluster in the same area experienced a mixture of failures, from complete destruction of a mobile/manufactured home, removal of the roof structure of a single-family home built in 1936, minor damage to a single-family home built in 1949, and moderate damage to Rutland Baptist Church.

6.5 Schools

The Nashville tornado affected several schools in its path. Preliminary damage assessments to each are available in the PVRR (Roueche et al., 2020). While on-site, the FAST had the opportunity to inspect two Mt. Juliet schools in person - West Wilson Middle School and Stoner Creek Elementary School - thanks to assistance provided by the local fire chief. Visits were also made to Donelson Christian Academy but access was not granted. A summary of the FAST observations are provided below. Several other schools with less severe damage, including Mt.

Juliet Christian Academy, East Nashville Magnet School, and others, were not assessed by the FAST.

6.5.1 Mt. Juliet Schools

West Wilson Middle School was primarily built in the 1970s with an add-on section in (approximately) 2012. The worst damage was in the 1970s section (closest to tornado path) in the SE corner. Approximately 1200 students are enrolled at this school. The school used suspended ceilings throughout, except in some interior rooms such as bathrooms, where there was a hard ceiling in place. The add-on section switched the ceiling type from hard to suspended ceiling in the bathrooms. Ceilings were supported by steel joists, while roofing appeared to be primarily corrugated metal. Shelter-in-Place was designated as hallways. Had students been sheltering in the hallways closest to the tornado, injuries up to and including loss of life could have occurred based on the observed structural damage (Fig. 6.5.1 insets (1), (2) and (3)). Locations with hard ceilings showed no signs of damage. Suspended ceiling tiles were missing throughout the building interior. In the rear part of the structure, suspended ceiling track failure nearly occurred. Ceiling tile dropout also occurred in the newer section, but at a lower rate. It is unclear if this section of suspended ceiling was braced laterally.

Stoner Creek Elementary was constructed in 1987. The structural system consists primarily of CMU block (with evidence of grouted and reinforced sections) with steel joists and steel roof beams. The roof deck was corrugated metal, and suspended ceilings were used throughout. Approximately 600 students attend this school. The school had a section of collapsed roof and walls on the south wing closest to the tornado path (Fig. 6.5.2). Ceiling tile dropout was observed similar to that of the older section of the West Wilson school (Fig. 6.5.1 insets (4), (5), (6), and (7)).

Figure 6.5.1. Overview of damage to West Wilson Middle School and Stoner Creek Elementary School in relation to the approximate tornado path (red arrow). Mt. Juliet Christian Academy sustained less severe damage but was not investigated by FAST.

Figure 6.5.2. Collapsed CMU wall and roof beams at the south wing of Stoner Creek Elementary School. Steel I-beams and evidence of grouted and reinforced masonry were observed.

6.5.2 Donelson Christian Academy

According to Dr. Keith Singer (head of Donelson Christian Academy), the primary damage to the single-story wing of the school was due to the 3 portable classrooms on-site, which was evidenced by the frame of one of the modulars still positioned atop the south wing of the academy (Fig. 6.5.3 inset (1)). The FAST was not permitted access inside, but Dr. Singer informed the team that the only failures in the designated safe areas (hallways) were non-structural with some ceiling tiles dislodged in one area, but otherwise these refuge areas performed well. Construction appeared to include single 2”x8” plates anchored to a grouted lintel/bond beam at top of the CMU wall. The remainder of the wall was ungrouted. The FAST noted frequent separation of the top lintel course from the rest of the wall.

Figure 6.5.3. Representative images showing damage to the Donelson Christian Academy. (1) shows the frame of a portable classroom atop the south wing of the academy; (2) shows roof trusses still attached to the CMU bond beam with portions of the wall below collapsed. (3) shows a toe-nail connection between roof trusses and the 2x8 sill plate.

6.5.3 Dodson Chapel United Methodist Daycare Center

The **Dodson Chapel United Methodist Daycare Center** (previously Dodson Elementary School until 2008) was located in Hermitage, a few miles east of Donelson Christian Academy. The structure was originally built in 1934, according to property records, although some alterations likely occurred since then. The structure consisted of wood-frame walls with brick facade and site-built wood trusses. The roof used dimensional lumber atop the trusses with an asphalt shingle roof. The gymnasium located in the southwest of the building appeared to be an addition, but the year of construction is unknown. The building consisted of CMU walls with open web steel joists and likely corrugated metal panel cladding, however the cladding was all stripped off.

The center was destroyed by the tornado, with most damage occurring on the southern portions of the building (Fig. 6.5.4). The south end wall of the gymnasium collapsed inward, as well as an exterior classroom wall on the south side of the building. Portions of the roof substrate (dimensional lumber) were stripped off the southern-facing slopes of the roof. Most fenestration was blown out of the south and west walls, with little damage on the east and north walls. The damage patterns suggests that the tornado passed to the north of the church.

Figure 6.5.4. Observed damage sustained by the Donelson Chapel United Methodist Daycare Center, including (1) collapse of the end wall of the gymnasium with evidence of torsional racking of the building; (2) collapsed walls and complete roof removal in a classroom on the south side of the building; (3) clean failure of the CMU blocks near the corner of the gymnasium with no evidence of reinforcement or fully grouted cells in the wall below the bond beam. FAST noted very little fenestration damage on the east and north walls of the building.

6.6 Government Buildings

The tornado impacted two government buildings in Germantown, specifically a building for the Tennessee Department of Children's Services and the Tennessee Department of Human Services. Both were located just west of the Cumberland River. Structurally, the buildings utilized reinforced concrete masonry walls with a brick facade. The roof structures consisted of steel I-beams with open web steel joists and corrugated steel decks. The **Department of Human Services** building was located closest to the tornado path, with the tornado possibly translating directly over the building, and suffered the heaviest damage. Approximately 30% of the walls collapsed, and nearly 50% of the roof structure collapsed. Failure was noted at the splice between the reinforcement extending up from the footing and the rebar extending through the CMU walls in multiple locations, similar to that observed in Coulbourne et al. (2015). It is unclear where failure initiated, but the failures were generally directed along the path of translation, indicating the strongest winds occurred on the backend of the tornado. Figure 6.6.1 shows failures at the base of the wall and at the connection of the roof beams to the bond beam, with the embed plate still fastened to the roof beam.

Figure 6.6.1. Total collapse of a government building in Germantown (GPS: 36.1740, -86.7822). The steel frame structure had infill CMU walls and brick veneers. Bent and snapped rebars were observed at the anchorage points.

The **Department of Children's Services** was located immediately south of the Department of Human Services and did not sustain any visible structural damage. Three HVAC units were blown off the roof, however, and the building was marked unsafe by local officials.

6.7 Historic Buildings

FAST observed several buildings listed on the National Register of Historic Structures that were severely impacted by the Nashville tornado, including **Hopewell Baptist Church** (East Nashville), **Church of the Assumption** (Germantown), the **Geist, John, and Sons, Blacksmith Shop and House** on Jefferson St. just east of Germantown, **First Baptist Church of East Nashville** (just west of Five Points), and the **Holly Street Fire Hall** (Lockeland Springs). D2D assessments were conducted at all but Hopewell Baptist Church and First Baptist Church of East Nashville, though street view imagery was captured for these locations. A summary of their performance is provided in Table 6.7.1. In general, structural performance was on par or worse than surrounding structures, highlighting the enhanced vulnerability of many historic buildings in the US to wind.

Table 6.7.1. Summary of damage to buildings on the National Register of Historic Structures. Locations are hyperlinked to post-tornado street view images.

Name	Location	Year Built	Damage Sustained
Hopewell Baptist Church	Buena Vista	1920	Severe due to collapse of brick steeple
Church of the Assumption	Germantown	1858	Collapse of rear wing gable; roof cover damage.
Geist, John, and Sons, Blacksmith Shop and House	Germantown	1900	Collapse of all brick wythes on front wall.
First Baptist Church of East Nashville	Five Points	1950	Minor roof cover damage; broken windows.
Holly Street Fire Hall	Lockeland Springs	1917	Partial roof collapse; most windows broken.

In addition to the specific buildings mentioned above, several regions such as Germantown, Buena Vista, and Lockeland Springs are also historic districts, despite containing a mix of old and new construction. General trends regarding the performance of the more historic buildings were difficult to identify, in part due to the relatively narrow width of the vortex. In these areas it was often difficult to parse out whether the variability in damage was due to differences in structural systems, localized shielding effects, disruption of the vortex structure or translation, or other factors. A case study is provided below for Germantown to illustrate some of the challenges.

