StEER: Structural Extreme Event Reconnaissance Network

28 MAY 2019 EF4 TORNADO IN LINWOOD, KANSAS:
FIELD ASSESSMENT STRUCTURAL TEAM (FAST)
EARLY ACCESS RECONNAISSANCE REPORT (EARR)

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Executive Summary

An EF4 tornado occurred in eastern Kansas on May 28, 2019 causing considerable damage in Linwood, Kansas, and surrounding areas. Damage mostly consisted of single-family residential structures, although one daycare facility south of Lawrence, Kansas, was destroyed. The tornado ultimately resulted in 18 injuries and no fatalities.

This report provides a preliminary summary of the damage and impacts of the tornado, and details on-site investigations conducted by researchers from the University of Kansas and the University of Missouri in Kansas City. The on-site investigations were funded by the Structural Extreme Events Reconnaissance (StEER) network. Founded under an NSF EAGER grant, StEER seeks to build societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities.

On-site investigations were conducted in the impacted areas of Lawrence, Linwood, and Bonnor Springs, Kansas. Using a combination of door-to-door forensic engineering assessments and Unmanned Aerial Vehicles (UAV), a Field Assessment Structural Team (FAST) directly investigated 271 buildings impacted by the tornado focusing on the structural systems, observed damage (or lack thereof), and context of the observed damage in relation to the building attributes, surrounding terrain, and proximity to the tornado path. These 271 structures are believed to be representative of buildings damaged by the tornado, but not all damaged structures were surveyed. Notably, one area south of Lawrence, Kansas, was not accessible to FAST members.

Preliminary observations from the FAST investigation include the following:

1. There are no public shelters in the impacted areas for residents to safely shelter in during tornadoes. This is particularly alarming for Douglas County that hosts a large student population living in above-ground apartment buildings.
2. Many damaged single-family wood-frame structures lacked a sufficient load path. This is representative of the current and outdated building codes and inspection protocols (or lack thereof) adopted in the impacted area.
3. Considering the lack of public shelters and insufficient load paths for many residential buildings along the tornado paths, and assumed consistency in construction style throughout the impacted cities, the impacts of the tornado were only limited by its path not hitting dense areas in these cities and the lack of fatalities is extremely fortunate.
4. Vulnerability of older manufactured homes continues to be a critical issue, driven in part by poor anchorage practices and weak assemblies as was observed in this study.
5. Unreinforced masonry buildings also continue to be particularly vulnerable. The Building Blocks Day Care was completely destroyed; should the tornado have occurred during typical workday hours, this structural failure could have resulted in injury and death for many small children.
6. Tree-fall in outer regions of the tornado path caused severe structural damage and vehicular damage, and heightened potential for loss of life, in buildings that otherwise would have likely performed adequately, similar to observations from the 2019 tornadoes in Alabama.

This FAST StEER team recommends additional research is performed on the best locations for public tornado shelters for the regions known to be susceptible to tornadoes, including Kansas. A recent New York Times article highlighted the tragic state of structurally dangerous schools in the U.S., including those in Tornado Alley[1]. This team recommends northeastern Kansas and the entire U.S. take a much closer look at strengthening the types of buildings utilized for housing groups of children (e.g., schools and day cares).

All observations and findings provided in this report should be considered preliminary and are based on the limited scope of FAST. Specific recommendations of areas worthy of further investigation are offered at the conclusion of this report.

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[1] Peek, L. (2018). "America's Deathtrap Schools." New York Times Opinion, April 7, 2018. https://www.nytimes.com/2018/04/07/opinion/sunday/americas-deathtrap-schools.html

Introduction

May 2019 may be a record-breaking month for frequency in tornado reports including an unprecedented 13-day tornado streak with at least eight tornado reports per day across the U.S. (see Figure 1).[2] Tuesday, 28 May 2019 was the 12th day in the streak that resulted in an EF-4 tornado ripping through parts of northeastern Kansas.

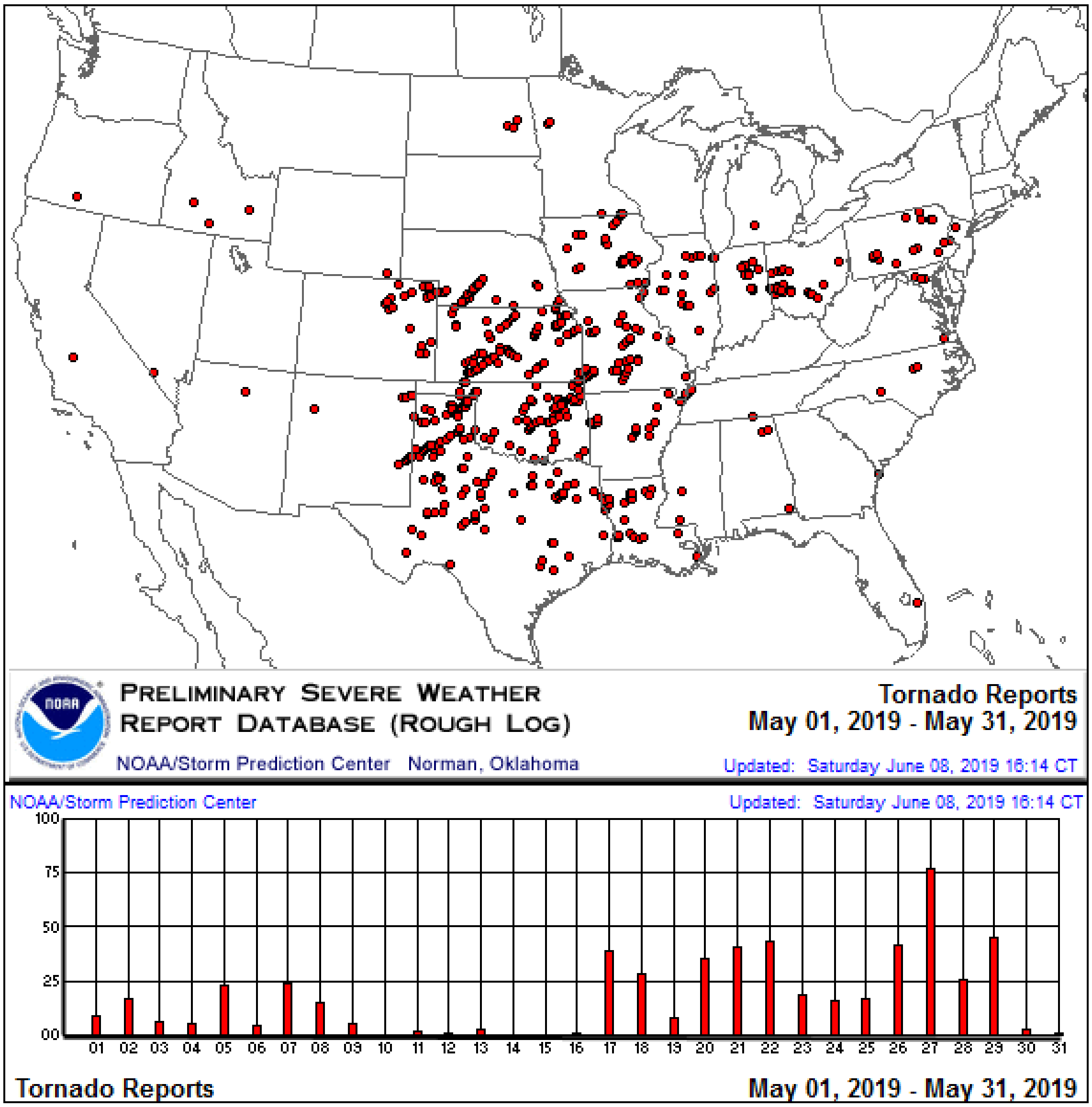


Figure 1. Frequency and Location of U.S. Tornado Reports in May 2019 (Image obtained from NOAA 2019a).

[2] NOAA (2019)a. Monthly Severe Weather Summary May 2019. NOAA National Weather Service Storm Prediction Center, June 1, 2019. https://www.spc.noaa.gov/climo/online/monthly/1905_summary.html#

At 1:56 p.m. on May 28, 2019, the National Weather Service issued a tornado warning for parts of northeastern Kansas (see Figure 2 for a timeline of communication from the Douglas County Emergency Management Social Media page). At 6:05 p.m., a large and destructive tornado touched down near Lone Star Lake in Douglas County, Kansas, and stayed on the ground for 31.8 miles, eventually lifting in southern Leavenworth County, Kansas. It was rated an EF-4 by the National Weather Service, which estimated a maximum wind speed of 170 mph and diameter of 1 mile. There were no fatalities but 18 injuries were reported.[3] Loss of livestock (cattle) was also reported.

