P1A.3 Damage survey of the North Texas Tornadoes: 26 December 2015

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1. INTRODUCTION

A tornado outbreak occurred during the evening of 26 December 2015 across portions of North Texas. In all, there were 12 confirmed tornadoes in 8 counties. Unfortunately, 13 people lost their lives and there were numerous injuries as two of the strongest tornadoes struck Dallas-Fort Worth (DFW) suburbs. Most fatalities occurred in vehicles near the Interstate 30/George Bush Turnpike interchange in Garland, Texas (Fig. 1). Damage survey teams were dispatched the next day by the Fort Worth National Weather Service (FWD) to determine characteristics of the tornado paths.

The survey team utilized the Enhanced Fujita (EF) scale to rate damage severity developed by the Wind Science and Engineering Research Center (WSERC, 2006). This scale lists increasing degrees of damage (DoDs) to 28 damage indicators (DIs). DIs involved various building types as well as other items. The EF scale was adopted by the National Weather Service (NWS) in 2007. Not surprisingly, we found that tornadoes exploited construction deficiencies in building connections, sometimes causing more severe building damage. Therefore, we adjusted EF ratings downward where there was poor construction.

The damage survey team found two major tornado tracks near Dallas, Texas. One tornado traveled from Midlothian to Ovilla to Glenn Heights and will be referred to herein as the MOG tornado. This tornado traveled 14 km, was up to 110 m wide, with maximum damage intensity of EF3 (Fig. 2). The other major tornado, produced by a second supercell, traveled from Sunnyvale to Garland to Rowlett and will be referred to herein as the SGR tornado. This tornado traveled about 21 km, was up to 500 m wide, with maximum damage intensity of EF4 (Fig. 3).

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Fig. 1. Tornado crossing Interstate 30 in Garland, Texas illuminated by a power flash. View looks east. Cars were tossed from the highway killing 10 people. Image courtesy of Scott Peake.

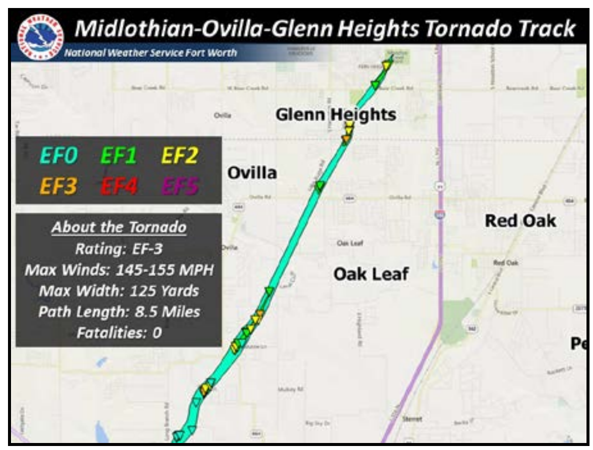

Fig. 2. Damage track of the MOG tornado.

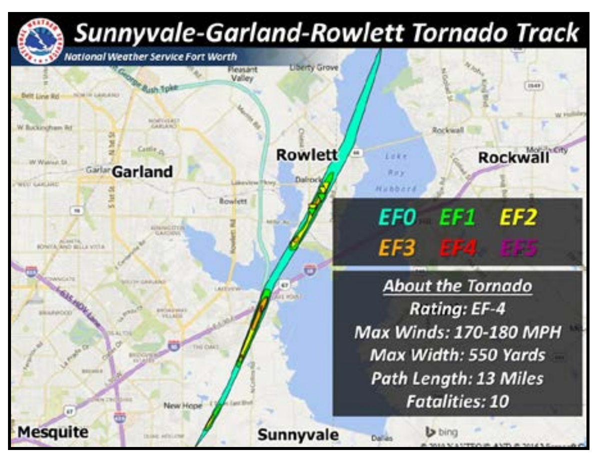

Fig. 3. Damage track of the SGR tornado.

