828 Damage Survey and Analysis of the 20 May 2013 Newcastle-Moore EF-5 Tornado

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1. Introduction

a. Background

Detailed tornado damage surveys have been performed since the 1950s (e.g., Fujita, 1959), but became more quantitative with the introduction of the Fujita Scale in 1971 (Fujita 1971, Edwards et al. 2013). Since the 1970s, Fujita and collaborators, National Weather Service personnel (sometimes part of larger national or regional assessment teams, e.g. the Quick Response Team (NWS 2011)), and various groups of engineers performed surveys on many tornado outbreaks and individual violent tornadoes (e.g., FEMA 2007, Prevatt et al. 2012, Kuligowski et al. 2013). One example is the 3 May 1999 Moore, OK, tornado with an NWS-led survey (Speheger et al. 2002) and several surveys by engineering groups (Gardner et al. 2000, Marshall 2002, Pan et al. 2002, FEMA 2003).

The 20 May 2013 tornado affected the cities of Newcastle, Moore, and Oklahoma City, Oklahoma. The official path length for the tornado, as recorded in *Storm Data*, was 22.28 km (13.85 mi) and was up to 1,737 m (1,900 yards) wide. The tornado killed 24 people, injured 212 others, and damaged over 4,000 structures, with over 1,000 structures having damage exceeding EF2 intensity. A team of surveyors from the National Weather Center (NWC; University of Oklahoma, CIMMS, National Severe Storms Laboratory, the Norman National Weather Service Forecast Office and the Warning Decision Training Branch) and two private organizations (Haag Engineering and Insurance Institute for Business and Home Safety) began surveying tornado damage on 21 May 2013 and continued the survey process for the next several weeks.

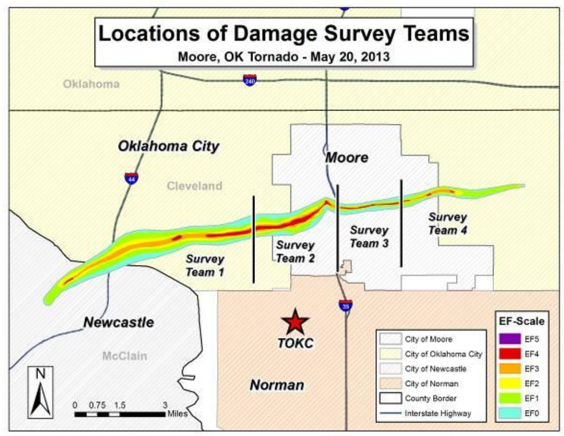

Figure 1: Path of the 20 May 2013 tornado and survey team areas.

In this paper we describe the effort to organize the ground survey teams immediately following the event, provide an overview of the tornado evolution, and review specific aspects of the damage survey (in particular, assigning EF5 ratings to residential structures). We will present comparisons of the tornado path and damage to data from several nearby radar facilities.

b. Ground surveys

Ground surveys were performed by four teams with each team responsible for a segment of the path (Fig. 1). Following the completion of

EF-Rating	Number of DIs
Unknown or not EF DI	31
0	2,057
1	825
2	506
3	462
4	363
5	9

Table 1: Summary of damage indicators surveyed.

surveys on 21 May 2013, team members reviewed the collected ground survey data and aerial imagery. Areas which were closed off due to on-going emergency operations or were in need of further investigation based upon the aerial photography were identified. Follow-up surveys were completed by original surveyor teams and additional staff from the NWC starting on 22 May 2013 and for the next several days; nearly 25 people conducted ground surveys. In total, 4,252 damage indicators (DIs) were evaluated by the surveyors, of which 4,221 were defined DIs within the Enhanced Fujita (EF; McDonald et al. 2006) scale (Table 1).

The large number of structures evaluated by the survey teams was made possible through the use of aerial imagery and detailed ground surveys of multiple areas along the tornado's path. By inferring the construction quality and the resulting rating of several structures at these areas along the path, the surveyors could use the aerial imagery to remotely evaluate, and eventually rate, structures which were not specifically inspected on the ground.

Damage information collection was centralized using the NWS Damage Assessment Toolkit (DAT; Camp et al. 2014). The DAT consists of an application available for smartphones and tablets, as well as a web application[1] for access via laptops or desktop computers. The use of the DAT during the surveys allowed teams to send information back to a centralized server, where the information was used to update the track path and width as the surveys were ongoing.

The DAT interfaces allow surveyors to select the EF-rating for a particular DI according to the corresponding Degree of Damage (DOD) observed. The DOD level corresponds to a particular EF rating (0 to 5), thus the DAT allows surveyors to record and disseminate damage information with a single tool. Each DI was geotagged with the option to add other metadata, such as a photograph.

c. Aerial surveys and imagery

An aerial survey completed from an Oklahoma Highway Patrol helicopter on the morning of 21 May 2013, before significant clean-up had begun, greatly aided the survey process. One of the co-authors (LaDue) performed the survey with a single circuit of the tornado path. In total, 314 aerial images were collected, with associated geolocation information. Surveying was also assisted using high-resolution satellite imagery made available via the Google Crisis map and later within the DAT. Aerial imagery collected by the Civil Air Patrol was also used to help finalize ratings.