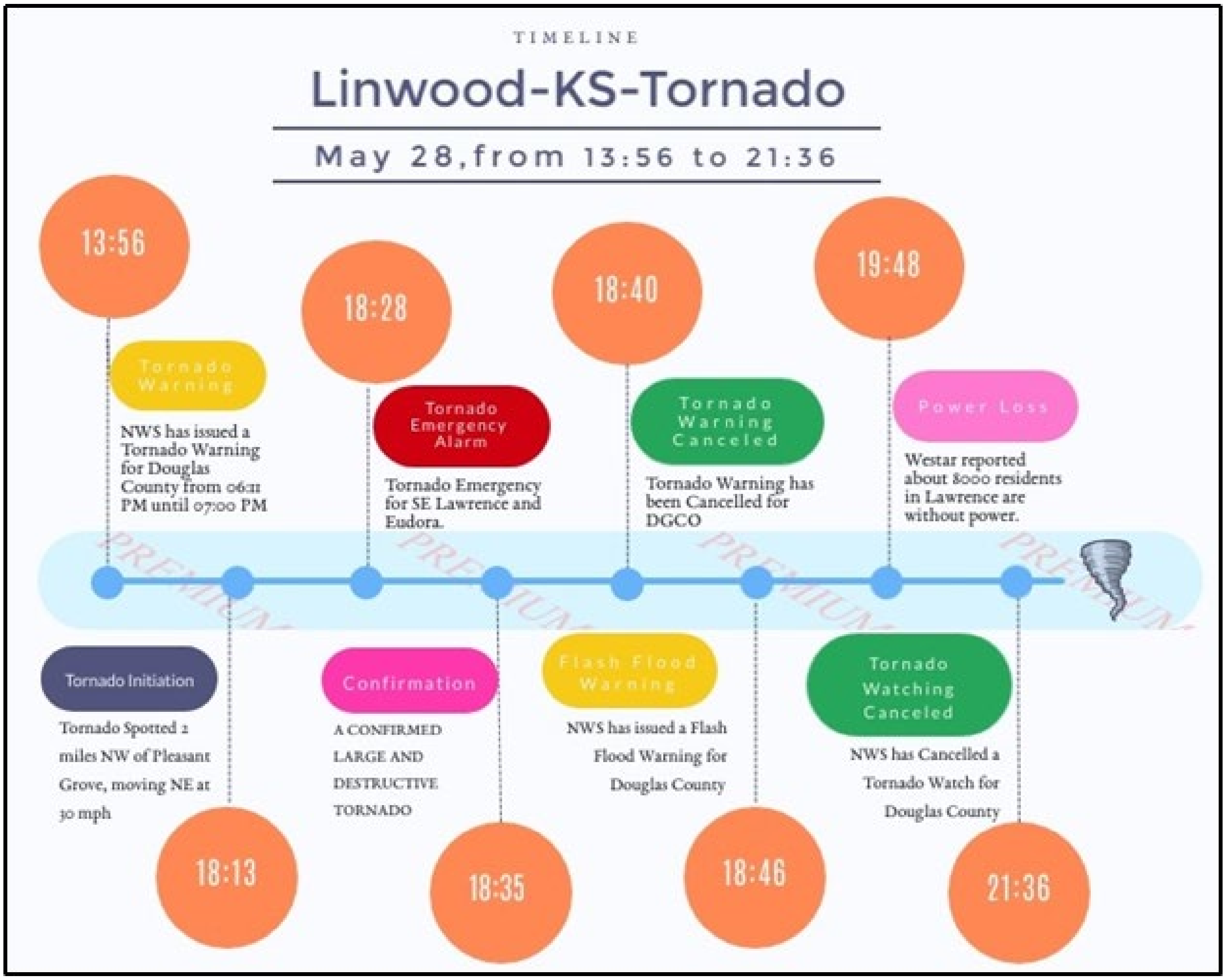


Figure 2. Timeline of Risk Communication and Tornado Touchdown for Douglas County

The tornado, referred to herein as the Linwood, KS Tornado, caused destruction along the tornado path. The most severe damage occurring near Linwood, Kansas. The tornado impacted mostly single-family wood-frame structures and ancillary structures like garages and barns. It also impacted a small number of commercial structures. It uprooted trees, overturned cars, and

[3] NWS (2019). "28 May 2019 Tornadoes." National Weather Service, May 28, 2019. www.weather.gov/eax/28May2019_Tornadoes

downed power lines. Tornado debris was reportedly found 50 miles away from its path. At least 14,000 residents lost power.[4] Numerous roads were closed due to storm damage.

On May 31, 2019, three days after the tornado, a Field Assessment Structural Team (FAST) deployed to survey and document damage using a combination of door-to-door surveys and Unmanned Aerial Vehicle (UAV) fly-overs. The objective of this **Early Access Reconnaissance Report (EARR)** by the Structural Extreme Events Reconnaissance network is to:

1. Provide an overview of the reported tornado;
2. Apply the StEER event strategy in response to the tornado;
3. Summarize the activities, methodologies, engineering perspectives and preliminary findings of the Field Assessment Structural Team (FAST) following on-site deployments; and
4. Identify regions or topics warranting additional investigation.

It should be emphasized that all results herein are preliminary and based on the rapid assessment of data within 1 week of its collection. As such, the records have not yet been processed by the StEER Quality Assurance protocol. Damage ratings discussed herein are based largely on the judgment of the field investigator on the ground and will be updated when the full dataset is released on DesignSafe under Project ID PRJ-2397. The raw data is now available for viewing in the Fulcrum Community page:
https://web.fulcrumapp.com/communities/nsf-rapid.

Meteorological Background

The storm system responsible for the tornado on May 28th, 2019 developed in the early afternoon in southeastern Kansas. This system anchored on a warm front at approximately 4:00 PM CDT, which provided a source of forcing and enhanced low-level wind shear. These conditions lead to the development at 6:05 PM of a wedge tornado south of Clinton Lake in southwestern Douglas County that would grow to be one mile wide. The tornado moved northeast at an EF-3 intensity as it passed through southeast Lawrence. The tornado grew in strength after crossing the Kansas River, reaching its peak EF-4 intensity as it approached and passed through Linwood, with estimated wind speeds of 170 mph. The tornado continued northeast, gradually weakening before dissipating west of Bonner Springs in Wyandotte County, Kansas. The tornado travelled approximately 32 miles for 55 minutes, injuring 18 people (NWS 2019).

The National Weather Service Storm Prediction Center issued an outlook on Tuesday morning at 11:50 AM CDT – roughly six hours before the tornado touched down – which placed much of northeastern Kansas, northern Missouri, and parts of western Illinois at a “Moderate” risk level for severe storms that would be capable of producing large hail, damaging winds, and tornadoes

[4] Belshe, S. (2019). “Tornado touches down in Douglas County, causing power outages around Lawrence.” The University Daily Kansan, May 28, 2019. www.kansan.com/news/tornado-touches-down-in-douglas-county-causing-power-outages-around/article 44f1dfe6-81b9-11e9-a159-3f92401b042c.html

(see Figure 3).[5] A second, less-severe EF-2 tornado resulted from this storm system as well, beginning southeast of Kearney, Missouri, and travelling 5.84 miles before dissipating north of Excelsior Springs. No injuries have been reported as a result of the second tornado at the time of this writing.

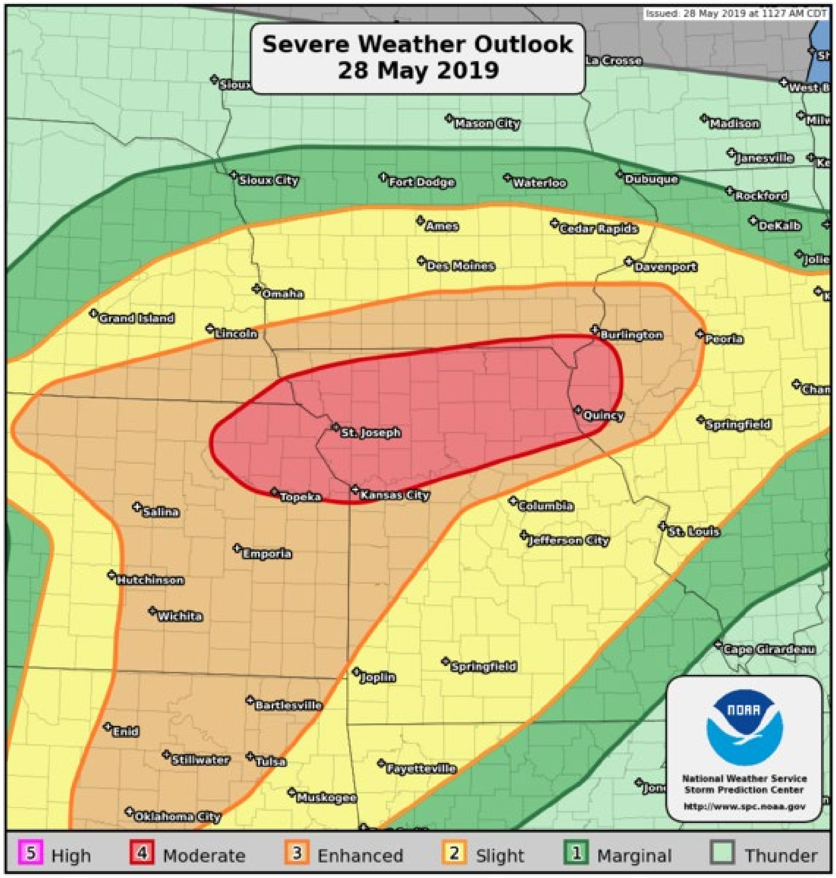


Figure 3. Severe Weather Outlook issued by the Storm Prediction Center at 11:50 AM CDT (Image obtained from NOAA 2019b).