The Germantown neighborhood, north of Jefferson Street in Nashville, is a residential community originally consisting of houses built by European immigrants (Irish, Italian, Swiss, German and Jewish) from the 1840s through 1920s. Through efforts of an active neighborhood association and established guidelines from the Historic Zoning Overlay District, some of the historic buildings and character are preserved. There are many restored historic (19th and early 20th century) solid (multi-wythe) brick masonry houses, newer infill construction in similar style and scale, and several multi-family developments, restaurants, bars, shops and businesses. The structures along the north of Germantown are predominantly single-family residential construction, while to the south of the neighborhood, the construction consists of several multi-story apartment building complexes. Germantown today is one of the most architecturally heterogeneous neighborhoods in Nashville.

Tornado damage in the Germantown Historic District was mixed, as highlighted in Figure 6.7.1. Most damaged structures are found along the west and south sides and along the south-east corner of the district. Many commercial structures (drug store, bank and car repairs) along Rosa Parks Boulevard (west side of Germantown) were destroyed, while damage to the homes just east of the commercial area, along 7th Ave. North varied from moderate damage to complete destruction. The **Church of the Assumption** located on this street suffered failure of its multi-wythe masonry gable wall on its west-facing elevation. Several of the multi-story apartment complexes along the southern borders (Jefferson St.) had moderate to severe damage, and many of these buildings partially lost their roof structures. The FAST observed that many of the historic homes in the middle of Germantown (near Monroe St. on the northern edge of the tornado path), suffered little to no damage.

Two possible hypotheses are proposed for the variable building performance: (1) structures on the north of Germantown are somewhat sheltered by the newer (and taller) structures built along Jefferson St., and (2) the structural resistance of the multi-wythe brick masonry structures combined with heavy roof structures are more capable of sustaining low to moderate wind loads without damage than are the newer light-framed wood apartment buildings. The vortex appeared to be relatively narrow here as well, although intensity was still high enough to collapse all or portions of several buildings along Jefferson St.

The distribution of damage observations in Germantown appeared different from damage observations among the three other Nashville neighborhoods surveyed (Fig. 6.7.2). Many undamaged structures were along the north edge of the tornado swath and the most severe damage was along the south edge, and not along a notional centerline as occurred in other neighborhoods. A second interesting fact was overall, the FAST rated 59% of the surveyed structures in Germantown as having minor or no damage, as compared with 34%, 33% and 22% of surveyed structures so rated for the Five Points, North Nashville and Lockeland Springs neighborhoods, respectively (Fig. 6.7.3). There are many variables still unknown that make it difficult to assess the significance of these statistics. However, they suggest that the unique characteristics of Germantown, its heterogeneous structural systems, and/or the tornado strength variations in that area, may warrant further investigation. Ultimately, uncertainty with these statistics underline some of the unique challenges in specifying causality to variable observed damage based solely (or mainly) upon field data. Note that the StEER quality-control verifications (DE/QC process) have not yet been conducted on any wind-damage rating data for this Nashville tornado.

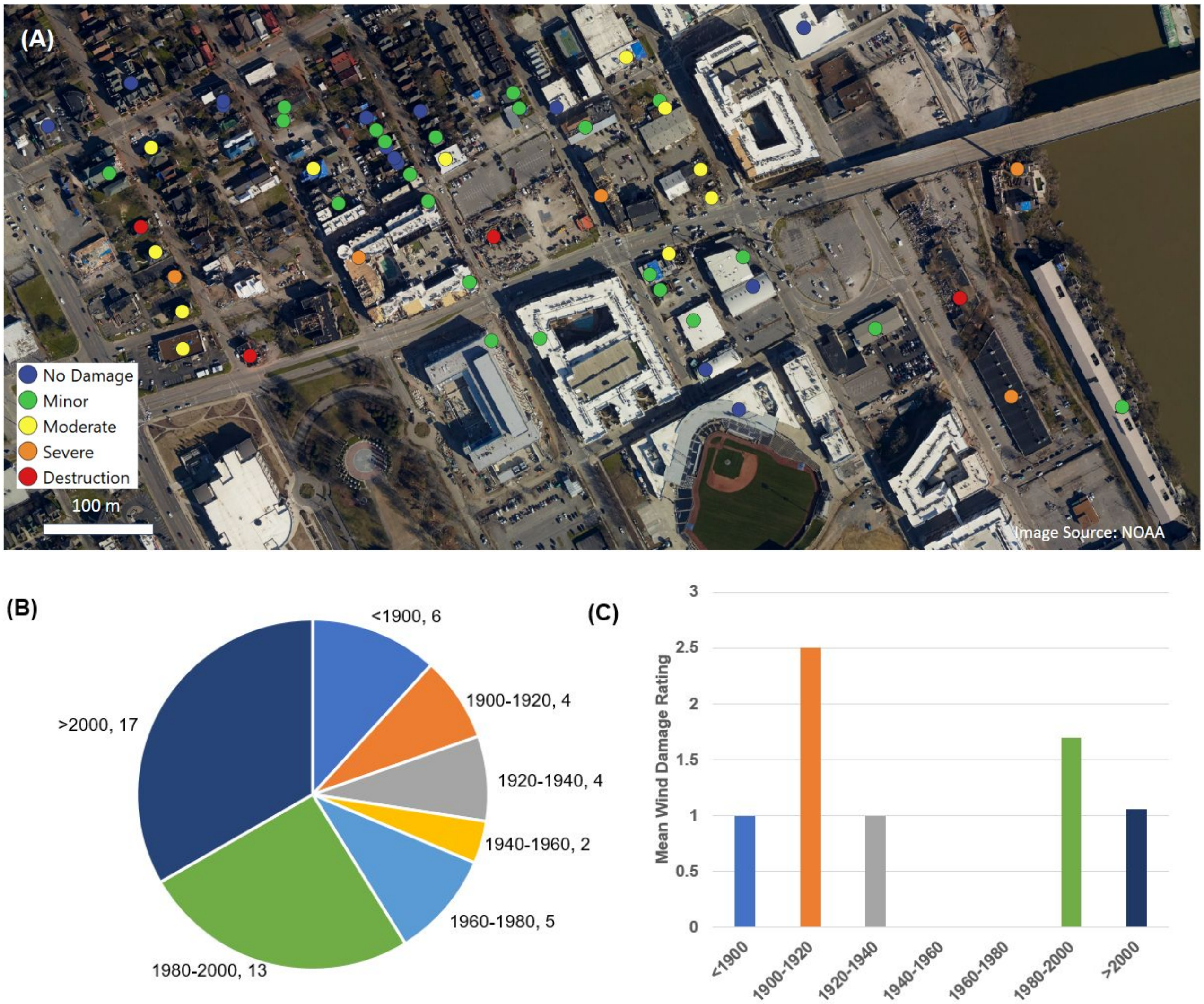


Figure 6.7.1. Summary of preliminary wind damage ratings in Germantown by year built. (a) wind damage ratings overlaid atop post-tornado imagery; (b) year built distribution of buildings sampled by FAST; (c) mean wind damage rating by era of construction.