2. WEATHER SITUATION

The synoptic setup during this event was characterized by a strong surface cyclone located along the Red River between the Texas and Oklahoma border and a strong upper trough located over the Southwest United States. Subjective surface analysis indicated the surface cyclone was centered near Wichita Falls, TX at 1600 UTC (Universal Time Code) on 26 December 2015. The cyclone moved east towards the Sherman/Denison, TX communities by 0000 UTC on 27 December 2015. A strong cold front was located from the surface cyclone to the southwest moving across Fort Worth, TX and Goldthwaite, TX at this time with a warm front extending to the northeast across Oklahoma and Arkansas (Fig. 4).

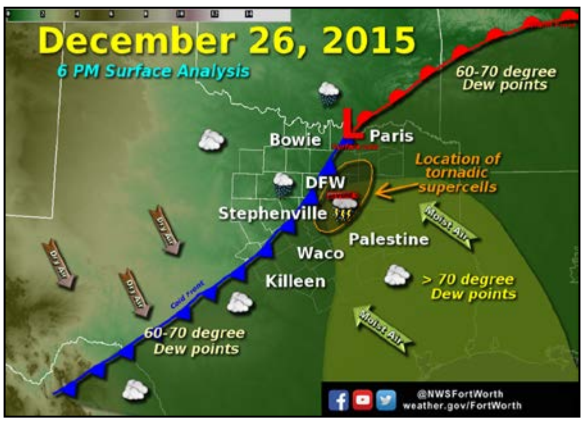

Fig. 4. The position of surface synoptic weather features from 0000 UTC subjective analysis. The approximate area of the MOG and SGR tornadoes that occurred near this time is highlighted in the orange oval to the south of the surface low. (FWD, 2015).

The supercells that produced the MOG and SGR tornadoes were located to the south of the surface low, in between the southeastward moving cold front and the surge of low-level moisture, as indicated by the area of greater than 21.1˚C (70˚F) dew point air advecting northwest towards the front.

Comparison between the 1200 and 1800 UTC rawinsonde observations (RAOBs) released at FWD revealed the impacts that strong warm air advection, positive moisture advection, and large scale forcing for ascent had on the thermodynamic and kinematic environment in which the supercells evolved that would produce the MOG and SGR tornadoes.

A capping inversion was noted on the 1200 UTC RAOB sounding (Fig. 5) with moderate MUCAPE (most unstable convective available potential energy) of 1793 J/kg. Deep layer shear was strong with over 50 kts of 0-6 km bulk shear observed. Strong low-level wind shear, as indicated by the clockwise looping and long 0-1 km hodograph, resulted in a storm relative helicity calculation of slightly over 300 m^2/s^2. Not only does the strong low-level wind shear provide strong horizontal vorticity for tilting and stretching into incipient supercell thunderstorms, it also represents strong large-scale forcing for ascent in the form of low-level warm air advection. This forcing for ascent is implied by the thermal wind equation and the presence of locally stronger warm air advection than elsewhere across the region due to the low-level jet in place to the southeast of the surface low (not shown).

The strong forcing for ascent helped to condition the thermodynamic environment, making convection initiation more likely by helping to lift and cool the morning capping inversion. This persistent lift and positive moisture advection resulted in complete removal of the capping inversion by the 1800 UTC RAOB (Fig. 6). The 1800 UTC RAOB showed an increase in MUCAPE to 2878 J/kg with very little change in deep layer and low-level wind shear which were already strong at 1200 UTC. Aside from the increase in MUCAPE, the most dramatic change to the thermodynamic environment was the increase in moisture. The 1200 UTC RAOB observed a 29.21 mm (1.15 in) precipitable water (PWAT) value which was over the 90^{th} percentile according to the station's PWAT climatology provided by the Storm Prediction Center (SPC, 2015). The 1800 UTC RAOB observed a 36.32 mm (1.43 in) PWAT which was well above the previous record for the station in late December (SPC, 2015). This increase in moisture certainly contributed to the increase in MUCAPE, but the impact on 0-3 km convective available potential energy (CAPE) was the most dramatic. The 1800 UTC RAOB showed a 7-fold increase in 0-3 km CAPE from the 1200 UTC RAOB with an observation of 144 J/kg of 0-3 km CAPE.