StEER Response Strategy

Following the tornadoes on 28 May 2019, a StEER Field Assessment Structural Team (FAST), consisting of Team Lead Dr. Elaina J. Sutley from the University of Kansas, deployed to capture perishable data regarding building performance. FAST conducted on-site assessments at three communities impacted by the tornadoes - Lawrence in Douglas County, Linwood in Leavenworth County, and Bonnor Springs in Wyandotte County, Kansas all on 31 May. The locations of the deployments were guided by public media reports and data (including photographs and estimated tornado path) collected by the National Weather Service Forecast Office that was made available through the Damage Assessment Toolkit.

[5] NOAA (2019)b. Public Severe Weather Outlook. NOAA National Weather Service Storm Prediction Center. May 28, 2019. https://www.spc.noaa.gov/products/outlook/archive/2019/pwo_201905281651.html

FAST conducted targeted door-to-door forensic assessments using the Fulcrum data collection platform, supported by high-resolution aerial imagery captured via a DJI Mavic Pro and a DJI Phantom 4 Pro. The aerial imagery is intended to provide imagery of roof damage along with 3-dimensional views of structures included in the door-to-door assessments and holistically capture the entire damage swath over larger areas.

Following the field deployment, the curation process was initiated on raw field reconnaissance data, culminating in publication on the NSF DesignSafe Cyberinfrastructure. Additional Field Assessment Teams are not anticipated, but analysis of the data and extraction of information and knowledge will continue through Virtual Assessment Teams (VATs) consisting of the same members as the FAST.

Local Codes & Construction Practices

Tornadoes are not considered in the wind design of typical structures impacted by the storms described in this report.[6] Notwithstanding, building codes and regulations are important to broadly understanding the wind vulnerability of impacted regions. This section will focus primarily on local codes and construction practices in Douglas and Leavenworth Counties in the state of Kansas.

Kansas does not have a statewide adopted building code. Each of the affected cities and counties have adopted different code versions. Beginning from the southern portion of the tornado path:

- City of Lawrence has adopted the 2015 International Building Code (IBC) and 2015 International Residential Code (IRC).
- Unincorporated Douglas County uses the 2012 International Building Code and 2012 International Residential Code but allows an exemption for agricultural buildings and accessory buildings under 120 sq. ft.
- City of Eudora has adopted the 2012 International Building Code and 2012 International Residential Code.
- Unincorporated Leavenworth County does not have an adopted building code for residential structures. They require permits but perform no inspections and do not issue occupancy permits.
- City of Linwood has adopted the 1997 Uniform Building Code (UBC). They issue permits and perform inspections and issue occupancy permits.
- City of Bonner Springs has adopted the 2015 International Building Code and 2015 International Residential Code.

Having different versions of the building code and in some cases, no building code affects interpretation of observed damage results. For example, some observers believe that damage is

[6] ASCE (2016). ASCE Standard 7 Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers, Reston, Virginia.

worse in Leavenworth County, thus the tornado must have gained force. But the county is also an area with no adopted building code nor a system of inspections, so other indicators of intensity should also be used in determining tornado intensity.

Further, different versions of the building code have different methods of determining wind pressures on structures. The Uniform Building Code uses a simple method of determining cladding and component wind pressure with service level wind speeds and the International Building Code references American Society of Civil Engineers Standard 7 (ASCE 7) which uses strength level wind speeds to determine pressures.

Taking the 2015 IRC or 2010 ASCE 7 as normative for purposes of estimating current design wind speeds, typical design wind speed in the affected cities and counties is 115 mph for a typical residential building (i.e., Category II), and 120 mph for a building that would pose substantial risk to human life in the event of failure (i.e., Category III). From this, then, the design wind speed for residences built to the current code is 115 miles per hour. The Linwood Tornado was classified as an EF-3 developing into an EF-4 according to the National Weather Service within the area of this survey. The estimated peak wind speed was 170 miles per hour—well above the design-level wind event for homes in this area.

Construction and installation of manufactured (mobile) homes is governed in Kansas by the Kansas Housing Resources Corporation, Kansas Manufactured Housing Program Manual, which includes regulations for installation of manufactured homes. These regulations are based on the federal Manufactured Home Construction and Safety Standards at 24 CFR 3280, known as the HUD Code. The HUD Code sections the United States into three distinct wind zones. The HUD Code wind maps are based on the wind maps from the 1988 ASCE 7 and use fastest mile wind speeds whereas ever since 1995 wind maps in ASCE 7 are based on three-second gust wind speeds. All counties within the State of Kansas fall within Wind Zone 1 of the HUD Code, which has an equivalent ultimate strength three-second gust design wind speed of 110 mph.

Reconnaissance Methodology

The Linwood, KS Tornado passed through mostly sparsely populated areas, but some residential and industrial properties were impacted. Door-to-door and unmanned aerial surveys were conducted using the procedures described below.

D2D Assessments

Door-to-door (D2D) damage assessments collected detailed perishable information regarding tornado effects. The survey included classification of construction types and documentation of damage.

The field reconnaissance plan was created the day before FAST deployed. GoogleMaps satellite images were used to virtually survey the land near the tornado path and identify structures that may have been affected by the tornado. Based on the reported maximum tornado width of 1 mile, structures within 0.5 miles of the tornado path defined by the National Weather Service were prioritized. The path was subdivided into 27 semi-arbitrary polygons (23 rural, 3 residential, and 1 industrial) where groups of structures were located near the tornado path. These 27 polygons are shown in Figure 4, where the magenta polygons are the rural areas, blue markers are the center points for the three (dense) residential, light blue polygons, and the industrial is shaded in red. The intention of the polygons were to identify locations of clustered building structures along the tornado's path to maximize time in the field and to provide a means for FAST members to communicate their location to one another. The 27 polygons did not encapsulate all structures within a half-mile radius of the path, but allowed for efficient and effective field team management. FAST members split into groups of 2 or 3 individuals and assigned specific subsets of the 27 polygons for D2D assessments, and then informed to work northeast or southwest to capture the entire path.

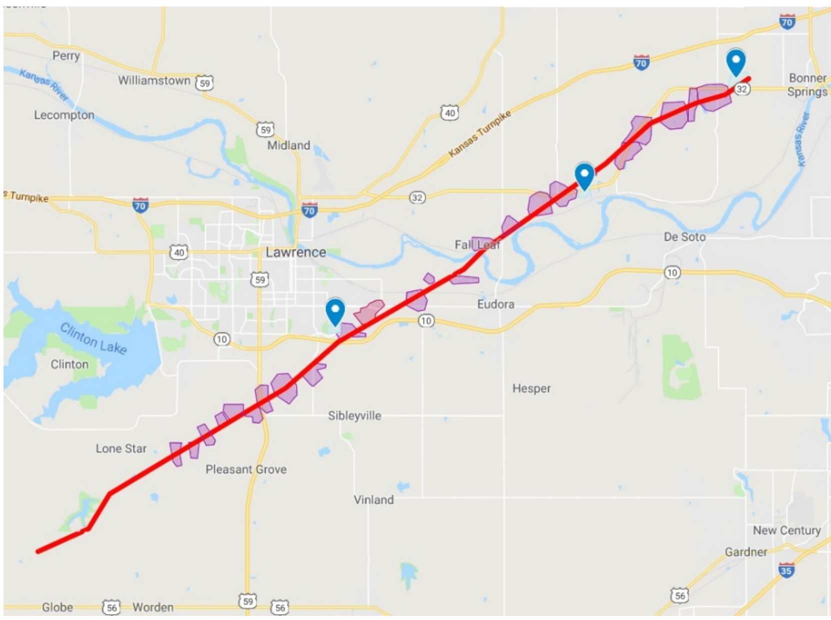


Figure 4. Linwood, KS, Tornado path. The 27 shaded polygons correspond to areas where structures were likely to have been impacted. FAST deployed to survey these 27 areas.

FAST members surveyed a sample of structures within each of the 27 polygons. Once onsite, an effort was made to systematically select structures located along an axis approximately perpendicular to the tornado path. For instance, if a residential road was oriented approximately perpendicular to the tornado path, FAST members might have chosen to survey every other house along the road. Within each area, an effort was made to survey structures located at increasing distances from the tornado path until undamaged homes were documented although not always possible due to the sparse (rural) building inventory. Working orthogonal to the path enabled documentation of the variation in damage intensity as a function of distance from the centerline of the tornado path as well as the breadth of tornado effects.

In an effort to be respectful and courteous to disaster victims, when a D2D team approached a residential sample, the team began the survey by first approaching and knocking on the front door. If an occupant was available, the team asked permission to survey the building(s) exterior, including requesting permission to photograph the building exteriors. If no one was available, the team performed their assessment.