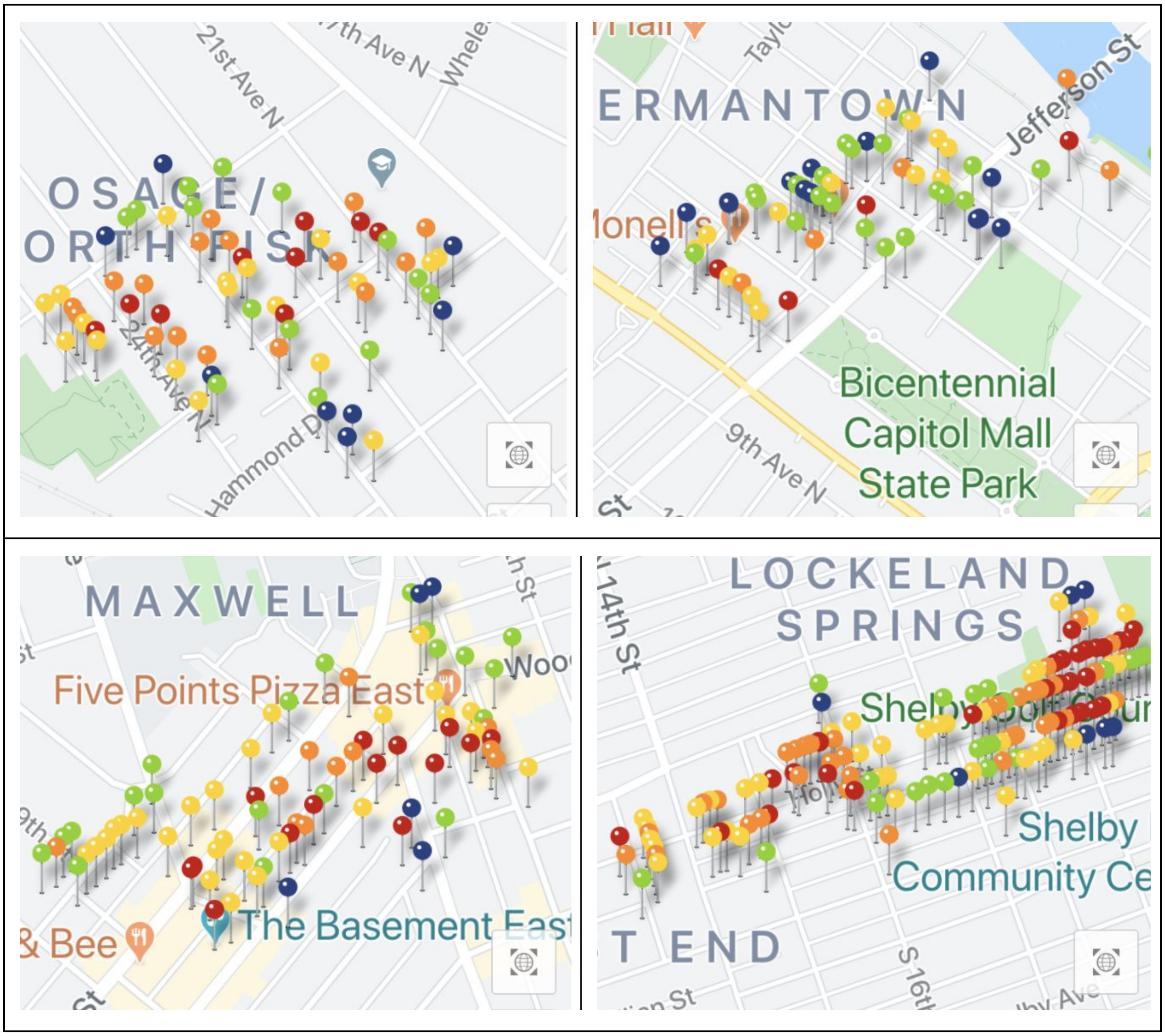


Figure 6.7.2. Comparison of damage rating clusters in four neighborhoods assessed by FAST in Nashville (clockwise from upper left): North Nashville, Germantown, Lockeland Springs and Five Points.

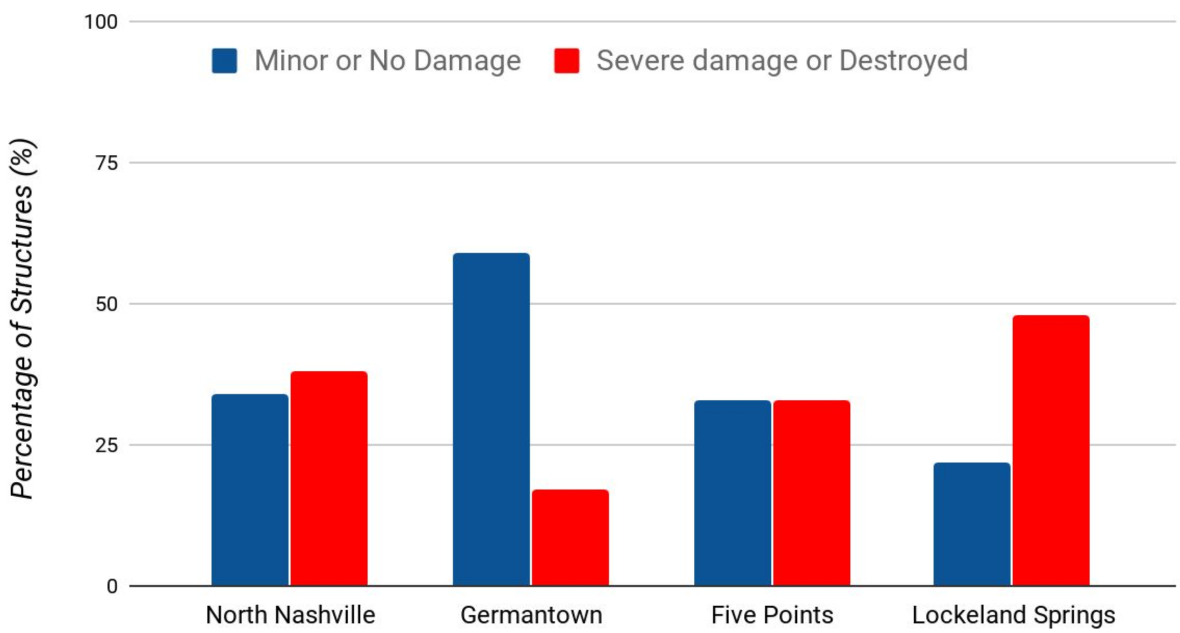


Figure 6.7.3. Preliminary distribution of damage in the four Nashville clusters assessed by FAST. Note that wind damage ratings are field-assigned and have not yet been fully quality controlled.

6.8 Religious Institutions

The FAST assessed the performance of ten church buildings within the paths of the Nashville and Cookeville tornadoes using D2D methods. Street View imagery captured several more. Of the ten churches with D2D assessments, three exhibited minor wind damage, two moderate damage, three severe damage and two were destroyed. Eight of the ten were located in the Nashville metropolitan area, including three in North Nashville, two in Germantown, and three in Lockeland Springs. Six of the churches could be considered heritage structures (Fig. 6.8.1). Each of these buildings were constructed with multi-wythe brick masonry walls and performance was generally of a similar nature to surrounding structures. The structural collapse exhibited in the **East End United Methodist Church** was disproportionate to surrounding residential structures, which exhibited mostly roof cover and fenestration damage.

Four of the churches suffered collapse of a gable end wall. The long spans and tall cathedral style ceilings can leave these end walls highly vulnerable to collapse under positive or negative wind pressures. Special consideration should be given to these end walls during future rehabilitation efforts for existing structures to minimize the potential for wind damage.

With the exception of one small, wood-frame church located in North Nashville that was completely swept away, each of the churches assessed could have provided a safe place of refuge to the community if persons had sheltered in their interior rooms or at least away from end walls; however, this observation does not constitute a recommendation that these structures be used for this purpose in the future.

Figure 6.81. Damage to six heritage churches: (a) East End United Methodist Church, with partial removal of the roof structure and collapse of some walls; (b) Assumption Church, with minor damage to edges of the metal roof and partial collapse of the gable wall on the northwest corner of the building; (c) Hopewell Baptist Church, with collapse of the brick steeple, damaging the roof and walls below; (d) the Church at Lockeland Springs, with only component and cladding damage visible; (e) St. John A.M.E. Church with collapse of the front foyer (Note the roof of this building is nominally flat with a small parapet and the roof structure did not experience observable damage); (f) First Baptist Church of East Nashville, with roof cover damage and broken windows.

6.9 Rural Areas

The FAST investigated a number of isolated homes and other buildings in more rural areas, including Allen Springs near Bowling Green, KY and portions of the tornado path through Gibson and Carroll Counties in Tennessee. Some observations from the FAST are itemized below by county.

6.9.1 Warren County, KY

- The damaged structures were located at the Allen Springs area, near Bowling Green.
- The damage path was narrow with a sharp gradient.

- There were several farm structures and livestock facilities destroyed, e.g., Figures 6.9.1 and 6.9-2. Structures consisted of an unanchored metal barn building and several unanchored wood structures. Falling trees impacted several of the structures.

Figure 6.9.1. Destroyed wood-framed farm structure (36.854049, -86.295355) with a few fallen trees, but most still standing.

Figure 6.9.2. Before (top) and after (bottom) total collapse of metal barn (36.852421, -86.302735). Wood posts were set in the ground with no positive connection to the 4” thick concrete slab. Wind resistance would have been minimal. A few felled trees nearby.

6.9.2 Gibson and Carroll Counties, TN

- Rural structural damage varied significantly due to differences in structural typologies and resistances.
- Structures even with anticipated higher resistances were prone to unexpected loads from windborne debris (Fig. 6.9.3).
- Residential construction practices varied with numerous structural collapses due to lack of anchorage in terms of metal ties or straps. These contributed to damage in structures with higher resistances.