Additional ground survey and aerial imagery from the Federal Emergency Management Agency[2] (FEMA) was also used, especially to help evaluate the level of damage to structures on the periphery of the tornado path.

d. Radar data

Several radar facilities were located close to the tornado path. The closest was the Oklahoma City Terminal Doppler Weather Radar (TDWR, herein referred to as TOKC; Istok et al., 2005) which was approximately 5 km from the tornado during the peak phase in tornado intensity as determined from damage. TOKC was selected not only for its very close range to the tornado, but also for the availability of 1-min, 0.5 degree

[1] A DAT data viewing website is available: http://goo.gl/7LTXnw

[2] Available at http://goo.gl/vcMjKu

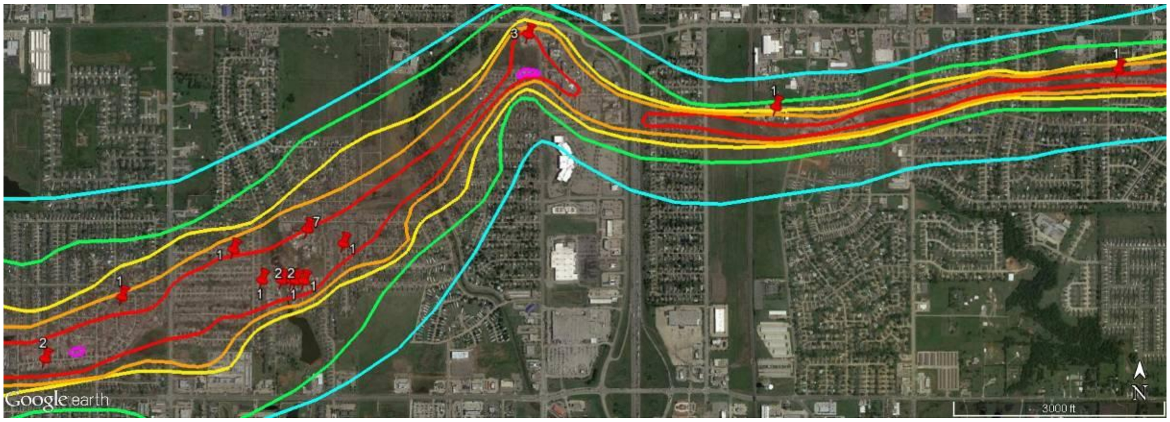

Figure 2: Map of fatalities (red pins) and contours of EF-scale damage (EF0: light blue; EF1: green; EF2: yellow; EF3: orange; EF4: red; EF5: magenta)

tilt scans for the duration of the tornado lifetime. This maximizes the potential to investigate the relationship from the Doppler velocity estimates of the tornado wind speeds to the EF-rating of the damage structures along the path.

Two WSR-88D (Crum and Alberty 1993) facilities were also located close to the tornado path: one being the operational Twin Lakes (KTLX) radar and the other being the Radar Operation Center's test bed radar (KCRI). Both radars supplied dual-polarization fields (Istok et al. 2009), which allows for comparisons of these fields to the damage at the ground.

2. Survey Results

a. Overview of damage

Officially, the tornado began at 1956 UTC along Oklahoma State Highway 37 near U.S. Interstate 44 in Newcastle, OK and intensified to EF4 intensity within 1.5 km of formation. The beginning of the tornado was debated and an analysis of the beginning of ground damage will be provided in a later section. The tornado continued northeast, crossing the Canadian River at Interstate 44 (2003 UTC), where it removed two sections of an unused, steel truss highway bridge from the bridge's concrete pillars. Just after the Canadian River (2005 UTC), the peak width of 1,737 m was determined from damage. The tornado continued through areas of southwest Oklahoma City near the Canadian River producing damage rated to EF4 and took a more easterly path than its initial northeastward movement.

The first EF5 damage was to two homes located a few blocks east of Briarwood Elementary School[3] (2017 UTC). The first fatalities of the tornado also occurred in the neighborhood immediately east of Briarwood. The tornado then turned back to a more northeast motion while moving through the neighborhoods between Briarwood Elementary and Plaza Towers Elementary schools (2017-2020 UTC). Plaza Towers and the neighborhoods nearby are where the majority (17 of 24) of fatalities occurred (Fig. 2).

After damaging Plaza Towers, the tornado continued northeast towards the intersection of S. Telephone Rd and S.W. 4th Street. Two blocks south of this intersection, along S.W. 6th Street, four homes were swept clean from their foundations and were assigned EF5 ratings. Near the Telephone/4th St. intersection, the tornado executed a loop (Kurdzo et al. 2014;

[3] While drafting this manuscript, details of a ASCE study describing probable poor construction practices at Briarwood Elementary were released to the media. Given the uncertainty, this manuscript refers to the damage at Briarwood as EF4 intensity, pending review of the ASCE report. This may not reflect the official rating (currently EF5) of Briarwood reported by the National Weather Service.

Figure 3: Debris trajectory analysis near N. Rockwell Ave. and N.W. 28th Street in Newcastle. The closest co-located WSR-88D radar volume scan is from KCRI around 1954 UTC.

2023 UTC), narrowed considerably, and accelerated in forward motion. The tornado briefly traveled southeast, severely damaging the Moore Medical Center, before turning back to the east at Interstate 35 (2024 UTC). The tornado continued travelling through the neighborhoods south of S.E. 4th St. while producing a narrow swath of EF4 damage. Three more homes were assigned an EF5 rating in east Moore. The tornado continued to narrow and weaken as it approached S. Sooner Rd. (2030 UTC) and finally dissipated about 5 km west of Lake Stanley Draper at 2035 UTC. The tornado traveled a total of 22.3 km in 39 minutes for an average forward speed of 9.5 m s^{-1}. The following subsections describe smaller segments of the path in more detail.

b. Damage prior to Highway 37

The first area with damage was near the McClain-Caddo county border; west of State Highway 76 along N.W. 16th Street (1945 UTC). The damage from this point to the official start of the tornado, consisted of lightly damaged home roofs, a variety of damage to outbuildings (a small shed was completely destroyed, while larger outbuildings experienced roof panel removal at worst), trees with large limbs removed and uprooted trees. All of the found damage prior to the official start of the tornado was assigned ratings at or below EF1.