FAST members aimed to document the effects of the tornado on as many structures as possible in a short amount of time while still capturing the critical, perishable field information needed for subsequent study. This information included: 1) clear photographs of each structure from multiple perspectives (at least one photo of each side of each structure), 2) accurate geo-location of structures, 3) the extent of structural and cladding damage, 4) site-specific characteristics that may require on-site forensic investigation, 5) unique structural features that would affect windstorm performance but would not otherwise be visible from photographs or aerial imagery, and 6) which hazards most probably caused the observed damage (e.g. wind, wind-borne debris, tree fall, rain, flooding, etc.). Although wind, rain, tree fall, and wind-borne debris were present throughout the survey area, team members used judgement to determine which hazard(s) most probably caused the observed damage to each structure.

The Fulcrum mobile smartphone application was used for data collection. The app allows FAST members to capture geotagged pictures with annotations, record videos, or collect audio notes from the field while they are either online or offline. Data is stored locally on the device and then uploaded to the cloud once connected to the Internet. The FAST members used a standardized form ("StEER Building – US Windstorm") established by StEER for documenting building damage. The form is useful for helping FAST members collect consistent data at each site, as well as providing consistency across StEER teams and events.

To improve the quality of D2D data, Virtual Assessment Structural Team (VAST) members will post-process the data submitted by FAST members using the Fulcrum app in the days to weeks after the survey. VASTs are mainly responsible for data enrichment and quality control for individual damage assessments submitted by FAST members. It is the VAST's job to insure uniform damage rating standards are used to characterize the damage documented by the FAST investigators, conduct a detailed Data Enrichment and Quality Control process, improve the quality of each entry considering the Fulcrum damage assessment forms, and supervise the transfer of this data into DesignSafe in accordance with uniform data standards.

Unmanned Aerial Surveys

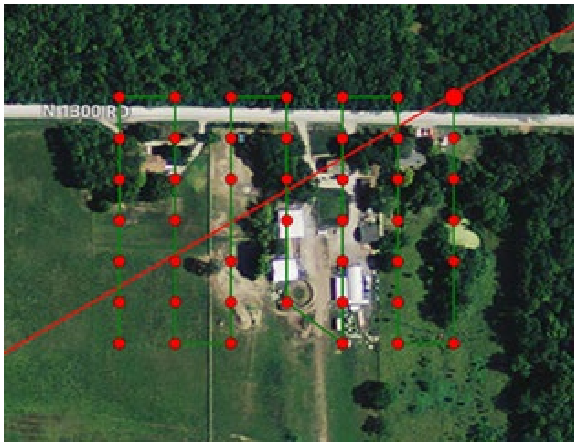
KU Team

A Mavic DJI and a DJI Phantom 4 Pro unmanned aerial vehicles (UAV) were used to survey tornado damage with a focus on capturing images of the roofs of individual structures. Seven locations with significant tornado damage were selected for the UAV surveys. Figure 5 depicts the locations of the flights. One of the UAV surveys was performed in southeastern Lawrence, Kansas. The remaining UAV surveys were carried out near Linwood, Kansas. In Figure 5, the "x" symbols represent the locations of individual UAV surveys and the red line shows the tornado path reported by the National Weather Service. For each UAV Survey, the Pix4D app was used to design a flight path that would allow photos to be taken of structures with significant damage. The parameters for UAV flights and camera are summarized in Table 1. To display the flight path and image locations, the images captured with the UAV camera were processed with the Pix4D mapper software. Figure 6 illustrates a green line corresponding to the flight path at each survey location and red dots indicating where images were captured. Sample images of tornado damage are provided in Appendix A.

Figure 5. Locations of UAV flights near Lawrence, Kansas, and Linwood, Kansas

Table 1. Flight parameters for the imagery captured via UAV

Flight	Start Time	End Time	Flight Pattern	Camera Angle	Side Overlap	Front Overlap	Altitude (m)
Location-1	11:03 AM	11:11 AM	Double Grid	90°	60%	60%	277.843
Location-2	12:46 PM	12:51 PM	Double Grid	90°	60%	60%	293.88
Location-3	12:58 PM	01:03 PM	Double Grid	90°	60%	60%	293.75
Location-4	06:53 PM	6:57 PM	Double Grid	90°	60%	60%	313.9
Location-5	06:35 PM	06:39 PM	Double Grid	90°	60%	60%	306.37
Location-6	04:54 PM	04:57 PM	Double Grid	90°	60%	60%	325.93
Location-7	05:40 PM	5:44 PM	Single Grid	90°	60%	60%	336.14



a) Location-1

b) Location-2 and -3

c) Location-4

d) Location-5

e) Location-6

f) Location-7

Figure 6. UAV flight paths and image locations

UMKC Team

The UMKC team flew one DJI Phantom 4 Pro UAV over two major locations when working with the KU UAV team. The two locations are centered at (see the polygons of the coverage in Figure 7).

1. 1663 N 1300 Rd, Lawrence, KS 66046 (about covering 42,144 m^2 or 10.4 acres)
2. 20361 Linwood Rd, Linwood, KS 66052 (about covering 198,675 m^2 or 49 acres)

Figure 7. UAV flying perimeters (courtesy of Google Earth Pro): 1663 N 1300 Rd, Lawrence, KS 66046, covering six residential buildings (left); and 20361 Linwood Rd, Linwood, KS 66052, covering 13 residential buildings.

The UAV is equipped with two imaging sensors. One is the native DJI Phantom 4 4K camera; and the other is the Sentera multispectral camera, which has two 4K sensors providing five spectral bands: blue, green, red, red edge, and near infrared (NIR) (see Table 2 for information on imaging locations, sensors, and products). Before flying, a smartphone app (AirMap[7]) was used to inquire the airspace classification. Both locations and the planned flying perimeters are not in the classification of any restricted airspace.

Table 2. Imaging locations, sensors, and products.

Location	Sensors used	Geotagged images
1663 N 1300 Rd, Lawrence, KS 66046	Sentera double 4K sensors	140 RGB images 140 NIR images
20361 Linwood Rd, Linwood, KS 66052	DJI Phantom camera	261 RGB images
	Sentera double 4K sensors	360 RGB images 360 NIR images

Sentera's FieldAgent App was used for the path planning and mapping operation, which is similar to the DJI native app (as shown in Figure 5). Referring to Figure 7, at the first location (Lawrence), the flying height was 150 ft above the ground; and the Linwood location, the height was 200 ft above the ground. The obtained imaging products are reported in the table below. The sentera double 4K data are primarily used to obtain the 3D mapping products. Figure 8 provides a side-by-side comparison of the acquired RGB image and the NIR image. It is stated that the NIR images when combined the RGB image could potentially provide more informative signatures if used for understanding the tornado scene.

[7] Airmap (2018). Airmax, Inc. https://www.airmap.com/

Figure 8. RGB images (left) and NIR images (right) at the same location (near 1663 N 1300 Rd, Lawrence, KS 66046).

Pix4D mapping was used for preprocessing UAV data. Figure 9 provides the intermediate mapping products and the final reconstructed 3D mapping. Low-resolution 3D mapping option was selected to achieve a rapid product. Even still, the resolution achieved a minimum of 1.4 cm / pixel for both locations.

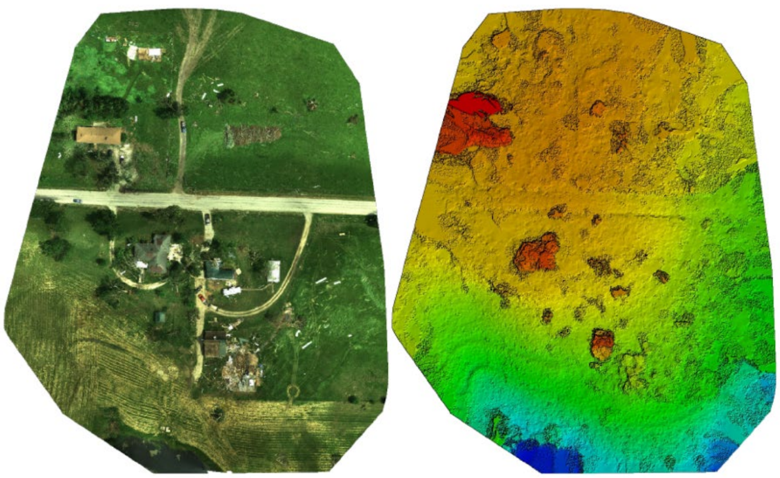


Figure 9. Pix4D processing products: Orthomosaic and Digital Surface Model (DSM) using the UAV images near 1663 N 1300 Rd, Lawrence, KS. Note: the DSM model can be used to assess the volume change of a structural or vegetation object if necessary for quantitative tornado damage assessment.

The low-resolution products were further exported into Google Earth. Figure 10 show the ‘before’ (top) and ‘after’ (bottom) using existing satellite images and the derived mapping product for the location of 20361 Linwood Rd, Linwood, KS 66052.

Figure 10. Pre-tornado (top) and post-tornado (bottom) disaster scene comparison using the existing satellite image (courtesy of Google Earth Pro) and the produced mapping product.

Figure 11 provides a comparison on of the same residential building captured from overhead using the UAV zoom feature versus an on-the ground photograph. These photos were taken near 1663 N 1300 Rd, Lawrence, KS 66046. In both cases, it is evident that the damage was caused by tree-fall, however, the aerial image captures the relative position of the damaged area to the roof system thus illustrating the benefits of using both D2D and aerial assessments.