- Steel silos failures (2 locations, Fig. 6.9.4) only used grouted connections with no mechanical anchors.

Figure 6.9.3. Debris field in rural/agricultural areas (36.087824, -88.340024) including corrugated steel from failed silos.

Figure 6.9.4. Steel silo failure (36.091628, -88.372416). Failure due to grouted or epoxy connection at base.

7.0 Observed Performance of Infrastructure

7.1 Power & Communications Infrastructure

FAST directly assessed power and communications structures in a few locations and also noted observations related to infrastructure performance. As would be expected, the tornado downed a large number of power poles, most of which were already repaired or being repaired by the time FAST deployed. This included high-voltage transmission line towers in Mt. Juliet and Nashville (Fig. 7.1.1, right); however, replacement of the structures had already been completed by the time the FAST deployed. A few power infrastructure assessments were recorded using the StEER Non-Building (Windstorm) Fulcrum app, but the impressively quick action of the power companies in repairing downed poles prevented more rigorous assessments. Some observations related to power are summarized below:

- Lack of power in Lockeland Springs/Barclay Drive areas as of March 10th.
- Power was still being restored in some areas but progressing well in Cookeville as of March 10 and 11th.
- Some road closures due to work on power lines in the West Nashville area.
- Lack of power in select Carroll County areas.

Specific observations made by FAST related to communications are summarized below:

- No internet available at the team's hotel in Lebanon March 8-10.
- Mobile connectivity available for teams in the field on March 9.
- Mobile data was slower in the Donelson area, but present (March 10).
- Full connectivity/no gaps in coverages were observed in most regions on March 12
    - Mobile data connectivity was intermittent in Barclay Drive area (March 12)
    - Mobile data connectivity was intermittent in North Nashville around 14th Ave. & Underwood St. (March 12).
- No data, no voice was available near the treefall site in Waverly (March 13, Location: 36.1080°, -87.9047°).

Figure 7.1.1. Illustrative damage to power infrastructure observed by FAST: (left) damage to power poles and traffic signal structure in Mt. Juliet (36.186894, -86.41586); (right) lattice towers in Mt. Juliet (Location: 36.184661, -86.464333) supporting 500 kV high-voltage transmission lines replaced after being damaged in the tornado, per the TVA.

7.2 Airports

The John C. Tune Airport was briefly accessed on March 11. The FAST observed substantial wind and windborne debris induced damage (including flight of large objects such as a dumpster) to some of the hangars and other buildings. On one hanger, a steel column base plate was noted to have been ruptured in tension (Fig. 7.2.1). Airport maximum wind speed was estimated by the NWS around 160 mph (per conversation with an airport official). The FAST did not have much opportunity to provide more than a cursory assessment of the airport due to access, time, and weather limitations.


Figure 7.2.1. Baseplate damage and steel tension rupture in a collapsed hangar at the John C. Tune Airport.

7.3 Roadways

No direct tornado-induced roadway damage (e.g., scouring) was observed by the FAST. As is common after significant tornado events, some roads are likely to be damaged during the recovery process however, due to the overloads induced by hauling heavy equipment and debris that exceeds axle weight limits. Restrictions at locations like John C. Tune Airport or Germantown commercial district were due to security concerns and not infrastructure performance.

8.0 Observed Evidence of Hazard Intensity

Tornado hazard intensity can be informed from a number of non-building sources, including tree-fall direction (e.g., Fig. 8.1), sign failures, light poles, and other non-building structures. In total, the FAST documented 49 tree-fall locations and six pole-style wind hazard indicators in ground-based assessments to augment the aerial imagery, streetview, and other sources for documenting hazard intensity. For the Cookeville tornado, Lombardo and his team collected detailed information on tree-fall, street sign damage, debris start and end points. They also noted areas of significant topography and terrain. Aerial imagery was also collected and will be used to assess tree-fall patterns. Lombardo and his team will do a further analysis of hazard intensity, including topographic influences as part of a NOAA VORTEX-SE project, especially in the Cookeville area. The presence of such topography has been shown to significantly influence tornado characteristics including the path and intensity (e.g., Satrio et al., 2020). Initial, ground-based tree-fall pattern observations suggest a fast-moving tornado relative to its rotational speed. A brief summary of some of the hazard indicators that will be used to estimate intensity is available at the following link: UIUC Cookeville Summary.

Wood and Liao documented extensive treefall in Waverly, TN, noting complex topography that may have affected the patterns (Fig. 8.2). UAS was utilized to capture aerial views of the patterns. UAS was also utilized in the Barclay Drive / Lockeland Springs area of Nashville to document tree-fall patterns for analyzing impacts of topography and identification of the tornado path. Similar to Lombardo and his team, this data will be used to assess tree-fall patterns in this area of varying topographic features and train detection algorithms for other events.

Figure 8.1. Treefall (in NE direction) at Shelby Golf Course just east of Lockeland Springs.

Figure 8.2. Tree fall damage near Waverly, TN documented by Wood and Liao. Aerial view from approximately 250 ft above ground level.

9.0 Recommendations for Further Study

FAST primarily focused assessments on the EF3 Nashville tornado and the EF4 Cookeville tornado. Clusters of buildings were assessed in multiple regions along the length of the path in the former, while the Cookeville tornado was characterized almost in its entirety. FAST sampled diversely from single-family residences, multi-family residences, schools, religious facilities, and commercial buildings. Preliminary review of assessments logged by the FAST in these areas, in addition to observations by the team members as they traveled throughout the impacted areas, have led to the following recommendations for future study:

- **Recommendation #1: A rigorous assessment of disproportionate element strengths in the vertical load path of modern single-family homes is needed.** In modern homes, FAST observed straps and anchor bolts at some links of the load path, yet with toe-nails and other weak connections at other links. These disproportionate capacities within the load path severely limit the full wind capacity of these structures, since it is the weakest link which is the most critical. A rigorous analysis (numerical and/or laboratory testing) is needed that encompasses every link of the load path in order to educate builders, homeowners, and other stakeholders, and inform future building codes.

- **Recommendation #2: Tornado vulnerability and risk mitigation studies are needed for existing schools in tornado-prone regions of the country, echoing numerous previous engineering studies,** such as Prevatt et al. (2012) [see Appendix C] and Coulbourne et al. (2015) [see Appendix E]. Thankfully the Nashville tornado was not an EF4 or EF5 and it occurred outside of school hours, but the high winds exposed once again the lack of safe sheltering options in many of the nation's existing schools. Had the tornado occurred during a school day, serious injuries or fatalities would likely have occurred due to structural collapses in the designated places of refuge. The performances of the schools mirror similar poor performances noted in numerous past tornado studies, but as structural engineers, StEER will continue to recommend this until it is heeded.
- **Recommendation #3: Continued studies are needed on the poor performance of large volume low-rise buildings, particularly tilt-up precast concrete construction.** FAST observed disproportionately poor performance of these facilities, with catastrophic collapse of several in Mt. Juliet. It is unknown whether these were occupied and if so, the sheltering choices and injury status of those who were present, but the failures posed significant risks to life safety and highlight the lack of safe failure sequences in these and similar structures.
- **Recommendation #4: Continued research and investment is needed on methods for measuring or more reliably estimating wind speeds in tornadoes.** While the community continues to use it, the current EF Scale method remains an imperfect, indirect method for estimating wind speeds from damage. It is unknown whether EF scale provides reasonable estimation of tornado intensity and/or peak wind speed. The most direct means to know tornado strength is to measure it - all other approaches merely provide estimates based upon incomplete models of tornado wind flows and their interaction with structures and using very generalized estimates of structural capacity. **Detailed and focused assessment of tree-fall, directionally-informed building damage data, wind-borne debris swaths, and other hazard intensity data are needed to better understand the time-varying wind field.**
- **Recommendation #5: Investigate the structural details of homes where fatalities and serious injuries occurred with support of local officials**. Tornado fatality risk is commonly associated with mobile/manufactured homes, yet very few of these structures were affected in these tornadoes that killed 24 persons. Risk factors for fatality and serious injury in non-mobile homes are needed that go beyond broad structural classifications (e.g., mobile home vs. permanent home) in order to better inform the public as to tornado sheltering practices, safe construction methods, and more. County and state emergency management agencies can be of great assistance in this effort by providing reliable information regarding where fatalities and injuries occurred as much as possible.