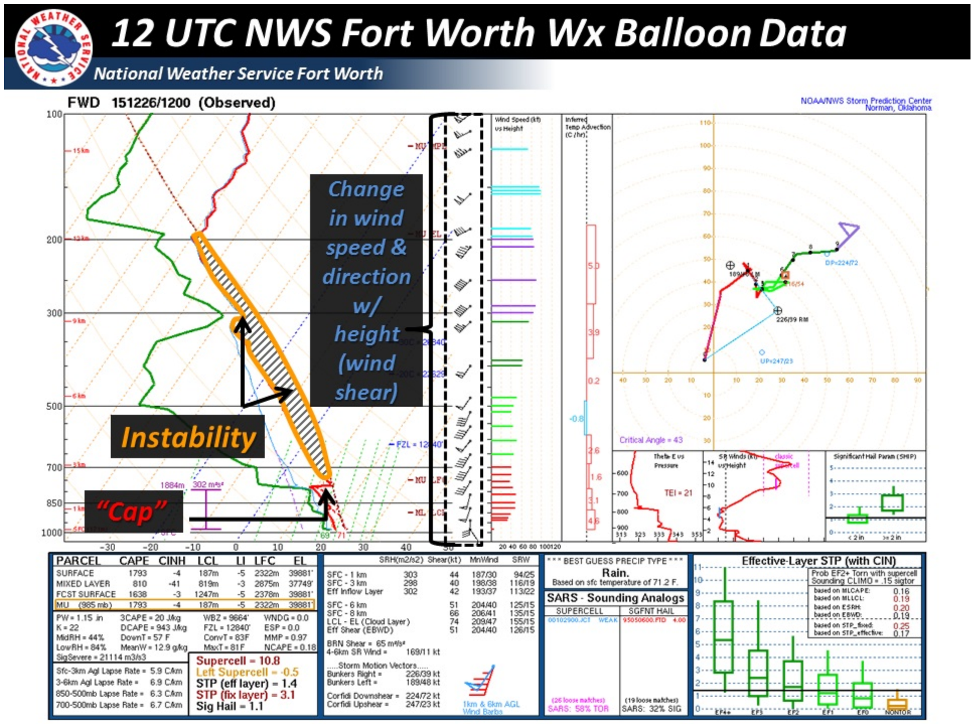

Fig. 5. The RAOB taken at the NWS office at Fort Worth, TX on 1200 UTC on 26 December 2015 (FWD, 2015 and SPC, 2015).