Figure 11. Aerial and ground comparison of a residential building in Lawrence, KS: the zoomed-in capture from the UAV mapping (left); and smartphone image taken at the ground level (right).

Observations by Structure Type

Despite that the tornado path was mostly through sparsely populated areas, significant building damage was observed and is reported here. Several structural types were impacted. For the following discussion, damaged structures were categorized as either; 1) Single-Family Wood-Frame Structures (i.e., houses), 2) Auxiliary Structures (e.g., barns, sheds, detached garages), or 3) Social Structures (e.g., churches, schools). There was also considerable evidence of wind-borne debris and effects on vehicles. Damage states for wind[8], described in Table 3, were used as general descriptors of observed damage for each record collected. Meeting any of the criteria for one of the damage states qualifies the structure to reach that damage state. The spatial distribution of the 271 structures captured in the D2D assessments and classified by damage state is provided in Figure 12. In Figure 12, the red line depicts the NWS tornado path, the black triangles provide the NWS survey points used to classify the tornado's intensity, and the colored circles depict the D2D assessments.

[8] Vickery, P. J., Skerlj, P. F., Lin, J., Twisdale Jr., L. A., Young, M. A., and Lavelle, F. M. (2006). "HAZUS-MH hurricane model methodology. II: damage and loss estimation." *Nat. Hazards Rev.*, 7(2), 94-103.

Table 3. Damage state criteria (adapted from Vickery et al. 2006)

Damage State	Component (window, door, garage door) failure	Roof cover / wall cladding failure	Roof sheathing failure	Roof structure failure	Wall structure failure
0 - No visible exterior damage	No	No	No	No	No
1 - Minor	≤ 1 component	< 15%	No	No	No
2 - Moderate	> 1 component and < 20%	≥ 15% and ≤ 50%	< 5%	No	No
3 - Severe	≥ 20% and ≤ 50%	> 50%	≥ 5% and ≤ 25%	< 15%	No
4 - Destruction	> 50%	> 50%	> 25%	≥ 15%	Yes

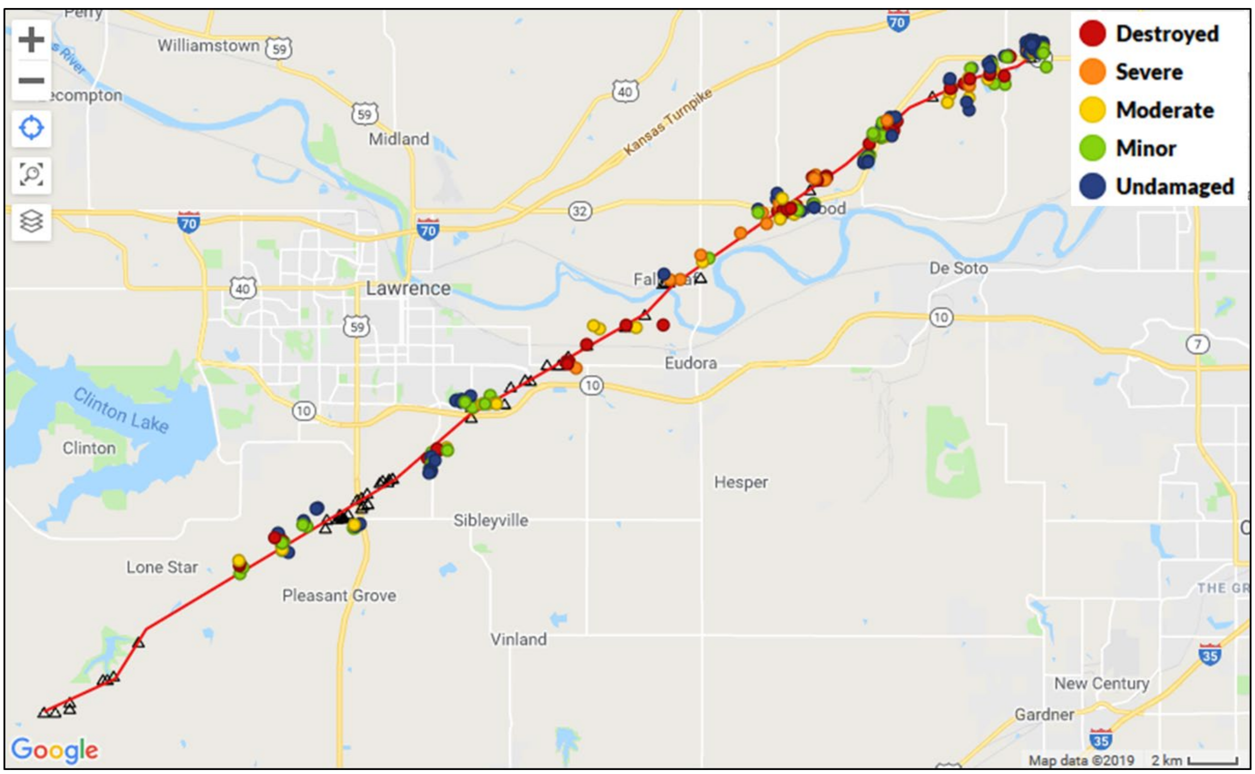


Figure 12. Spatial distribution of damage state classification along the NWS tornado path

Single-Family Wood-Frame Structures

Approximately 200 single-family wood-frame structures were surveyed in this investigation. These structures varied in size and distance from the tornado path. Given the location, it is believed that all or most of these structures served as primary residences. Thus, damage to such structures is highly impactful to their inhabitants. It is also highly probable that structures in damage states 3 (Severe) required inhabitants to dislocate, and certain that structures in damage state 4 (Destruction) required dislocation.

Figure 13 provides the number of single-family wood-frame structures assigned to damage states 0 through 4 out of a population of 201 single-family wood-frame structures surveyed after the Linwood, KS, tornado. The majority (57%) of surveyed homes experienced no-or-limited damage, which typically consisted of minor roof shingle loss or failure of one window, door, or garage door.

However, 85 homes, approximately 42% of those surveyed, exhibited moderate or worse damage. Most of this damage was due to wind or tree-fall, although there was evidence of damage caused by wind-borne debris. Many structures with moderate or worse damage were also exposed to rain or flooding damage, but these were mostly secondary; loss of roof or wall structures made the homes vulnerable to rain damage.

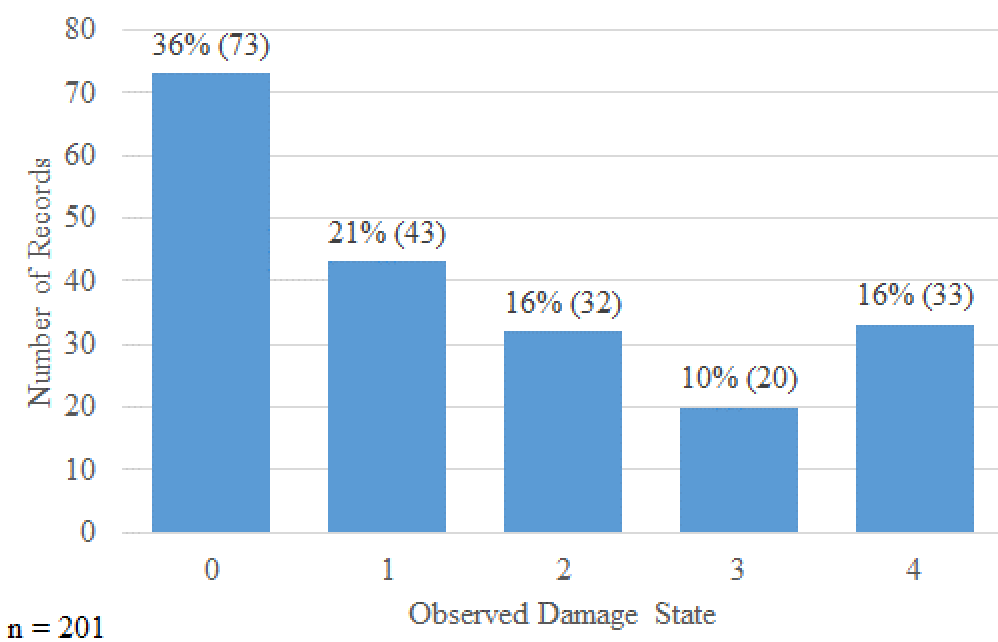


Figure 13. Number of single-family wood-frame structures assigned to damage states 0 through 4 following the Linwood, KS tornado, out of a total population of 201 surveyed single-family homes.

A total of 33 homes, 16% of the records taken in the field, were destroyed. Not included in this sample were 5 additional structures with damage so severe that the type of the structure was indiscernible (e.g., the building was completely swept from the slab). Structures assigned damage state 4 had such severe damage that repair is not feasible.

FAST members observed that damage was occasionally inconsistent with the distance of the structure from the center of the tornado path. Many times, locals agreed that structural damage and tree fall varied even within the same lot or property. For instance, one home would have been severely damaged, while its neighbor or the auxiliary structures on the same property exhibited only minor damage. These observations are likely due to some combination of local variations in tornado intensity and positioning, as well as landscape features, construction quality, or other factors.