High-resolution satellite imagery made a tree fall analysis possible. The analysis was completed by one of the authors (Speheger) and revealed an intermittently confluent damage pattern, suggestive of a weak vortex (e.g., Karstens et al. 2013), starting approximately 0.9 km northwest of Highway 76 and N.W. 16th St. There was also a 1.1 km break in consistent damage between Castle Creek Dr. and Kirkham Dr. along N.W. 24th St, even though the location has large areas of trees and several structures located along the path. Another confluent damage pattern was apparent just southwest of the official start location (Fig. 3), with one small shed completely destroyed. However, the path then entered two open fields. The tree line between the fields was observed to not have any damage (Fig. 3).

The close proximity of the start of the tornado to two polarimetric WSR-88D radars allows for a detailed investigation for the presence of a tornadic debris signature (Ryzhkov et al. 2005). The hook echo, and associated rotation signature within the Doppler velocity field, of the storm over the damage path prior to the official start ranged from 32.4 to 35.6 km away from KTLX. This corresponds to the radar beam centerline being located between 350 and 400 m above the ground.[4] KTLX collected three volumes of data while there was damage on the ground prior to the official start time. For KCRI, the hook echo was between 16.5 and 19.8 km, which correspond to the radar beam centerline located between 175 and 210 m above the ground. KCRI also collected three volumes, with damage at the ground, prior to the official start of the tornado.

An analysis of the properties of the polarimetric fields similar to Bodine et al. (2013) was performed on both the KCRI and KTLX data.

[4] Terrain elevations across the start of the damage path and the elevations of KTLX and KCRI were very similar (approximately 390 m).

Time (UTC)	KTLX Z (dBZ)	KTLX Z_{DR} (dB)	KTLX CC	KCRI Z (dBZ)	KCRI Z_{DR} (dB)	KCRI CC	KTLX V_r (m/s)	KCRI V_r (m/s)	TOKC V_r (m/s)
1945				--	--	--		18.5	16
1947	--	--	--				24		21.75
1950				48.8	-1.37	0.61		24.75	33.25
1951	41.5	-2.66	0.61				35.5		38
1954				47.8	-1.09	0.58		37.5	42.5
1956	43.4	-2.56	0.52				27		27.5

Table 2: Summary of polarimetric field and Doppler velocity analysis for volumes with damage on the ground prior to the official tornado start time. Values displayed for reflectivity are the 90th percentile of qualifying pixels within the vortex; differential reflectivity and correlation coefficient values are for the 10th percentile of qualifying pixels within the vortex.

For each volume, where the peak reflectivity within the tip of the hook echo exceeded 43 dBZ, the pixels within the Doppler velocity vortex signature (determined to be 1 radial and gate outward—from the vortex signature center—from the pixels containing the maximum Doppler inbound and outbound velocity) were used to create distributions of reflectivity, differential reflectivity and correlation coefficient. This is different than Bodine et al. (2013) which used a 2 km radius to find pixels for creating distributions. Using Bodine et al. (2013) T1 thresholds (reflectivity: 43 dBZ; correlation coefficient: 0.82), the 90th percentile of reflectivity values and 10th percentiles of correlation coefficient and differential reflectivity were found. The results of this analysis are summarized in Table 2.

The first volume in which the peak reflectivity within the tip of the hook echo exceeds 43 dBZ was recorded around 1950 UTC by KCRI (Fig. 4). While 50% of the pixels satisfied the reflectivity exceeding 43 dBZ and correlation coefficient less than 0.82, a subjective interrogation of the polarimetric and velocity fields yields a lacking texture, especially within the correlation coefficient field, in identifying tornadic debris.

The KCRI volume collected around 1954 UTC (not shown) yields a much more favorable subjective interrogation, while the percentage pixels exceeding the T1 thresholds increases to 75%. However, the radar data is in contrast to the damage, and lack thereof, found in the area (Fig. 3).

The two KTLX volumes around 1951 and 1956 UTC yielded far less percentage of pixels exceeding the T1 thresholds (6% and 10%, respectively) than the volumes from KCRI,

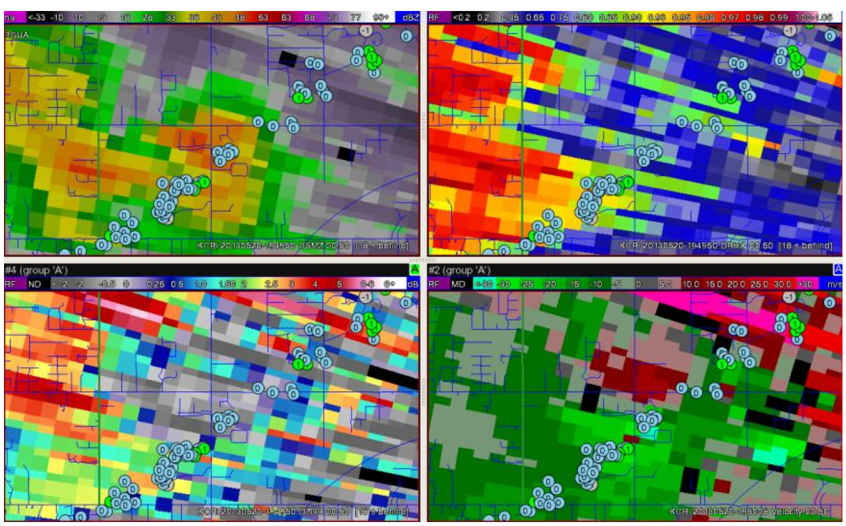

Figure 4: 0.5° tilt from KCRI around 1950 UTC. Top-left: reflectivity; top-right: correlation coefficient; bottom-left: differential reflectivity; bottom-right: Doppler velocity. All panels have roads (blue), county lines (green) and the damage points overlaid.