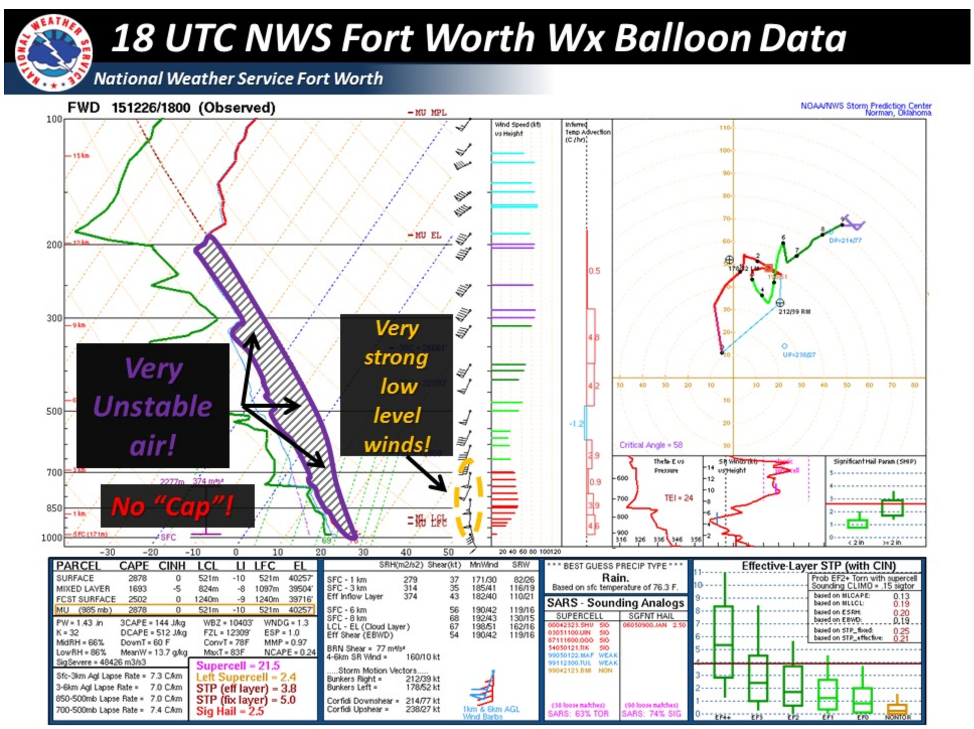

Fig. 6. The RAOB taken at the NWS office at Fort Worth, TX on 1800 UTC on 26 December 2015 (FWD, 2015 and SPC, 2015).

The presence of low-level CAPE indicated that low level free ascent was possible allowing for stronger low-level updrafts and more efficient tilting and stretching of horizontal vorticity into the vertical. The combination of thermodynamic and kinematic parameters observed on the 1800 UTC RAOB fell within the parameter space of EF3 and EF4 tornadoes based on a climatology of the effective layer significant tornado parameter (STP) made available from the SPC sounding table on the RAOB (Fig. 6, bottom right).

3. RADAR ANALYSIS

The primary storm mode for the convection that produced tornadoes across North Texas on 26 December 2015 was discrete class supercell. The average storm motion for these storms was to the north-northeast at 35 to 40 kts. This was within line of the projected storm motion from the hodographs when employing the Bunker's right moving supercell storm motion calculation. The storm relative anvil level winds (9 – 11 km) above ground level (AGL) did a good job predicting the storm mode and were right in the middle of the parameter space for classic supercells within the supercell thunderstorm archetype spectrum (Figs. 5 and 6 on the right-hand side below the hodographs).

The storm that produced the MOG EF3 tornado was a relatively long track supercell that developed west of Waco around 2200 UTC and continued to move north-northeast to the west of the Interstate 35 corridor until the storm moved north of Hillsboro, TX. The storm crossed I-35W near Itasca, TX and continued north-northeast over western Ellis County. At 0001 UTC (Fig. 7) the storm produced a tornado near Mid-Way regional airport near Midlothian which continued northeast over the next 12 minutes producing damage rated between EF0 and EF3 through the communities of Ovilla and Glenn Heights.

The tornado dissipated at 0013 UTC and the storm continued towards downtown Dallas. The storm crossed I-20 south of Dallas at 0019 UTC and started to weaken as supercells from the south and southeast started to strengthen, producing more rainfall within the inflow region of the MOG supercell and interrupting the flow of warm, moist air into this storm. This storm continued to produce copious amounts of rainfall which resulted in street flooding in Dallas, but it did not produce any more tornadoes. The SGR storm quickly became dominant to the southeast of the MOG storm.

The storm that produced the SGR EF4 tornado developed between Waxahachie and Ennis in eastern Ellis County around 2350 UTC. This storm rapidly intensified as it moved north-northeast towards the city of Sunnyvale as the MOG storm to the northwest weakened. The SGR storm produced a tornado beginning at 0045 UTC. There were multiple reports of a large tornado from storm spotters as the tornado approached I-30. As the storm crossed I-30 at 0051 UTC, radar data showed a classic tornado debris signature (TDS) (Fig. 8).