One interesting two-story single-family house was situated about 0.1 mile south of the tornado path in the Bear Lake neighborhood west of Bonner Springs, Kansas, where the tornado intensity was on the order of EF-2 or EF-3 ratings. The most striking aspect of the damage was that the structure was missing its easternmost wall (Figure 14). The westernmost wall of the home, which was oriented parallel to the roof trusses, was also bowed outward. Such damage implied that although walls perpendicular to roof trusses were laterally braced by the trusses, walls parallel to the trusses may not have been braced laterally along their lengths. It was also reported that the ceiling of a porch on the south wall of the house was bowed upward and that 2x4 framing supporting the porch ceiling exhibited shear-type failures.

Figure 14. Single-Family house missing east side of the wall.

Figure 15 shows two other destroyed single-family wood-frame structures located in the Bear Lake neighborhood west of Bonner Springs, Kansas. The damage to these homes was attributed to wind damage. Roof structures, attached garages, and porches were the most severely damaged features of these homes. Photos in Figure 16 illustrate the effects of wind pressures on doors. One photo shows a bowed garage door, the other shows missing exterior and interior doors. The exterior door was dislodged with the door frame fractured and the interior door was dislodged with the entire frame separated from the surrounding wall. Residents survived the tornado sheltering in the back of their walk-out basement. Incredibly, it was reported that a 20-lb barbell was found 25 feet from its original location.

Figure 15. Views of two destroyed single-family wood-frame structures in the Bear Lake neighborhood west of Bonner Springs, Kansas.

Figure 16. Damage to garage door (left) and interior house door (right).

The most acute damage to structures occurred near Linwood, Kansas, where numerous structures sustained catastrophic damage. An example is shown in Figure 17, which provides photos of what was the front of a home and a close-up image taken of the back-side of the home where the first floor wall (missing) rested on the wall of the walk-out basement (shown). There was no evidence of anchors used to tie the framing of the first floor to the basement walls. Given the catastrophic nearby damage, it is not discernable whether proper anchorage of wall framing would have saved this home from destruction. However, lack of anchorage and roof-to-wall straps were observed consistently with damaged wood-frame structures. Nailed connections were clearly not sufficient in resisting the uplift and lateral loads experienced by these structures.

Figure 17. Catastrophically damaged single-family structure in Linwood, Kansas. Photos of the front of the home (left) and the joint where the first-floor walls (missing) rested on the basement walls (right).

In addition to the lack of engineered connections and anchorage impacting the connection of wood members, several homes used steel beams for longer spans. Figure 18 depicts two cases where these steel beams were unrestrained and resting on the structure with no connection. The weight and additional gravity load on top of these steel beams is sufficient for typical gravity-load purposes, but was not sufficient in resisting the uplift and lateral loads experienced during the tornado. In the right image of Figure 18, the fallen steel beam resulted in vehicular damage. Following the topic of restraints, exterior columns, often on the front porch or on the front side of homes, often shifted during the tornado (see Figure 19).

Figure 18. Unrestrained steel beams.

Figure 19. Shifted columns.

Fortunately there were not many manufactured (mobile) homes along the tornado's path as these structures are particularly known for high physical vulnerability. Of the manufactured homes captured in the study, severe to complete damage was observed as shown in Figure 20.

Figure 20. Severely damaged manufactured home (left) and completed destroyed manufactured home (right).

Auxiliary Structures

Approximately 60 auxiliary structures were surveyed. The term auxiliary structure is used here to include barns, sheds, detached garages, gas stations, and warehouses. Figure 21 shows the number of auxiliary structures assigned to each damage state.

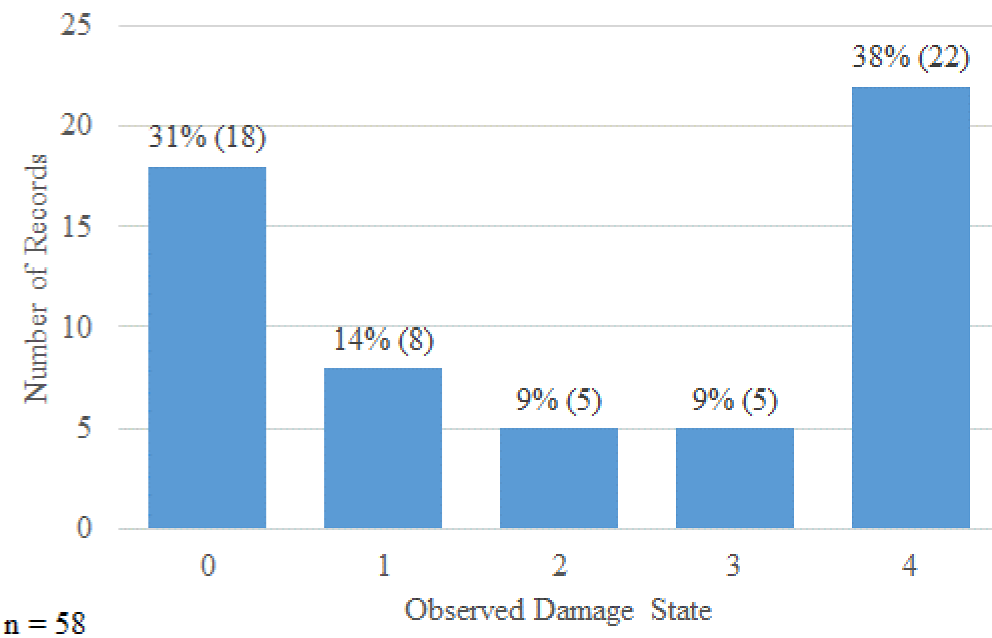


Figure 21. Number of auxiliary structures assigned to damage states 0 through 4 following the Linwood, KS tornado, out of a total population of 58 surveyed auxiliary structures.

Of the 58 surveyed auxiliary structures, 32 (56%) exhibited moderate or worse damage, with 22 (38%) being destroyed. Some owners reported loss of property and injured livestock as a result of damage to these structures. Nevertheless, 26 (45%) auxiliary structures exhibited no or minor damage. Note that while FAST members aimed to execute the surveys systematically, the higher percentage of seriously damaged auxiliary structures, relative to single-family homes, may not be indicative of construction quality or vulnerability. Many of these structures have large garage-type doors, and are of different construction style than single-family wood-frame structures, and thus the internal and external pressure distribution and pressure changes, along with the structural systems, differ significantly. In many areas affected by the tornado, homes and nearby auxiliary structures often exhibited similar damage severity.

Some common types of damage to auxiliary structures include uplifting of metal roofs (Figure 22), bending of metal walls (Figure 23), damage to doors (Figure 24), and loss of roof shingles. Damage due to tree-fall on the structure was also observed.

Figure 22. Metal roof exhibiting uplift damage.

Figure 23. Damaged metal building envelope.

Figure 24. Damaged shed door (left) and garage door (right).

Although several damaged structures showed evidence of sub-optimal construction, some well-constructed buildings were also damaged. Figure 25 shows the remains of a well-constructed (and recently completed) detached structure serving as a barn and garage. The photo shows what remains of the western-most wall, which consisted of sandwiched 2x6 columns anchored to a concrete foundation and well-attached plywood sheathing. This structure, located between Linwood and Bonner Springs, Kansas, was directly in the path of the tornado.

Figure 25. Remains of a relatively well-constructed barn located between Linwood and Bonner Springs, Kansas.

Another interesting auxiliary structure is shown in Figure 26. This structure served as a primary residence, but was not constructed as a typical single-family wood-frame structure. Notably, the wider support spacing and weaker exterior sheathing likely led to the catastrophic damage that included large holes in the roof, split roof rafters, and severely moved interior walls.

Figure 26. Residential auxiliary structure with severe roof loss (top left), split roof rafters (top right), shifted interior walls (bottom left), and uplifted and released interior walls (bottom right).

Social Structures

Social Structures were defined as non-residential, non-commercial buildings typically used for assembly occupancy. Such buildings are often schools, churches, and public park buildings. Two churches, the Elm Grove Baptist Church and the Lawrence 7th Day Adventist Church, were more than 650 ft from the tornado path and experienced only minor damage. A picnic shelter for the Baptist Church was approximately 900 ft from the path but was destroyed via pancake-like collapse (Figure 27). Also of interest was the Building Blocks Day Care, located in a former public elementary school. Located 100 ft from the tornado path, the unreinforced masonry day care facility was destroyed (Figure 28).

Figure 27. Picnic shelter at Elm Grove Baptist Church.

Figure 28. Building Blocks Day Care.

Wind-Borne Debris

Considerable evidence of wind-borne debris was observed throughout the area affected by the tornado, with debris reportedly being found 50 miles from path of the tornado. Examples of large missiles impacting the ground or structures are shown in Figure 29.

Figure 29. Wind-borne debris: 2 x 18 in. lumber embedded in soil (top left), 2 x 4 in. lumber embedded in exterior wall of wood-frame home (top right), siding from auxillary structure inside neighbor's residential structure (bottom left), mattress stuck in tree (bottom right).