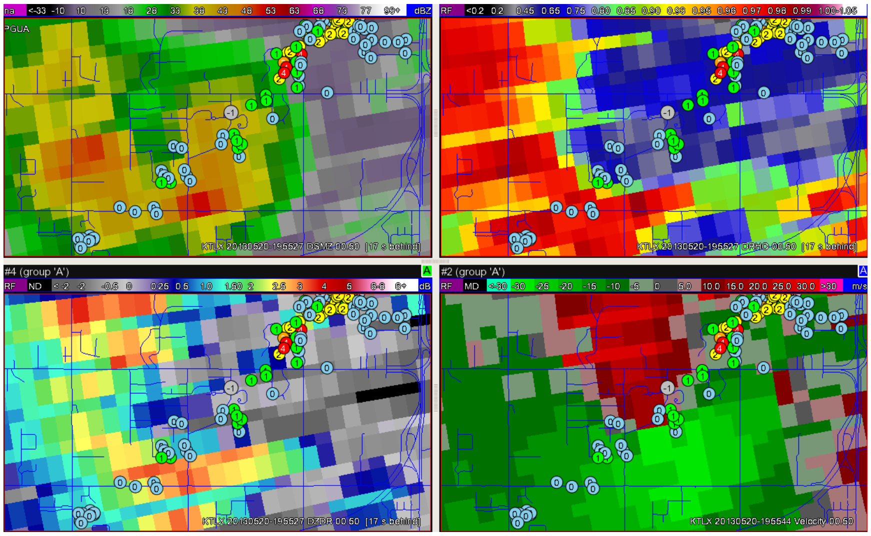

Figure 5: As in Fig. 4, except for the 0.5° tilt from KTLX at 1956 UTC.

though there were more pixels within the vortex. The two volumes also reveal similar results through subjective interrogation as the volumes from KCRI (Fig. 5; 1951 UTC not shown).

Rotational velocity derived from each radar's Doppler velocity data show similar values to those computed from TOKC (Table 2). The values computed (except for the 1945 UTC scans) also exceed the 20 m s^{-1} threshold found by Alexander and Wurman (2008) for radar-determined tornadic vorticies.

Video[5] from a local television station provided some video evidence to accompany the ground surveys and radar data. Prior to 1953 UTC neither a visible debris cloud nor a near ground funnel is visible. Just prior to 1953 UTC a debris cloud from the ground-based camera is visible briefly; it's inconclusive from the video whether rotation was present within the debris cloud. This is followed by what appears to be a small, and very short-lived, vortex in contact with the ground (but not cloud base) just a few seconds after 1953 UTC (approximately 7:27 in the YouTube video). Using TOKC data, this near-1953 UTC timeframe corresponds to the area just west of Rockwell Ave. pictured in Fig. 3. The ground-based video in the television station video was recorded from a location approximately 7.8 km NE of this location (near S.W. 149^{th} and S. May Ave).

A larger condensation funnel and, then, tornado is not apparent until 12 seconds prior to 1956 UTC. Several other videos and eyewitness accounts of storm chasers and meteorologists in area were reviewed by the Norman WFO. Many of these videos and accounts supported the tornado formation very close to 1956 UTC. Given the evidence present, especially a cumulative review of the video evidence, the official start time of the tornado was marked as 1956 UTC in *Storm Data*.

c. Western path segment

(This segment starts at the official start point and ends at S. Western Ave.)

The tornado officially formed in north Newcastle, south of Oklahoma State Highway 37 along Long Drive at 1956 UTC. The tornado immediately produced EF1 damage to trees (uprooted) and a home at the south end of Long Drive (collapsed garage doors). Ground damage surveyors noted that the damage began to intensify along Highway 37. The tornado moved northeast towards a subdivision north of

[5] Available http://www.youtube.com/watch?v=m18YuRxsdA8

the intersection of Highway 37 and Country Club Rd. Several homes in this subdivision were destroyed, with two being rated EF4. Some evidence of ground scouring is also present from this subdivision and along the tornado path to the northeast. The tornado then entered a neighborhood along N.W. 36th St. (2000 UTC), just south of the Canadian River, where several homes were assigned EF3 ratings. The tornado at this point had grown from an initial diameter of almost 600 m to nearly 800 m as it began to cross the Canadian River.

As the tornado crossed the Canadian River, it began to widen very rapidly. In the 5 minutes the tornado took to travel across the river and into the floodplain just east of Interstate 44, the tornado had more than doubled in diameter from approximately 800 m to its maximum diameter of nearly 1740 m. As the tornado crossed the Canadian River, it displaced two sections (approximately 70 m in length) of an unused, steel truss highway bridge from its concrete pillars. While there was a lack of DIs immediately east of Interstate 44, the few DIs present were rated EF3 at maximum, since the DI maximum DOD was EF3.

The tornado then travelled eastward, with the north edge of the tornado located just north of S.W. 149th St. Just west of S. May Ave., south of S.W. 149th (2008 UTC), the damage intensified to EF4 again with several homes rated to that level. Aerial and high-resolution satellite imagery revealed consistent ground scouring from this point until the tornado entered more urban areas of western Moore.