As the tornado crossed I-30, the tornado was at its strongest according to the damage survey. The tornado also resulted in 10 fatalities as the tornado tossed vehicles on I-30 and nearby roadways. The TDS at this location likely sampled large residential debris upstream at this time as the lowest radar level sampled over 1 km (3500 ft) above ground level. The tornado dissipated at approximately 0102 UTC based on storm spotter reports and the damage survey. The next low-level radar data at 0104 UTC showed a strong rear flank downdraft surge that was likely responsible for the dissipation of the SGR tornado 2 minutes earlier.

The radar derived rotational velocity (NROT) paths were utilized by the survey teams to approximate the damage path of the tornado. Archived Level 2 data helped to lead the team to the likely start and end of the path to help improve the efficiency and accuracy of the survey.

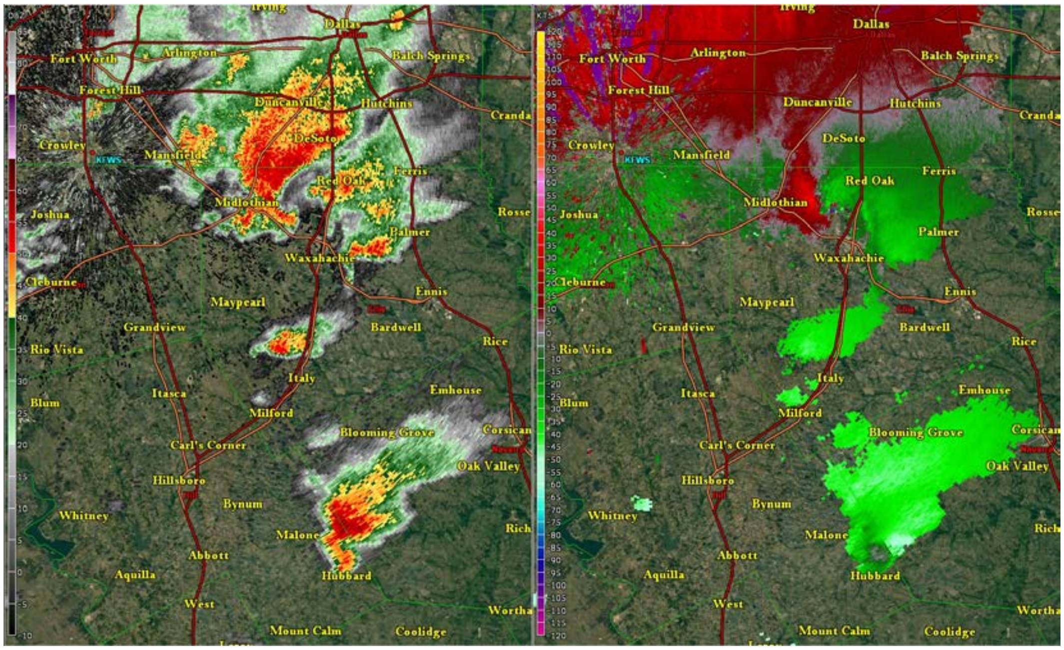

Fig. 7. Radar imagery from KFWS radar at 0001 UTC on 27 December 2015 while the tornado east of Midlothian was in progress. The cluster of cells to the east of this storm eventually produced the next tornado. Base reflectivity at the 0.5˚ degree scan is show on the left while base velocity at the same level is shown on the right.