Other topics beyond yet tangential to StEER's current mandate that are worthy of further investigation include:

- **Topic #1: Improved exploration of the intersection of epidemiological and weather risks.** The March 3rd tornadoes struck about a week before major societal changes were made in response to the COVID-19 risks, but by the conclusion of the FAST deployment, the local and national response to the COVID-19 threat had ramped up substantially. The intersection of epidemiological and weather risks has many implications from warning and preparedness messaging, to sheltering actions, to response and recovery, and even to research efforts. With COVID-19 risks continuing this year, and other epidemiological risks likely to happen in the future, more research is needed to explore implications of this intersection. In particular, recovery efforts from the March 3rd tornadoes are likely severely hampered in affected areas by COVID-19, but it is unknown to what extent without a baseline. It is also unclear to what extent current resiliency models account for these and similarly intersecting hazards.
- **Topic #2: Methods for quickly translating engineering reports to consumption by the general public for use in recovery for the current and future disasters.** The knowledge captured in previous tornado reports (see Appendices B-F), this current report, and subsequent products stemming from this report need to be more effectively translated to at-risk communities so that they are fully aware of the risks and mitigation possibilities. Interdisciplinary teams beyond engineering, including social scientists, graphic designers, communications/journalism, are needed to refine and translate this critical engineering knowledge through a broad array of mediums to facilitate more effective uptake by the general public and key stakeholders.

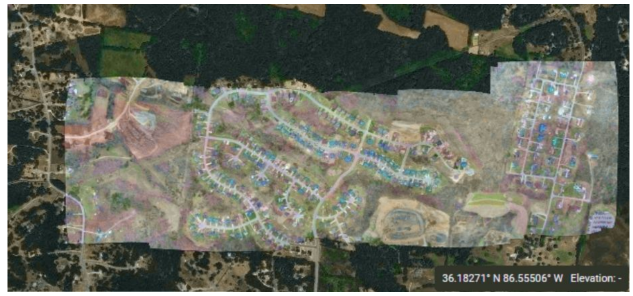
Based on the preliminary observations from this FAST and the current stay-at-home directives in response to COVID-19, StEER did not send additional FASTs to collect data in response to this event. Still StEER does encourage the community's continued engagement on the topics listed above. Researchers will continue to analyze these data to provide more rigorous findings and practical guidelines that can inform future construction.

Finally, it is important to recognize that many of the structural recommendations and lessons from the March 3, 2020 tornadoes build on or even directly echo those observed in prior tornadoes. A selection of findings from some of the major past tornadoes are included as appendices to this report: Tuscaloosa, AL (Appendix B), Joplin, MO (Appendices C-D), Moore, OK (Appendix E), and Dallas - Garland/Rowlett (Appendix F). An extensive list of recommendations from the Joplin, MO tornado are also freely available in the NIST report (Kuligowski et al., 2013). There is also a wide range of peer-reviewed literature that pertains to this topic. Continued recognition of these repeating patterns of failure are unfortunately necessary in order to achieve the series of incremental improvements that will bring about a more tornado-resilient society.

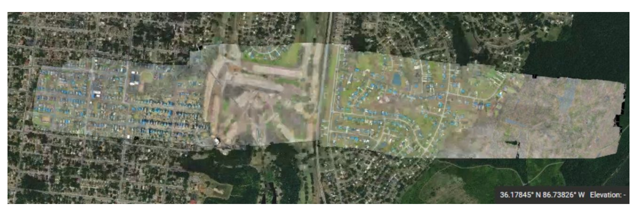
Appendix A. Properties of Unmanned Aerial Surveys

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Mt Juliet - CEVA Storage 36.1775°, -86.4628° Mavic Pro 2 03/08/2020 Polygon 310 ft 75 85% (Front), 75% (Side) 2,157 8 303.44 acres 2.84 cm (1.12 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Lebanon - Eastgate 36.1879°, -86.4168° Mavic Pro 2 03/16/2020 Polygon 329 ft 75 85% (Front), 75% (Side) 329 2 68.79 acres 2.89 cm (1.14 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Lebanon - Hartmann Plantation 36.1888°, -86.3386° Mavic Pro 2 03/16/2020 Polygon 251 ft 75 85% (Front), 75% (Side) 465 2 66.46 acres 2.32 cm (0.91 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Lebanon - StoneBridge 36.1893°, -86.3809° Mavic Pro 2 03/09/2020 Polygon 305 ft 75 85% (Front), 75% (Side) 2,231 6 363.57 acres 2.80 cm (1.10 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Mt Juliet - Triple Crown 36.1798°, -86.5348° Mavic Pro 2 03/09/2020 Polygon 317 ft 75 85% (Front), 75% (Side) 2,295 8 360.22 acres 2.91 cm (1.15 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Donelson Christian Academy 36.1840°, -86.6504° Mavic Pro 2 03/10/2020 Polygon 70 ft 75 85% (Front), 75% (Side) 1.146 2 13.06 acres 0.63 cm (0.25 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Nashville - Five Points 36.1764°, -86.7546° Mavic Pro 2 03/10/2020 Polygon 207 ft 75, 50 85% (Front), 75% (Side) 1,786 11 77.75 acres 1.92 cm (0.75 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Mt Juliet - West Wilson Middle School 36.1844°, -86.5105° Mavic Pro 2 03/11/2020 Polygon 200 ft 75 85% (Front), 75% (Side) 800 3 36.08 acres 1.83 cm (0.72 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Mt Juliet - Stoner Creek Elementary School 36.1846°, -86.5024° Mavic Pro 2 03/11/2020 Polygon 212 ft 75 85% (Front), 75% (Side) 380 3 24.92 acres 1.96 cm (0.77 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Nashville - Germantown 36.1760°, -86.7857° Mavic Pro 2 03/11/2020 Polygon 218 ft 75 85% (Front), 75% (Side) 1,662 10 97.66 acres 2.00 cm (0.79 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Nashville - Lockeland Springs & Barclay Drive 36.1750°, -86.7264° Mavic Pro 2 03/11 and 12/2020 Polygon 243 ft 75 85% (Front), 75% (Side) 5,293 11 425.90 acres 2.24 cm (0.88 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Nashville - Cockrill Bend 36.1779°, -86.8975° Mavic Pro 2 03/12/2020 Polygon 320 ft 75 85% (Front), 75% (Side) 1,241 3 201.41 acres 2.96 cm (1.16 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Waverly Area 36.1080°, -87.9047° Mavic Pro 2 03/13/2020 Polygon 275 ft 75 85% (Front), 75% (Side) 3,927 10 526.07 acres 2.53 cm (1.00 in)	
Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Charlton Square 36.1768, -85.5903 Mavic Pro 03/09/2020 Polygon 150 ft 90 80% (Front), 70% (Side) 452 1 22.86 acres 1.47 cm (0.58 in)	

Location ID: **Coordinates:** **Drone Type:** **Flight Date:** **Flight Type:** **Flight Altitude:** **Camera Angle:** **Overlap:** **No. Photos:** **No. Flights:** **Area Covered:** **Average GSD:**	Holland Ridge 36.1881, -86.3978 Mavic Pro 03/11/2020 Gridded 120 ft 60 70% (Front), 70% (Side) 936 1 26.6 acres 1.67 cm (0.66 in)	

Appendix B. Tuscaloosa (2011)[3]

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATIONS

Light-frame wood buildings do not, and will not, have the ability to resist EF4 or EF5 tornadoes. The Tuscaloosa tornado of 2011 was rated an EF4 tornado by the National Weather Service, and the authors of this report concur based on the method of rating a tornado at the strongest point along a touchdown path. Based on the information contained herein, and case studies not necessarily in this report but available on the web site http://esridev.caps.ua.edu/tuscaloosa_tornado/the following conclusions were reached:

1. The level of damage to light-frame wood buildings is not acceptable and can be reduced through new engineering design and construction practices.

2. The majority of residential buildings that suffer some level of damage in the path of a large tornado is caused by winds below the overall tornado EF rating assigned by the National Weather Service. Virtually all buildings in the path of a strong tornado, even along the outer edges where wind speeds are lower, are irreparable based on current design and construction practices. This provides incentive and an opportunity for tornado-resistant design and construction practices, which currently do not exist.

3. Damage to buildings on the outermost edges of the tornado appeared to be from inflow to the tornado vortex. This damage is mainly due to building penetration from debris strikes and wind speeds less than 130 mph.

4. Vertical load paths were not adequate, regardless of the age of the residential structure. Load paths appeared to be better provided on multi-family buildings.

5. Interior closets and bathrooms provide shelter at lower wind speeds on the edges of the tornado, but were no guarantee of survival. The concept of "safe spot" should still be taught, but a safe spot is not a substitute for a safe room or tornado shelter.