One home along S. Virginia Ave. (2013 UTC) had potential EF5 appearance (swept foundation), however the ground survey found that the base plates were secured using cut concrete nails (Fig. 6). Cut nails have much less pull-out resistance compared to bolts that have properly tightened nuts with washers. This is because the washers help distribute the load on the bottom wall plates over the area of the washers. Bolts also help resist lateral forces which could slide a home off the foundation.

Figure 6: Aerial image of swept foundation. Ground surveys found that the home was only secured to the foundation using cut nails, resulting in EF4 rating.

Just before crossing S. Western Ave., the tornado impacted two oil drilling and storage facilities (2015 UTC). Four tanks at these facilities were displaced; in the process of conducting ground surveys, 3 of those 4 were found. One was found only 200 m east of the origination point. Two were found further, one near Briarwood Elementary (1.4 km displacement) and another near S. Santa Fe Ave. (2.1 km displacement). The dimensions and weight of the tanks were not known.

d. Central path segment

(This segment starts at S. Western Ave. and ends at S. Bryant Ave.)

The tornado crossed S. Western Ave. just north of S.W. 149th. The tornado maintained its intensity, causing EF4 damage to several buildings, including a small strip mall and all of the buildings belonging to Celestial Acres horse training farm. Two propane storage tanks from the horse farm were lofted. The tanks weighed 10 tons empty and were displaced up to 900 m, one landing on top of Briarwood Elementary and the other in the neighborhood immediately east of the school. The tornado continued east from this location, leaving a swath of ground scouring, before impacting Briarwood Elementary school. The damage to Briarwood was assigned a rating of EF4[6]. Two wings of the school were completely destroyed. The school was

[6] See footnote 3 (pg. 3).

constructed with open web steel roof joists supported by concrete masonry walls. Walls had minimal vertical reinforcement and some of the steel joists were not bolted to the walls. The first fatalities due to the tornado occurred in the neighborhood immediately east of Briarwood.

The tornado began a more northeastward movement upon entering this neighborhood, producing EF4 damage up to 160 m across. The centerline of maximum damage from the tornado crossed S. Santa Fe Ave. near S.W. 15th St. in Moore (2018 UTC). The area of the EF4 and greater damage also expanded to nearly 350 m in diameter. The debris field again exhibited windrowing between S.W. 13th and 14th Sts. near Penn Lane. Penn Lane to Ridgeway Drive, bounded by S.W. 11th and S.W. 14th, marks the area where most of the fatalities occurred. This area is the location of Plaza Towers Elementary, where damage was assigned an EF4 rating and seven fatalities occurred (2019 UTC). More than one dozen homes south of Plaza Towers were swept clean from their foundations. These homes near or along S.W. 14th, were also assigned EF4 ratings and the locations of six fatalities. Most of the homes along S.W. 14th were built after the 3 May 1999 F5 tornado, yet only had base plate connections of concrete cut nails. This lead to only an assignment of EF4 rating per Marshall et al. (2003), which suggested either reducing the rating by 3 EF-scale numbers or using neighboring homes' ratings. The finding of homes with cut nail connections is consistent with Marshall (2002), which found poor construction practices, even within rebuilt areas of the 3 May 1999 tornado.

The tornado continued northeast through Tom Strouhal/Little River Park and into a neighborhood south of the intersection of S.W. 4th St. and S. Telephone Rd (2020 UTC). The tornado's area of peak intensity seems to have also reduced in size, with only a few houses in this neighborhood being rated higher than EF3. Four homes at the northwest corner of S.W. 6th St. and S. Telephone Rd. were rated EF5. All homes were found to be bolted to their foundations (with properly tightened nuts and washers), with wall studs toe-nailed to base plate connections.

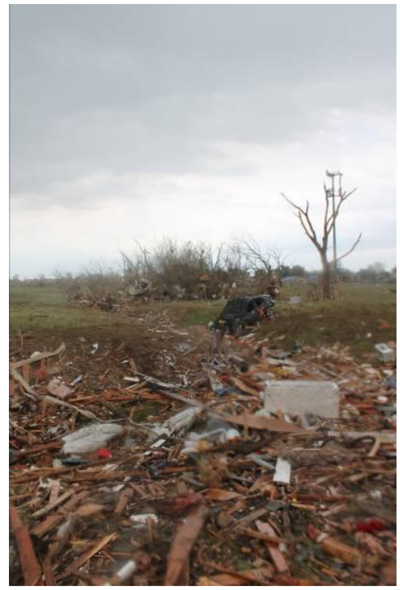

Figure 7: Picture looking down the tornado path from a home swept from its foundation. A denuded tree and lofted vehicle are visible. Another vehicle was lofted past the trees in the background.

The tornado at this point was travelling nearly due north towards the S.W. 4th and Telephone intersection, when it executed a loop (Kurdzo et al. 2014; 2023 UTC). This loop seemingly took place right over a convenience store, where 3 more fatalities occurred as the gas station was completely destroyed and debris swept to the south. The tornado exited the loop to the southeast, where it then severely damaged the Moore Medical Center (EF4) and possibly impacted the EF5 rated homes along S.W. 6th a second time.

The tornado lofted many vehicles that were parked at the medical center. Most of the vehicles were pushed or lofted southeast, but one was found to have been lofted back to the west and deposited in a field north of S.W. 6th St. One vehicle landed on top of the 2-story medical center. The tornado continued southeast, damaging and destroying several businesses (all assigned EF3 ratings—the maximum for the DIs present) near the medical center, before turning eastward over Interstate 35 (2023 UTC).