Vehicles

A number of tree-damaged vehicles were found parked near single-family wood structures that experienced major to severe destruction (Figure 30). Most tree-damaged vehicles had shattered windshields or other evidence of wind-borne debris damage, parts of trees resting on the vehicle, or completely collapsed roofs. Several vehicles overturned or relocated by the tornado were also observed (Figure 31). In one case, a recreational vehicle had exploded, similarly to damage observed to older manufactured homes (Figure 32).

Figure 30. Tree-damage to vehicles.

Figure 31. Vehicles overturned or relocated by the tornado.

Figure 32. Exploded recreational vehicle (RV).

Power Structures

A limited number of failed electric power structures were documented during the survey. As mentioned earlier, this survey was performed three days after the tornado, and notably, repair on the electric power network (EPN) infrastructure was on-going. Figure 33 provides an image of two types of EPN failures, namely a repaired conductor and pole structure that failed during the tornado near Lawrence. A brief conversation with the residents indicated that the power was restored in one day near that location. Figure 34 illustrates a timber pole that was to be installed near Linwood, KS. Based on a short discussion with repair crew, the wood pole was chemically processed to prevent decay in service.

Figure 33. Recovered local power distribution structures: repaired conductor lines (according to the resident) (left); and a reinstalled power pole (right).

Figure 34. An electric wood pole in-place ready for reinstallation. Also captured in this photo is the linear array of poles, which were all destroyed during the tornado and reinstalled rapidly by Kansas City Power and Lights (based on information from crew member).

Recommendations for Further Study

FAST members focused assessments on the impacted areas near Lawrence, Linwood, and Bonner Springs, Kansas. The area directly south of Lawrence was not accessible due to road closures. Preliminary review of assessments logged by the team 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:

1. Tornado alerts were sent out via social media, text messaging, and news outlets at least 30 minutes prior to the tornado touching down. These early warnings may have led to the

zero resulting fatalities. However, there are no public shelters in Douglas County and no clear place for people, particularly those living in buildings without basements, to shelter. Future research should investigate potential public sheltering locations, and make recommendations to the surrounding counties for future tornado safety.

2. Many severely and completely damaged single-family wood-frame structures had insufficient load paths characterized by a typical gravity-based design and without fasteners providing uplift and lateral resistance at the roof-to-wall connection, and similarly with minimal or no anchorage at the wall-to-foundation connection. This finding is representative of the age of construction and lack of adopted building code and systematic inspections required during building for sections of the impacted area. Consistent and updated building regulations and required building inspections are recommended for all jurisdictions.
3. Although a small sample, manufactured homes proved again to be particularly dangerous during tornadoes; more research and better standards are recommended for safer, affordable housing.
4. Collapsed garages and barns may have contributed to debris impacts on other structures. While it may not seem reasonable to require that these types of auxiliary structures be designed to stringent standards considering their occupancy class, future research should examine whether improving the construction of such “low-risk” structures could reduce impacts, and therefore damage, to more essential structures such as homes.
5. There was one day care facility captured in the sample; it was of unreinforced masonry construction and was completely destroyed. These types of failures cause significant disruption to society. More importantly, had the tornado occurred during the typical work day hours, this failure likely would have resulted in the loss of life of many small children. Unreinforced masonry structures are known for their high physical vulnerability and potential for resulting in loss of life; it is recommended that such types of buildings are not used for schools and day cares and that more research should investigate affordable and effective retrofits.

Appendix A - Sample UAV Images of Tornado Damage

Many images in this appendix include a red line corresponding to the tornado path, green lines corresponding to the flight path, and red dots corresponding to locations were images were recorded.

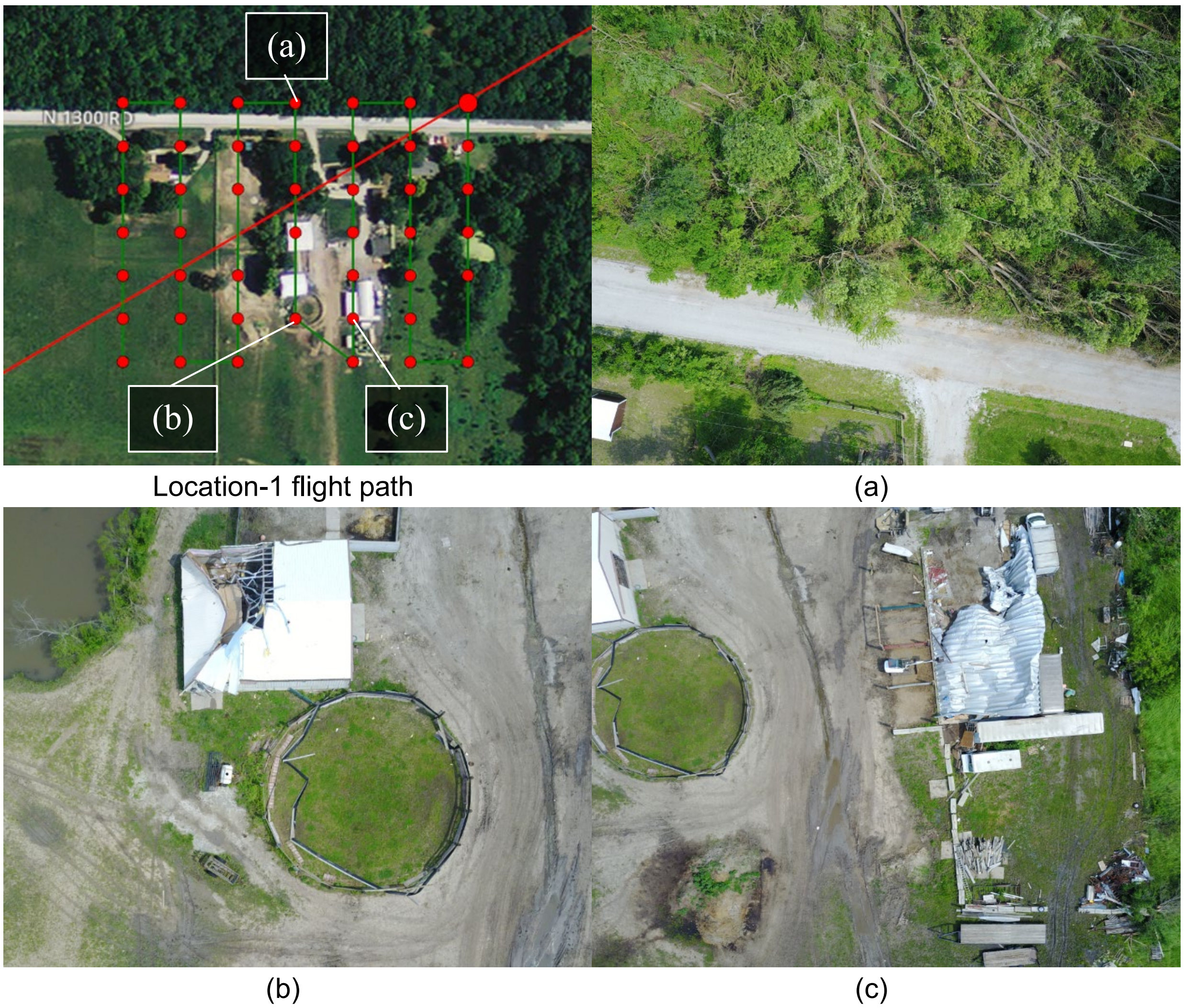
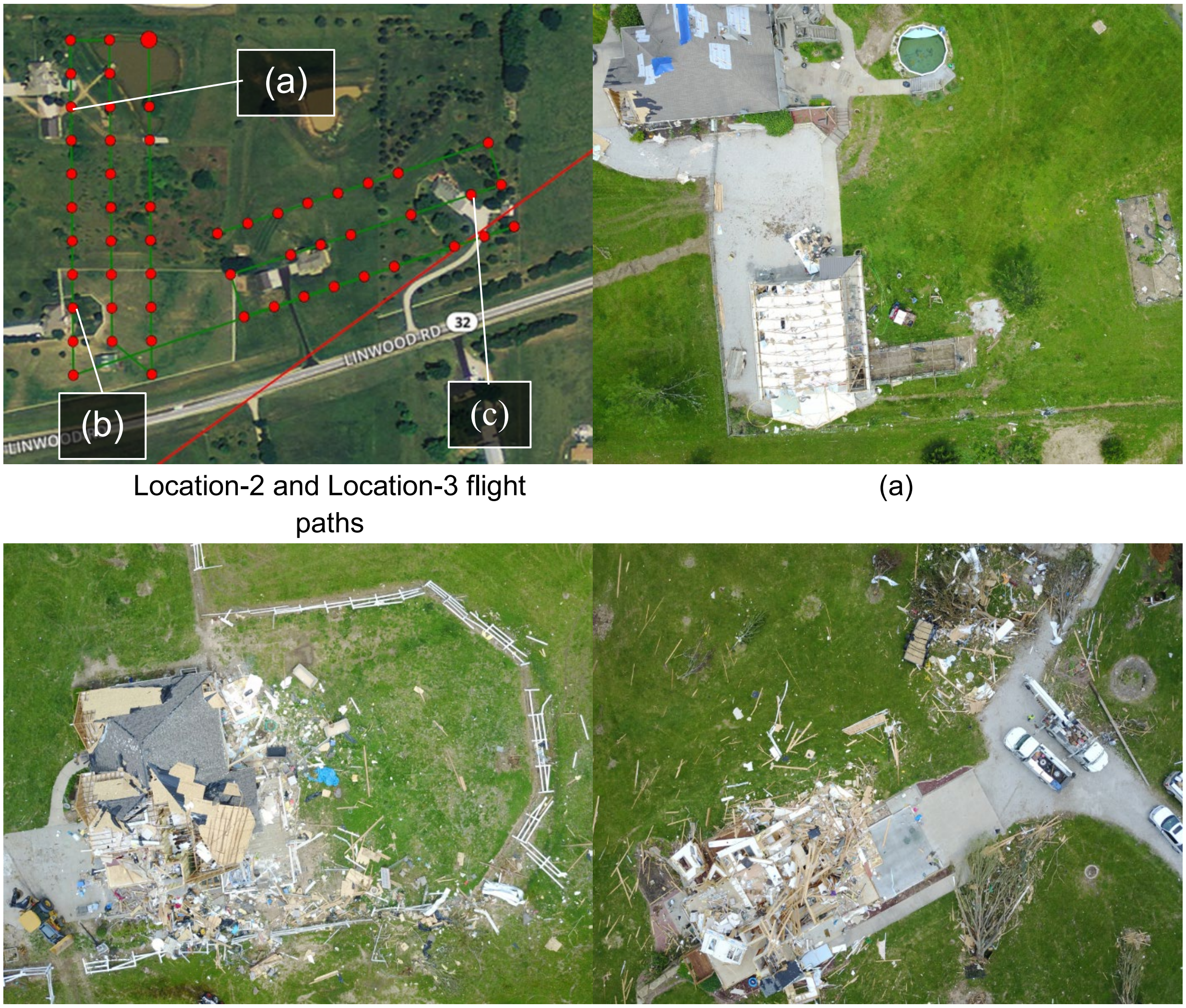