The following are the recommendations for further work on tornado loading of structures and mitigation of damage and loss of life:

1. Need to determine what tornado winds can be resisted with improved design and detailing. Identify realistic threshold wind speeds to address when trying to shift damage at the outer edges of a tornado, i.e. quantify the speeds at which certain failures occur so design strategies can be developed to prevent failure at those speeds. A systematic study needs to be conducted that

[3] http://www.davidoprevatt.com/wp-content/uploads/2011/08/tuscaloosa-tornado-report-final.pdf

focuses on the optimal threshold tornado wind speed for which engineers should be designing a system.This requires a thorough survey of possible improvements and design options that are practical and the corresponding wind speed at which these measures will be valid. A study should also be conducted on the cost-benefit ratio of these design options at various wind speeds to inform the calibration of the new dual-objective tornado design philosophy. This threshold is highly dependent on the structure type. For wood-frame buildings it is likely to be in the 130~150 mph range.

2. Develop a better understanding of the spatial characteristics of tornado loading. The current understanding of tornado loading on structures is not comprehensive or even comparable to that for straight strong winds because of the high level of turbulence and debris in a tornado. This is partially due to the lack of experimental procedures to accurately represent tornado loading. Unlike widely adopted scaled wind tunnel testing for wind loading on structures and components, it is very difficult to experimentally investigate the spatial characteristics of the loading on buildings within a tornado path. It is not clear how the lateral wind pressure and suction acts on different components of a structure, although some work has been performed on this issue (Sakar et al, 2008). Although applying design methods from straight wind cases will likely improve the resistance of buildings against tornadoes, designing using realistic and quantifiable tornado loading is most desirable. Studies in this topicshould be focused on scaled experimental work, numerical simulation, or in-situ tornado data collection.

3. Need acceptable and implementable approaches in design and construction to realize the damage reduction. A suite of design and retrofit measures should be developed to reduce structural and component damage up to the threshold wind speed. The measures for design and retrofit can be very different and may take many forms including adjustment factors for loading, prescriptive requirements, innovative analysis procedures, and additional load cases (such as the breached garage door case for attached garage wall and roof design). These measures must be backed by available products on the market that can be implemented by the current residential construction industry, possibly with minimal training. Implementing hurricane region construction practices and products in tornado-prone regions is a good starting point, but not necessarily an end solution.

4. Shelter inclusion for above threshold wind. For wind speeds exceeding the threshold, the alternatives of a shelter or safe room can provide life safety to building occupants. The shelter must be designed to handle both wind pressure and debris impact. The current guidelines (FEMA 320, FEMA 361 and ICC 500) to build safe rooms and shelters per FEMA or ICC recommendations can be adopted and enforced more for tornado prone regions. Shelters should

be included at the same time as the component and system philosophies are implemented as discussed above.

Appendix C. Joplin (2011) - ASCE Report[4]

CHAPTER 7 – CONCLUSIONS AND RECOMMENDATIONS

The 2011 Joplin Tornado was rated an EF-5 tornado by the National Weather Service and caused tremendous damage to both residential and commercial buildings in the affected area. Public safety was especially threatened by this event due to catastrophic failure of multiple critical public gathering facilities in the area, including extensive damage to several school buildings. The ASCE Joplin Tornado Investigation effort included residential buildings and critical facilities that were accessible during the investigation. The team utilized a well-developed tornado survey and damage mapping methodology which had been proven in other tornado damage surveys. Based on the information gathered in this study, the following conclusions can be reached:

1) The design and construction practice in tornado damaged commercial large-span box-shaped buildings lack the consideration or redundancy in connection detailing needed to prevent catastrophic collapse under extreme tornado loading. This was observed in most of the large span school buildings for which stability became a major issue after losing the roof. This loss of load path was partially due to the failure in enforcing the required anchorage details specified by the IBC. Although the team could only survey the damage to Walmart and Home-Depot shopping centers from a distance due to access restrictions. However, the research team believes that these box-shaped commercial buildings lack sufficient redundancy and material strength to provide protection from tornadoes and in-store tornado shelters (or safe areas) should be added.
2) Performance of existing and newly constructed residential structures is not satisfactory from a damage mitigation perspective. Although total devastation at the center on the tornado path is expected for light frame wood buildings, a significant amount of damage in the outer range of the path (where EF-0 – EF-2 wind speeds occur) can be reduced through strengthened connections and improvement in continuity of load path techniques used in hurricane-prone areas.
3) The damage pattern left by the Joplin tornado showed that only about 17% of the affected area experienced such high wind speeds that mitigation strategies would be uneconomical. The majority of the observed damage in the areas impacted by EF-0 to EF-2 wind speeds can however be mitigated using cost-effective measures. A clear trend of reduced damage can be observed from the center of the tornado path to the outer perimeters. These observations on the range of tornado damage directly lead to the proposed dual-objective design philosophy for tornado events.
4) The research team believes a dual-objective design philosophy and corresponding procedures should be developed for tornado hazard mitigation and made available to the communities that may be affected. The statistics from past tornado damage and intensity indicate that the benefit from implementing this philosophy can greatly help the community in preparation and recovery from tornadoes.
5) The procedures and practices currently enforced in hurricane-prone regions for residential buildings can be adopted to reduce certain levels of tornado damage. It is believed, and research has confirmed, that the vertical wind component in tornadoes is significantly larger than in hurricanes. This phenomena needs to be considered in developing design and construction techniques for residential buildings in tornado-prone areas.

The research team has developed the following recommendations for further work on tornado-structure interaction and hazard mitigation:

[4] https://ascelibrary.org/doi/book/10.1061/9780784412503

1) Develop special provisions for the design of critical facilities to resist tornadoes. Tornado events should be designed considering limit-states and loading conditions so that the stability of the structural components is ensured after the building envelop is breached. Safe shelters should be included in human-occupied critical facilities.
2) Develop a better understanding of the failure mechanisms of long-span structures such as shopping centers and school gymnasium buildings. There are a great number of similar buildings in the current building inventory, and their poor performance under tornado loading conditions presents a significant threat to public safety. It is recommended that detailed structural failure analysis (such as disproportionate collapse analysis) be conducted on damaged structures to find retrofit measures as well as develop a direction for future improvements.
3) Work towards a realistic design procedure for tornado hazard mitigation based on the dual level design philosophy developed from this investigation. This process needs research efforts in two major aspects. First is a better understanding of tornado wind-structure interaction so that a realistic threshold for the dual level application can be identified. The tornado wind forces need to be quantified in combination with certain failures observed in structures so that design strategies can be developed to prevent failure at those speeds. The threshold wind speed at which the design should shift from focusing on damage reduction to life-safety depends largely on the specific structural type and configuration. For wood-frame buildings it is likely to be in the 130~150 mph range. Secondly, practical and cost efficient design and retrofit measures should be developed to a) reduce structural and component damage up to the threshold wind speed and b) protect life safety through strengthening a portion of the structure (basement, small room, etc.) against wind speeds that are above the threshold and missile impacts. The measures for design and retrofit can be performance-based in nature but prescriptive recommendations with readily available products on the market should be provided. Analytical and experimental research in these areas is needed to achieve this objective.

4) Conduct an economic loss study on the societal impact of tornado losses. Identify the performance targets for community readiness for a tornado hazard. A systematic study needs to be conducted that focuses on a loss-based strategic planning framework for communities and regions affected by the tornado hazard. A study should also be conducted on the cost-benefit ratio of potential strategies in order to calibrate the parameters (such as threshold wind speed) for new dual-objective tornado design philosophy. Assembly based vulnerability methodology can be applied in assessing tornado induced economic loss analysis for individual buildings in addition to regional analysis to help homeowners weigh retrofit or design options.

5) Adopt the suggested additions to ASCE 7 Commentary on parameters important to tornado design. These recommendations will be taken to the ASCE 7 Wind Load Task Committee for consideration in the 2016 revision cycle.

6) The improvements in hurricane/seismic resistance of houses with improved structural lateral load paths should be considered for a better performance and a reduction in future tornado damage.