The tornado at this point had reduced in size, from approximately 1300 m over Plaza Towers to around 500 m as it entered the neighborhoods east of Interstate 35 (a time span of approximately 5 minutes). The tornado also began accelerating its forward motion. The damage along this part of the tornado track was consistent, with an EF4 core that was usually only a house or two wide. The construction quality along the track was also fairly consistent (even though the ages of the homes were spread among a few decades) with bolted base plates, but straight-nailed wall stud to base plate connections. The damage path exhibited ground scouring and vehicles were lofted in the area between S. Broadway St. and Tower Dr (2024 UTC).

One home, on Hunters Glen Ct., was rated EF5. While the home was determined to have straight-nailed base plate/wall stud connections, the EF5 rating was due to the presence of bent anchor bolts, removal of some of the base plates, and the nature of the debris scatter and denuded tree near the home (Fig. 7). Two vehicles from this area were also lofted, one potentially further than 100 m. The tornado continued an easterly track on the south side of S.E. 4th St. towards S. Bryant Ave.

Figure 8: Truck which was displaced by the tornado, however it was not lofted nor tumbled, but slid through a muddy field.

e. Eastern path segment

(This segment starts at S. Bryant Ave. and ends at the official end point of the tornado)

The tornado crossed S. Bryant Ave at Veterans Memorial Park. The tornado continued at EF4 strength into the neighborhood south of S.E. 4th, along S.E. 5th St. The tornado then crossed S.E. 4th and exited the higher density residential areas of Moore. From this point on, ground scouring was clearly present. One final home rated to EF5 was located north of S.E. 4th along a private drive east of S. Olde Bridge Rd. The home was mostly displaced to the north of the foundation, with windrowing of the debris. A vehicle from the residence was thrown 100 m to the northwest. The tornado then impacted a number of industrial buildings along Sunnylane Rd., destroying six buildings in total and damaging several others. The final EF4 damage of the tornado was found to two homes and one concrete building along County Lane, north of S.E. 4th. The tornado then tracked into mostly open areas near and east of S. Sooner Rd. The tornado was still producing significant tree damage, with many trees uprooted within the impacted tree lines.

The tornado impacted one last farm along S. Air Depot Road, halfway between S.E. 119th and S.E. 134th Sts. The home on the farm had the roof removed (EF2) and one outbuilding was completely destroyed (EF2). A parked truck at the farm was slid to the east-southeast by the tornado through a muddy field. The truck did not tumble, as the drag marks were clearly evident in aerial imagery (Fig. 8). The tornado then dissipated in a tree line 230 m east-southeast of the farm at 2035 UTC.

3. Radar Analysis and Damage Comparisons

The closest radar to the tornado was TOKC, located approximately 5.1 km from the path in Moore (see Fig. 1 for TOKC location). TDWR specifications are: C-Band (5.6 GHz); effective

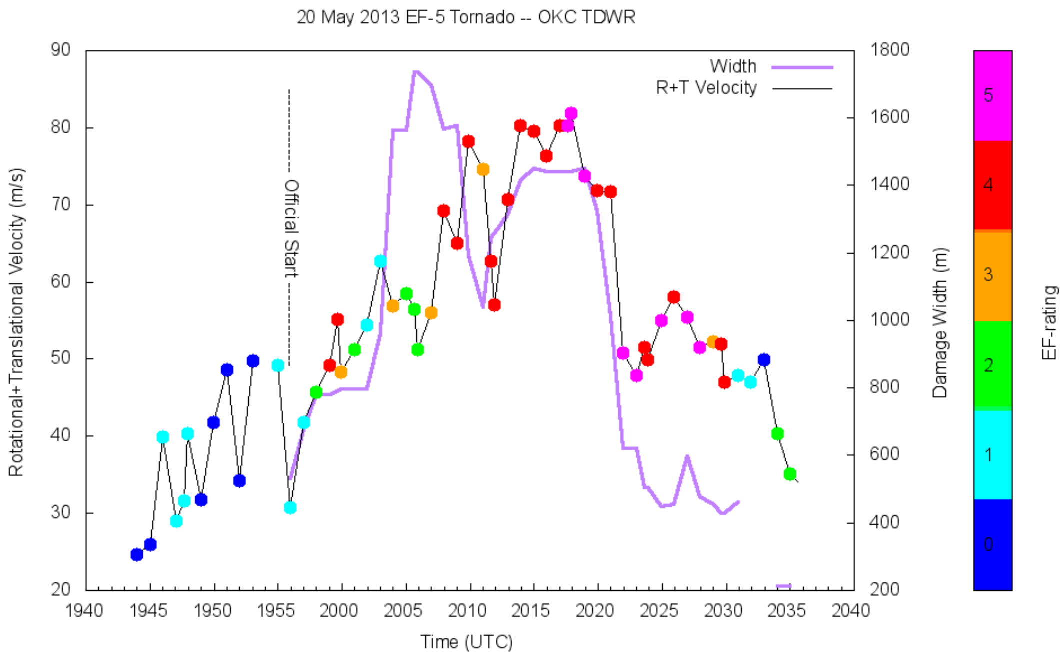

Figure 9: Rotational velocity from TOKC Doppler velocity data with maximum damage and damage width from ground survey information.

beamwidth 1.2° (~115 m wide at the 5.1 km approach of the tornado); gate length 150 m, 0.5° elevation angle scans once per minute except twice per minute every sixth minute; and peak power 250 KW (Istok et al. 2005).