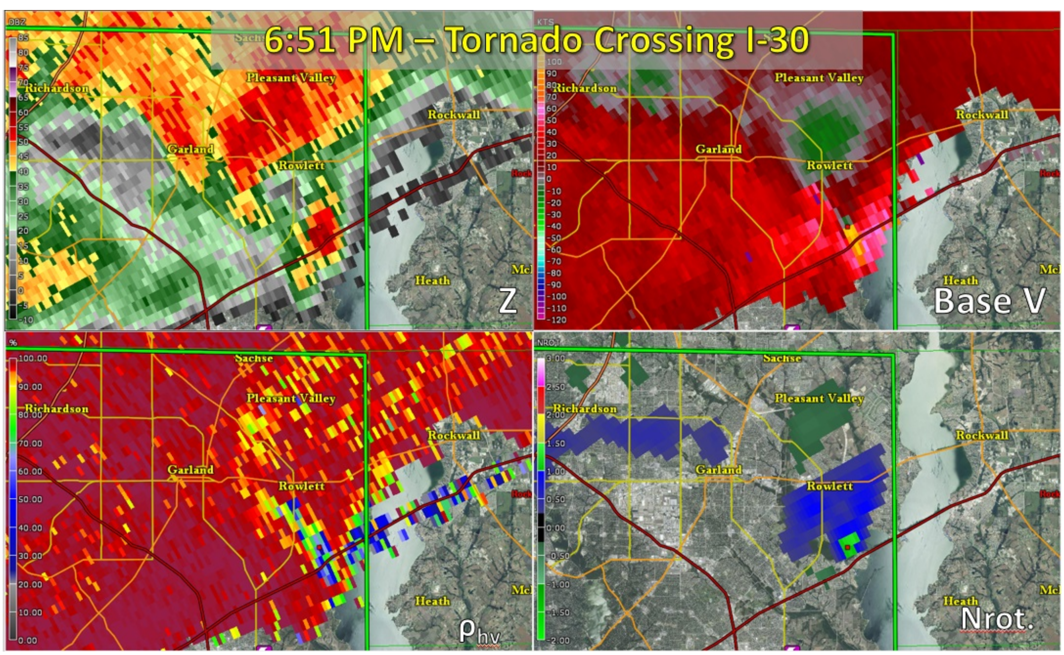

Fig. 8. Radar imagery from KFWS radar at 0051 UTC on 27 December 2015 just after the tornado in Garland crossed I-30. Note the classic "debris ball" signature in the base reflectivity panel (upper left). The $\boldsymbol{\rho_{hv}}$ field (bottom left) was very low and remained well correlated with intense rotation on the base velocity (top right) image. Gate-to-gate shear was over 120 kts and large enough to show up on the NROT panel (bottom right). The sudden jump in reflectivity (top left) in the base of the hook and low $\boldsymbol{\rho_{hv}}$ strongly suggested that lofted debris was being sampled by the radar.

4. TORNADO WARNING HISTORY

The FWD office issued 35 tornado warnings on the afternoon and evening of 26 December 2015 and a total of 5 severe thunderstorm warnings. The first tornado warning of the day was issued at 1943 UTC (2:43 PM), for areas well south of the Metroplex. The storm which became the MOG tornado was first identified as the cell which moved out of Hill County, into Ellis County at approximately 2130 UTC (4:30 PM) with a tornado warning for Hill and Ellis County. There were two storms within this warning, one of which developed to the east and produced no known severe weather. The storm to the west continued to strengthen and became the MOG tornado. A second warning was issued at 2328 UTC (5:28 PM), for the storm that caused the damage in Waxahachie, Ovilla, and Glenn Heights (Fig. 9).

As the storm moved into the DFW Metroplex, the number of people in the potential path of the storm grew rapidly. With the broadcast and social media interest increasing, the number of messages increased as well. Informational chat messages increased between FWD and the broadcast media, and the number of social media information increased, especially to Twitter and Facebook.

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WFUS54 KFWD 262328 RRA
TORFWD
TXC139-251-270015-
/O.NEW.KFWD.TO.W.0144.151226T2328Z-151227T0015Z/

BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE FORT WORTH TX
528 PM CST SAT DEC 26 2015

THE NATIONAL WEATHER SERVICE IN FORT WORTH HAS ISSUED A

* TORNADO WARNING FOR...
  NORTHWESTERN ELLIS COUNTY IN NORTH CENTRAL TEXAS...
  EAST CENTRAL JOHNSON COUNTY IN NORTH CENTRAL TEXAS...

* UNTIL 615 PM CST

* AT 528 PM CST...A SEVERE THUNDERSTORM CAPABLE OF PRODUCING A
  TORNADO WAS LOCATED NEAR ITASCA...OR 12 MILES NORTH OF HILLSBORO...
  MOVING NORTH AT 45 MPH.