Appendix D. SEAKM Report on the Joplin, MO Tornado [5]

Structural Engineers Association of Kansas and Missouri Report

"Investigations and Recommendations based on the May 22, 2011 Joplin, Missouri Tornado"

March 2012

Structural Engineers Association of Kansas and Missouri
Joplin Tornado Committee Members

Curtis Geise PE, SE	Committee Chair	Corresponding Members
Cheri Leigh PE		Donald Scott PE
Harold Sprague PE		Ed Huston PE
Jon Shull PE		Ronald O. Hamburger PE, SE
Malcolm Carter PE, SE		
Perry Green PhD		
Thomas Heausler PE, SE		
Randy Bernhardt PE, SE		

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[5] https://www.yumpu.com/en/document/read/51878022/joplin-tornado-committee-report-structural-engineers-association-

Executive Summary:

The Joplin Tornado of May 22, 2011 was one of the most damaging events to hit the State of Missouri in regards to casualties and costs. There were over 160 deaths, 1,100 injuries and over three billion dollars in damages attributed to this one incident. The human aspect of the storm's impact to society, the local community, along with people directly involved with clean-up operations and the rebuilding of the city, will not soon be forgotten. In the light of the magnitude of devastation to the built environment, the Structural Engineers of Kansas and Missouri (SEAKM), a chapter of the National Council of Structural Engineers Association, formed a Committee to investigate the performance of some of the buildings that were struck by the tornado, either directly or indirectly.

In general, buildings that are built to established governing building codes, such as those published by the International Building Code Council, are not required to resist tornado force wind loads. Tornado wind speeds vary and can be in excess of two hundred and fifty miles per hour. The International Building Code (IBC) establishes a base line of ninety miles per hour as a minimum, based on the IBC 2006, and will vary depending on the area of the country the building structure is to be built. In consideration of several articles that have been published recommending that tornado prone areas should be designed to hurricane force winds, such as those along the coastal regions, and some building systems are more prone to collapse during a tornadic event, the Committee has compiled this report of observations and recommendations.

The Committee's observations of wood structures indicate that the vulnerable aspect of these types of buildings is maintaining a direct and complete load path of connections, from the roof diaphragm to the foundation system. Connections in wood with nailing procedures outlined in prescriptive guidelines need to be reviewed, for both the International Residential Code and the International Building Code. Overall, the wood structures observed were of an older generation of construction materials and methods, while, the newer commercial buildings appear to have performed better. Typically, wood structures have an inherit redundancy within the framing system, considering the multiple interior walls intersecting and their connectivity to the outer structural frame, but with larger wood structures, in particular today's larger homes, being built with bigger open spaces, this redundancy is reduced.

Pre-engineered Metal Buildings are typically designed and constructed to provide column free spaces for the owner and user. The one pre-engineered building that was investigated, although not directly in the path of the tornado, incurred damage to the envelope and standing seam metal roof. The damage or failed areas appear to be consistent with over pressures that were beyond the code design wind loads. Fortunately, the main structural frame remained intact and did not collapse. These building types are a staple in society, used for churches, manufacturing facilities and various other businesses, but can be vulnerable to tornado events.

Structural steel and concrete framed buildings performed better to resist the extreme wind loading by the tornado; although, not without damage. St. John's Hospital and their Medical Office Buildings (MOB) received damage, but the structural frames remained stable. The buildings envelope material was severely damaged, with most of the destruction caused by the ballasted roof systems used throughout the complex. Essential facilities, such as the hospital, need to consider a comprehensive tornado preparedness plan when considering the layout of the facility and the respective infrastructure. Emergency generators, electrical switch gear, mechanical systems and the building structures that support them need to consider the implications of impact of wind borne debris. It is reported that the backup generator building had cars impact the side of the building during the tornado, which caused partial collapse and render the facility inoperable.

Hard wall structures are a building type that is constructed to be very efficient in the use of materials, while providing the most building square footage for the minimum amount of capital. These buildings are typically noted as "Big Box Stores," where a couple of these types of buildings encountered a near direct hit by the tornado. The high wind speeds that occurred caused significant damage, including roof deck connection failure, leading to the failure of several structural framing members, and in some cases, almost total collapse of the hard wall system.

The roof deck diaphragms of buildings have a propensity to fail first when tornadic type winds are imposed onto the building structure. This is most evident in hard wall buildings, as well as, some concrete and structural steel buildings. Roof deck diaphragms are an essential building component that typically does not incorporate a redundant load path, once failed; other structural members will most likely fail, as seen in both hard wall structures investigated.

The Committee offers the following recommendations:

1) Implement a state wide building code in all 50 states, in particular Kansas and Missouri.

2) Determine if the use of mechanical deck connections for steel metal deck thicknesses of 22 gage or less should be mandatory.

3) Verification by designer's that roof deck fasteners consider simultaneous uplift tension and diaphragm shear reflecting the different wind and seismic factors of safety in accordance with the Steel Deck Institute Diaphragm Design Manual - Third Edition.

4) Require a job specific design of open web steel joist (OWSJ) connections to primary framing members and of joist girder connections.

5) Develop code requirements for a greater robustness, or redundancy for hard wall building type systems. These may be in the form of specifying a defined base moment design; a maximum length of continuous wall prior to a full height lateral load resisting member, wall or frame; or a system of continuous cross-ties.

6) Codes should require storm shelters, or an area of refuge in retail stores, manufacturing buildings and similar types of structures with a certain number of occupants, in particular for employees that may be inside the building during a tornado event. Design could be based on the principles of International Code Council ICC-500, *ICC/NSSA Standard for the Design and Construction of Storm Shelters*, and FEMA 361, *Design and Construction Guidance for Community Safe Rooms*.

7) Codes need to require storm shelters with the design based on ICC-500, or FEMA 361, for all elementary, middle and high schools, as well as other critical facilities, such as police and fire stations, emergency preparedness centers of control and other post disaster structures including hospitals.

8) Codes need to review and consider requiring essential buildings to use impact resistant glazing systems and door units, similar to hurricane prone region requirements for areas prone to tornados.

9) Codes should prohibit the use of ballasted roofs in all construction.

10) Research the concept of implementing similar design considerations for wind load distribution to diaphragms, drag struts and chord attachments in high-risk tornado areas that are currently codified for seismic lateral force distribution.

11) Increase inspection requirements for big box structures in tornado prone regions, similar to those imposed in the Florida Building Code for hurricane prone regions.

12) Review and update prescriptive practices for residential construction to ensure a continuous load path through connections, from roof to foundation.

13) Place a renewed emphasis on code specified special inspections, with improvements to the requirements for special inspection of wood framed buildings, including residential.

14) Encourage installation of tornado shelters for those structures that are in existence, community or individual shelters. Shelters should be in conformance with the recognized standards mentioned above.

15) Further study the impacts to design and construction practices if Codes require the design of buildings for EF-1 tornado wind speeds; equivalent to 86 -110 mile per hour, three second wind gusts for tornado prone areas, which covers approximately eighty-five percent of the rated tornados that occur in the United States.

16) The continuation of the study of tornados, to further develop appropriate code design equations to be used in building structures. The current equations consider straight line winds, which are significantly different that those winds near the vortex of the tornado, where uplift forces are considerably higher and turbulent winds occur.

It is understood that tornados are an extreme loading event, with a low probability of occurrence, but it is also evident that society is impacted by these events and as professionals we need to lead in determining if and when enhancements to the Building Codes are required. We understand that most buildings do not need to be entirely designed to the maximum wind speeds of a tornado, but we need to be prudent in our building designs and consider these events to some extent. We have the training, experience, research and tools available to implement changes.

Appendix E. Moore, OK (2013)[6]

Chapter 5
Conclusions and Recommendations

Conclusions

The wind speeds associated with EF4-5 tornadoes create catastrophic damage, including near total destruction of most buildings. In some cases however, seemingly minor initial failures propagates failure to additional components until major structural failures occur. This can be prevented through either the strengthening of the weakest link in the load path, or by providing adequate structural redundancy such that these initial failures, and the additional stresses they may put on the structural system, do not cause complete collapse. However, each building is designed for specific loads, and when those loads are exceeded by significant amounts damage is to be expected.

Therefore, the conclusions and recommendations from the team in the following section, taken from observations of the damage, are not meant to imply that the buildings performed more poorly than expected, because there is no evidence that suggests the buildings failed at below design wind speeds. However, in the authors' opinion, the observed damage reveals construction built without detailed attention to continuous load paths and structural redundancies, and without sufficient attention to codes and standards that have required certain steel and masonry details to be followed for many years. Proper construction (i.e., compliant with relevant codes and standards, including a continuous load path) may not have prevented the catastrophic damage during this tornado, since unfortunately the strongest winds in the tornado appeared for the most part to travel directly over the schools and critical facilities. But it may prevent premature failure in a smaller tornado or further away from the center of a violent EF4 or EF5 tornado. It could also provide a higher margin of safety that would enable better performance of the structures even when the design loads are exceeded.