Maximum rotational velocities ($(V_{out} – V_{in}) / 2$) were found from each TOKC 0.5° tilt; the translational velocity of the vortex was determined for each scan and added to the rotational velocity. Velocities were first dealiased with the technique described in Jing and Wiener (1993) with any further dealiasing manually performed by hand. The width of the damage for each volume was determined first by finding the location of the center of the vortex signature from the TOKC velocity data. Then, a circle, centered on the vortex location, was subjectively fit to the width of the damage. The EF-rating was subjectively assigned to the volume, using the highest damage rating near the center of the velocity signature (e.g., an EF5 rating near the edge of the best-fit circle was not used).

Plotted in Figure 9 are the velocity data compared with the damage width and damage ratings from the ground surveys. Several interesting things are seen in the plot. The first is the presence of EF0- and EF1-quivalent (29+, 38.5+ m/s, respectively) winds prior to the official start of the tornado; then the decrease in winds to near minimum EF0-quivalent at the official start of the tornado. The first EF4 damage was correlated with very modest TOKC velocities (45-50 m/s) compared to EF-scale estimated minimum wind of 74 m/s for EF4 (McDonald et al. 2006). The maximum width of the tornado occurs approximately at 2005 UTC, yet the velocities were fairly moderate (50-55 m/s). While those wind speeds correlate well to the observed damage, it’s difficult to make a definite comparison given the lack of substantial DIs between 2001 and 2008 UTC. The peak winds measured by TOKC (81.9 m/s) are co-located with found EF5 level damage at the ground and occur when the tornado is at its closest approach to TOKC (5.1 km; beamwidth of ~115 m). However, the TOKC winds (81.9 m/s) are well short of the 90 m/s wind speed estimate for EF5 damage to occur. Finally, the decrease in tornado width, starting at approximately 2021 UTC, greatly affected the ability of the radar to collect the maximum wind speeds within the

Figure 10: A close up of a home's base-plate-to-foundation connection. Shot pins were used to secure the base plate to the connection, with bolts not even being used in the corners.

tornado. The effective beamwidth increased from 145 m to 280 m (2021 UTC to 2035 UTC) as the diameter of maximum winds decreased to less than 300 m (estimated from radar).

This radar analysis was fairly limited and subject to much uncertainty. The first uncertainty is the wide beamwidth of the radar compared to the damage width along the tornado's path. The second is the height of the beam from TOKC. Even at the tornado's closest approach to the radar, the beam height is around 45-50 m above the ground. The EF-scale uses 10 m for the wind speed estimate height. Further, the EF-scale uses the 3-second gust and no smoothing of the velocities was completed for this analysis. Finally, there is much uncertainty in Doppler radar wind speed estimates when debris is present within the volume (Dowell et al. 2005). This analysis shows that much caution should be used when using coarse radar measurements (with respect to tornado size) in evaluating the strength of the tornado using those data.

4. Discussion

a. Determining EF-5 for single family homes

The surveyors considered any single family home in which the foundation was swept clean for assigning an EF5 rating. The first of such homes was located on S. Virginia Ave. south of S.W. 149th (Fig. 6). While the slab was swept clean and the debris strewn downwind for some distance, ground surveyors found that the base plates were only secured using concrete nails. Given this exceptionally weak foundation connection, the final rating for the home was EF4. Many homes within the tornado path had weak foundation connections precluding them from possible EF5 assignment (Fig. 10).

The first EF5-rated home was located on S.W. 147th St. The second EF5-rated family residence was the second house east of the first. These homes were constructed using 2"x4" wall studs that were straight-nailed and toe-nailed into a double-plated base plate (effectively 4"x4"), with the base plate being bolted to the concrete slab foundation (secured with nuts and washers) around the perimeter of each home. With both homes, the walls were completely removed, and large sections of the base plates were pulled away from the foundation. Consequently, the bolts anchoring the removed base plates were bent with the nut still secured to the bolt.

A discussion ensued about how to apply the EF-scale to the aforementioned residential damage. The observation of whole walls removed (including at least part of the base plate) while bending anchor bolts implies continuity in the load path, at a minimum, from the wall-rafter

Figure 11: One of 4 homes assigned an EF5 rating near Moore Medical Center. All four homes were swept from their foundations, with removal of base plates and bent anchor bolts. The resident of this home was injured sheltering from the tornado in the bathtub.

connection to the foundation. As is often the case with EF4+ damage in urban areas, determining the wall-rafter connection (and other connections) was not always possible[7], because the evidence for making such a determination could not be located. In the absence of additional load path information, the construction quality for these structures was deemed compliant with the local building codes. Nevertheless, these structures were considered candidates for the expected value wind speeds associated with residential structures (DI FR12), or 200 mph, resulting in the assigned EF5 ratings.

The largest cluster of EF5-rated homes occurred near S.W. 4th St. and Telephone Rd. in Moore. Four consecutive residences on S.W. 6th Street were assigned EF5 ratings (Fig. 11). These homes were constructed similarly to the previously described homes that were assigned EF5 ratings. These four homes had single base plates, which were bolted with properly tightened washers and nuts; wall studs were also connected to the base plate with toe-nail connections. However, it is important to note that the tornado performed a loop immediately north of this location. Thus, it is quite possible, perhaps likely, that the core flow of the tornado passed over these homes twice. This observation raises questions about how to incorporate the duration of exposure to tornadic winds for a given DI in assigning an EF-rating. Do longer durations always result in more intense damage? If so, how would such information be incorporated into the EF-scale?

b. Use of non-DI damage and damage context

The tornado in Moore hit thousands of buildings, mostly residences. Given the large number of buildings, the rating of the tornado relied less on the context of surrounding damage and non-DIs and more on the DOD for each DI. However, damage context and non-DIs were helpful in the rating of some more isolated, higher-end DODs. The EF5-rated residence on Hunters Glen Ct. is an example where context increased confidence in determining the final rating (Fig. 7; LaDue 2011). First, two vehicles from the location were lofted. Second, a tree east of the home was denuded. Third, debris from the home was not found in any large portion and the debris was windrowed towards the east.

c. Miscellaneous notes on damage

A quick review of the damage points reveals a fairly lopsided damage path, with the southern half typically a little further out from the damage centerline than the northern half (Fig. 1). It's entirely possible that some rear-flank downdraft damage was included on the southern periphery of the tornado path.