Figure A.1. Sample images of tornado damage at Location-1



Location-2 and Location-3 flight paths

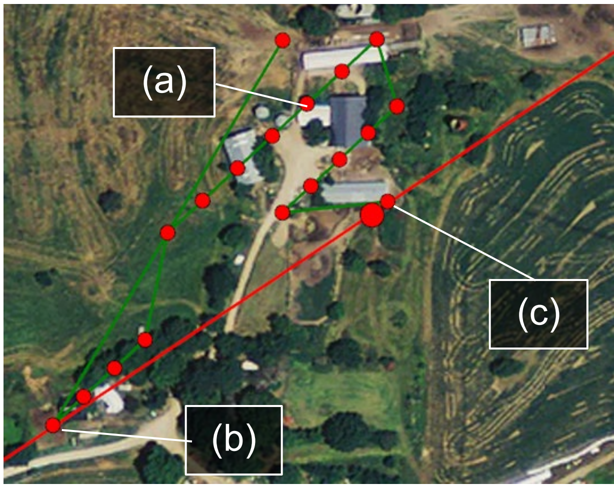
(a)

(b)

(c)

Figure A.2. Sample images of tornado damage at Location-2 and Location-3

Figure A.3. Sample images of tornado damage at Location-4



Location-5 flight path

(a)

(b)

(c)

Figure A.4. Sample images of tornado damage at Location-5

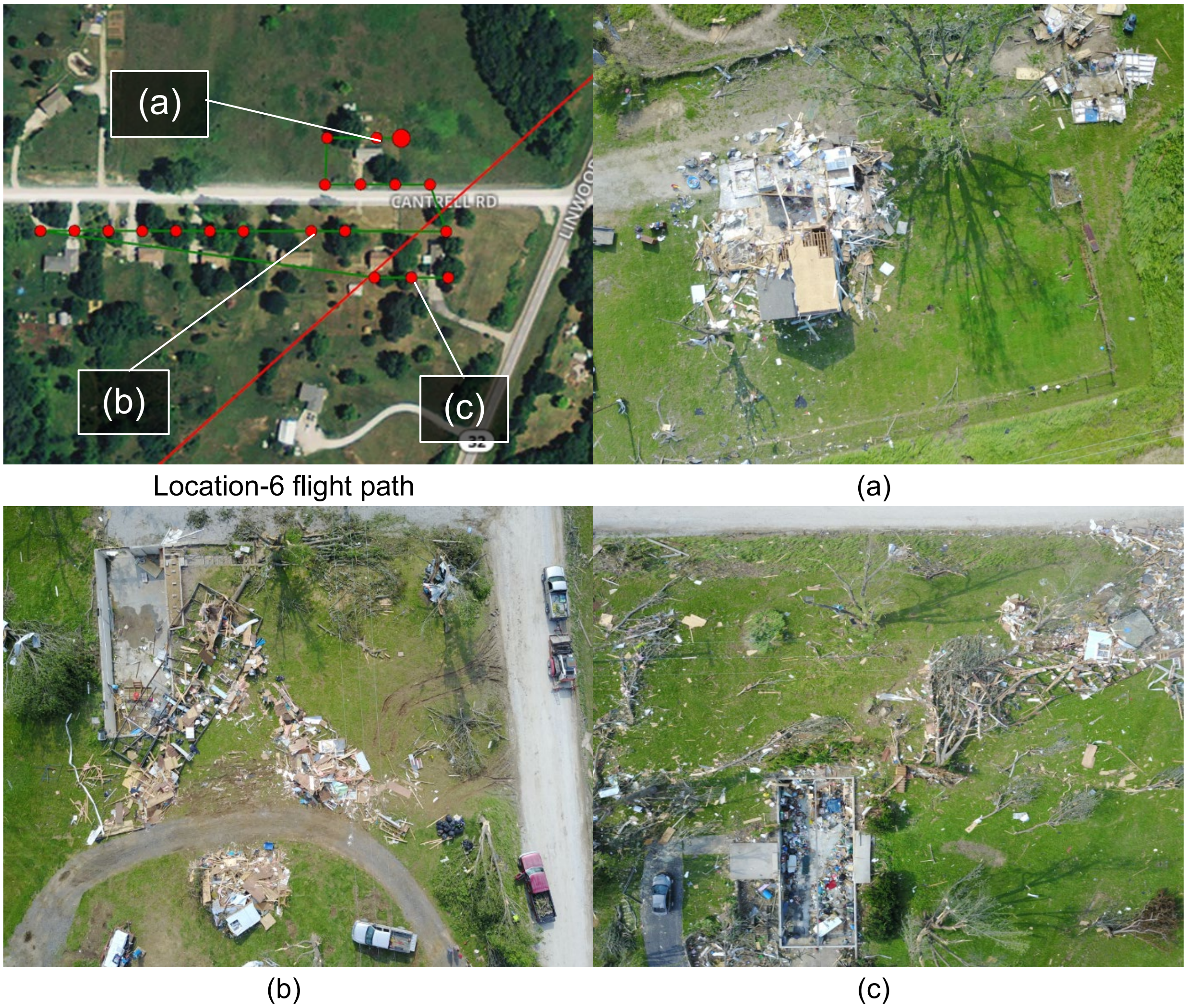
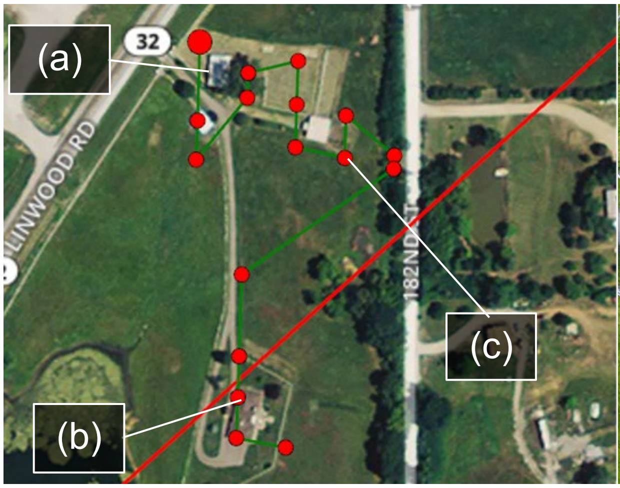


Figure A.5. Sample images of tornado damage at Location-6



Location-7 flight path

(a)

(b)

(c)

Figure A.6. Sample images of tornado damage at Location-7

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About StEER

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. StEER's vision is to *build 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; (2) leveraging its distributed network of members and partners to coordinate early, efficient and impactful responses to disasters; and (3) broadly engaging communities of research, practice and policy to accelerate the potential to learn 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.

StEER relies upon the engagement of the broad NHE community, including creating institutional linkages with dedicated liaisons to existing post-event communities and partnerships with other key stakeholders. While the 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 with overseeing the design and operationalization of the network.
- **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 Assessment Technologies, guiding StEER's development of a robust approach to damage assessment across the hazards.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data.

StEER's response to these tornadoes preceded the formation of its official policies, protocols and membership, which are still in active development. All policies, procedures and protocols described in this report should be considered preliminary and will be refined with community input as part of StEER's operationalization in 2018-2019.

StEER Event Report Library

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