From the observed damage, and discussions with building managers and occupants for buildings located in the tornado impacted area, the assessment team concludes that:

1. In some structures, specifically the Highland East Junior High School multipurpose building, the Briarwood Elementary School multipurpose building, and another local school multipurpose building, a dedicated or specific lateral load resisting system was not evident.
2. In some long-span steel structures, such as the Moore Lanes bowling alley, the lateral force resisting system was visible, but depended heavily on the metal deck of the wall and roof diaphragm that are particularly susceptible to failure in high wind events. The primary failure modes were uplift of steel roof deck that failed at puddle welds, steel

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[6] https://sp360.asce.org/PersonifyEbusiness/Merchandise/Product-Details/productId/233132635

member to member connection failures, flange buckling of steel beams, and column base plate connection failures. This was particularly evident at the Moore Lanes bowling alley and the strip mall, where the failure of the metal decking systems, apparently from out-of-plane wind loading, contributed to yielding of the primary structural system.

3. Failures in reinforced masonry systems primarily initiated in connections at boundary conditions, i.e., bond beam at the top of the wall and anchorage to foundation. Several apparent non-compliance issues with the codes and standards in practice at that time were also observed, although there was no clear evidence that these were by themselves the causes of failures in this event. The most critical non-compliance issues were the insufficient development lengths of reinforcement both at the roof and foundation level, and the lack of continuous horizontal reinforcement in the bond beams.
4. Kelley Elementary School, which was heavily damaged and rebuilt after the 1999 tornado, included specially designed corridors to provide safety in a tornado event (FEMA 2009).
5. The critical facilities and schools assessed by the team all relied upon "Best Available Places of Refuge" rather than dedicated tornado shelters. The performance of these areas had mixed results. In the Moore Medical Center the occupants survived without injury. At Briarwood Elementary, only minor injuries were sustained. At Plaza Towers Elementary School however, seven fatalities occurred in the designated place of refuge (Kuligowski et al 2013).

Recommendations

The ASCE/SEI Assessment Team believes revisions to practice and/or codes should be considered so that life safety can be preserved in the many existing buildings that are used for shelter and that provide important community and critical functions. These revisions can also reduce the damage to buildings not in the center of the tornado path.

The following are the specific recommendations of the ASCE/SEI Team:

1. Critical facilities should consider in their design the strengthening of the building envelope and designing for continuity of operations, including provisions for emergency power, water supply and sewer as recommended in FEMA P-908 Recovery Advisory 6, *Critical Facilities Located in Tornado-Prone Regions: Recommendations for Architects and Engineers*. Evidence from the Moore Medical Center supports this recommendation since even though it was located near the center of an EF5 tornado path, the structural system remained largely intact after the event. Failures of the building envelope however ultimately caused it to be demolished after the event. Similarly, the Mercy Hospital in Joplin, MO suffered substantial damage to the building envelope and was demolished after the 2011 EF5 tornado, even though the main structural system remained intact.
2. Schools and other buildings that are essential for the protection of a community or will likely be used to shelter large numbers of people in a tornado event should be designed to include a tornado shelter designed in accordance with ICC 500. A tornado shelter will most often be the more economical option for providing occupant protection, and can

consist of a strengthened room within the overall structure. However, the benefit of enhancing the design of the entire structure to ensure life safety is that it can also reduce damage in all but the direct impact of violent tornadoes.

3. Existing critical facilities should consider the feasibility of retrofits to strengthen the building envelope. While some facilities damaged during tornadoes are being rebuilt with tornado-resistant designs (the new Joplin hospital for example), communities ought to be proactive in seeking to prevent the damage if feasible, rather than simply rebuilding stronger after the event. FEMA P-424 *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds* specifically states that strengthening the building envelope is typically the most cost-effective way of reducing damage in most schools, so long as a continuous structural load path is already present.
4. ASCE should consider adopting enhanced tornado design criteria as part of revising ASCE 7 to guide practitioners in appropriate tornado designs. Other organizations whose mission is to help the practice of structural engineering, such as the Applied Technology Council (ATC) and the National Council of Structural Engineering Associations (NCSEA), should augment ASCE's efforts in this regards to provide practical design guidance.
5. Schools and critical facilities in tornado-prone regions should be examined for vulnerability to catastrophic collapse caused by a tornado event. Many of the critical failure mechanisms identified in this report have been identified in the 1999 Moore tornado, the 2011 Joplin tornado, and others. As such there is a strong possibility that many existing schools contain the same vulnerabilities. Those that have these vulnerabilities should be examined, retrofitted as required to prevent collapse and reduce damage, or have storm shelters or safe rooms installed.

Appendix F. Dallas - Garland/Rowlett (2015)

Online Damage Report

The 2015 Christmas Tornado Outbreak

View from Rockwall, TX looking towards the I30/I-90 interchange as a strong tornado passes over (via Todd Ward)

University of Florida's Wind Hazard Damage Assessment Team
http://windhazard.davidoprevatt.com/

PI: David O. Prevatt, Ph.D., PE, dprev@ufl.edu

Contributing Author:
David B. Roueche, MS, NSF Graduate Research Fellow.

Graduate Students:
Arpit A. Bhusar
Allan M. Gutierrez
Anshul D. Shah
Mitali S. Talele
Aravind Viswanathan

29 December 2015

E·S·S·I·E
Engineering School of Sustainable Infrastructure & Environment

Gator Engineering
University of Florida

Wind Hazard Damage Assessment Team
Engineering School of Sustainable Infrastructure and Environment
University of Florida
29 December, 2015

Executive Summary

2015 has been a reasonably active year for tornadoes but as of mid-December tornado-related fatalities was extremely low, at only 10 deaths - five less fatalities than the record low 1986 yearly total. All that changed in this past week that saw 38 tornadoes, 47 weather-related fatalities and 2,000 damaged or destroyed structures spread over five states. This report by University of Florida's Wind Hazard Damage Assessment Team remains focused on ascribing causes and effects for structural damage and deaths due to tornadoes. Our thoughts go to the communities and families directly affected by these tornadoes, for whom sadly the Christmas holidays may never be quite the same.

The structural damage from an engineering perspective was not unexpected, with the vast majority of damage occurring to single-family residences, structures that are nominally designed for wind load magnitudes just a quarter to one-third as strong as any tornado. We see the same structural deficiencies known to be vulnerable in high winds and the resulting damage patterns are similar. The demographics of community buildings are also the same, and the profound sense of loss remains. The disasters beg the question have we done enough to protect our communities?

The tornado damage from this tornado outbreak could have been much worse. Had the Texas tornado outbreak shifted two to three miles to the west, it would have affected more densely populated communities rather than passing as it did mainly over Lake Ray Hubbard and the outskirts of the towns. And, although two Mississippi tornadoes were on the ground for nearly 150 miles combined, they fortunately traversed over a sparsely populated region with few small towns and so damage was limited.

As engineers we understand that the 23-27 December 2015 tornado damage is the product of both the strength of the hazard (the tornado) and the vulnerability of the buildings. It is clear that, barring some future scientific invention or unforeseen influences of climate change, hazard risk from tornadoes will not be reduced. However, the structural vulnerability can be mitigated by building stronger, retrofitting existing homes and by providing more protection for occupants. Therefore, communities confront an economic decision to determine the acceptable level of engineering for protecting life and property, and all communities make that choice, whether implicitly by accepting the status quo or explicitly by adopting tornado-resilient building practices.

Without a doubt, more buildings and urbanization is increasing the tornado vulnerability of communities, by enlarging the size of potential tornado "targets". Indeed, had the Garland/Rowlett tornado occurred 30 years ago, only 876 homes would have been within the damage path as opposed to the 2250 homes in 2015. But more importantly, continuing to build future communities in accordance to existing building codes that lack tornado-resilient provisions for stronger buildings will exacerbate the damages. The cost to retrofit structures for tornado-resilience is much more than the cost of building tornado-resilient structures in the first place, so putting off the decision to strengthen our communities now guarantees high costs later – either through future tornado damage or costs of retrofitting.

How much longer is it prudent for us to continue playing this game of chance with tornadoes? We have better knowledge of the tornado strengths and distribution of wind speeds (Lombardo et al, 2015), and our studies show that much of the damage is not inevitable (Prevatt et al, 2012), buildings can be made to resist the forces at reasonable costs, as is the case for hurricane-resistant structures in Florida (Gurley and Masters, 2011). Engineers will need to lend voice along with other community leaders to advocate for more resilient residential infrastructure. Investing in better infrastructure now will save money by reducing the level of rebuilding, repairing, and debris removal otherwise needed after the next tornado (Simmons et al, 2015).

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