Another possibility is that due to the enormous amount of debris in the air, debris damage was identified in the ground-based and aerial images and marked as wind damage. The magnitude of debris impacts on the periphery of the tornado track is no more apparent than along S.W. 12th, 13th and 14th Sts. between Macalpine St. and S. Janeway Ave. While many of the homes were rated EF0, the severity of damage impacts, which included sizeable holes in roof structures, with all southward facing windows broken, led to most of these EF0 rated duplexes to be demolished (Fig. 12).

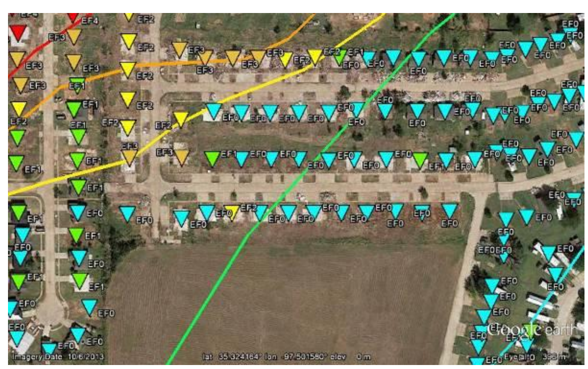

Figure 12: Google Earth image showing several EF0 or EF1 rated duplexes which were subsequently demolished due to debris impacts.

[7] When possible, adjacent homes with roofs still attached or partially attached, top plate to roof connection was investigated.

d. Use of high-resolution survey information in post-analysis activities

The near-real time communication of the tornado path via the use of the DAT at the Norman WFO webpage allowed for private entities, such as DirecTV, to modify billing procedures for those affected by the tornado. The building-by-building rating is also being used by the Health Department to distribute surveys to better understand resulting injuries and reactions to the tornado.

e. Improving future surveys

While all of those involved with the survey tried to ensure that the path was entirely complete, it was revealed while drafting this manuscript several points along the path which either needed to be marked with the appropriate DIs or DODs. Also, several locations most likely needed further investigation, yet none was completed. This was most likely due to the fact that many follow-ups to completed surveys were done in *ad hoc* fashion and no formal review of the collected data was truly completed until several weeks after the tornado.

Groups attempting such efforts in the future should make it a priority to have immediate and formal post-survey meetings to review the findings. It is important to not only review general tasks, such as where exactly surveys took place, but also that for high-end damage appropriate evidence was collected (such as the documentation of a home's critical load path connections). Individual surveyors should also be highly cognizant in making sure that all areas which may indeed need upgrading of the rating are reviewed by the team in total. While the individuals on the ground may have determined no upgrade in rating was needed, it's possible other teams came across similar damage. This would allow for notes and photographs to be compared and a more complete decision, as to upgrade or not, to occur.

Teams attempting such a high-resolution documentation effort should have a data sharing platform available for most, if not all, survey participants. The effort documented here used the NWS DAT (Camp et al. 2014). This allowed for nearly instantaneous sharing of findings, with necessary geolocation data and, at times, photographic evidence.

Geolocated aerial photography was also key in allowing survey team members to find areas which needed further investigation or areas that had not been investigated at all. Aerial photography was also absolutely necessary in order to remotely rate all of the potential damage points along the tornado's path. Key to aerial photography is not just single images of damage, but multiple oblique angles. This can assist in determining damages to vertical surfaces.

5. Concluding Remarks

This study presented an overview of an effort by a multi-agency team, spanning both public and private institutions, to document the 20 May 2013 tornado which impacted the cities of Newcastle, Oklahoma City and Moore, OK. The tornado was officially 22.3 km (13.85 mi) long with a maximum width of 1737 m (1900 yds). The tornado was on the ground for 39 minutes. This tornado was responsible for 24 fatalities and 212 injuries.

The surveyors implemented a technique combining targeted, detailed ground surveys in combination with aerial imagery in an attempt to survey nearly all of the impacted structures along the tornado's path. The survey team found the tornado produced peak damage rating of EF5, which occurred to a few homes, located at several locations along the tornado's path.

An upgrade to EF5 requires careful attention to the connections of the critical load path (foundation to base plate, base plate to wall studs, wall to roof). Ideally, the connections would follow engineered guidance, such as the Wood Frame Construction Manual (WFCM; American Forest and Paper Association 2006), and framing connections (i.e., wall to roof) would be clipped instead of just nailed together. However, such connections most likely exceed local traditional building practices and local building codes, as is the current guidance in evaluating construction quality within the EF-scale (McDonald et al. 2006).

For the 20 May 2013 Newcastle-OKC-Moore tornado, a home was assigned an EF-5 rating when there was evidence that the wind load was transferred to the base-plate-foundation connections. Specifically, this was determined when the following conditions were all found:

- swept foundation;
- foundation to base plate connections were bolts with properly tightened nuts and washers; spacing between bolts did not exceed 6 feet;
- removal of large percentage of the base plates from the foundation;
- some anchor bolts were bent.

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