  HAZARD...TORNADO AND QUARTER SIZE HAIL.

  SOURCE...RADAR INDICATED ROTATION.

  IMPACT...FLYING DEBRIS WILL BE DANGEROUS TO THOSE CAUGHT WITHOUT
           SHELTER. MOBILE HOMES WILL BE DAMAGED OR DESTROYED.
           DAMAGE TO ROOFS...WINDOWS AND VEHICLES WILL OCCUR.  TREE
           DAMAGE IS LIKELY.

* THIS DANGEROUS STORM WILL BE NEAR...
  MAYPEARL AROUND 540 PM CST.
  VENUS AROUND 545 PM CST.
  WAXAHACHIE AROUND 600 PM CST.
  MIDLOTHIAN...GLENN HEIGHTS...RED OAK...OVILLA AND OAK LEAF AROUND
  605 PM CST.
  CEDAR HILL AROUND 610 PM CST.
  LANCASTER AROUND 615 PM CST.

THIS INCLUDES THE FOLLOWING INTERSTATES...
 INTERSTATE 35W BETWEEN MILE MARKERS 15 AND 17.
 INTERSTATE 35E BETWEEN MILE MARKERS 400 AND 411.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

TAKE COVER NOW! MOVE TO A BASEMENT OR AN INTERIOR ROOM ON THE LOWEST
FLOOR OF A STURDY BUILDING. AVOID WINDOWS. IF YOU ARE OUTDOORS...IN A
MOBILE HOME...OR IN A VEHICLE...MOVE TO THE CLOSEST SUBSTANTIAL
SHELTER AND PROTECT YOURSELF FROM FLYING DEBRIS.

&&

LAT...LON 3213 9699 3226 9709 3224 9720 3255 9709
      3255 9679
TIME...MOT...LOC 2328Z 201DEG 40KT 3219 9708

TORNADO...RADAR INDICATED
HAIL...1.00IN
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Fig. 9. Tornado Warning issued by FWD for the MOG tornado.

The MOG tornado warning was set to expire at 0015 UTC (6:15 PM), but the storm was approaching the county line between Ellis and Dallas by 0000 UTC (6 PM). Thus, a new tornado warning was issued for portions of Ellis and Dallas County, in effect until 0045 UTC (6:45PM). This warning covered much of Dallas County, including the areas which would be impacted by the Sunnyvale, Garland, and Rowlett tornado (Fig. 10).

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BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE FORT WORTH TX
601 PM CST SAT DEC 26 2015

THE NATIONAL WEATHER SERVICE IN FORT WORTH HAS ISSUED A

* TORNADO WARNING FOR...
  NORTHWESTERN ELLIS COUNTY IN NORTH CENTRAL TEXAS...
  CENTRAL DALLAS COUNTY IN NORTH CENTRAL TEXAS...

* UNTIL 645 PM CST

* AT 600 PM CST...A SEVERE THUNDERSTORM CAPABLE OF PRODUCING A
  TORNADO WAS LOCATED OVER OVILLA...OR NEAR GLENN HEIGHTS...MOVING
  NORTH AT 40 MPH.

  HAZARD...TORNADO AND QUARTER SIZE HAIL.

  SOURCE...RADAR INDICATED ROTATION.

  IMPACT...FLYING DEBRIS WILL BE DANGEROUS TO THOSE CAUGHT WITHOUT
           SHELTER. MOBILE HOMES WILL BE DAMAGED OR DESTROYED.
           DAMAGE TO ROOFS...WINDOWS AND VEHICLES WILL OCCUR.  TREE
DAMAGE IS LIKELY. THIS STORM HAS A HISTORY OF PRODUCING TORNADOES...
IF YOU ARE IN THE PATH OF THIS DANGEROUS STORM...TAKE COVER
IMMEDIATELY!

* THIS DANGEROUS STORM WILL BE NEAR...
  OVILLA AROUND 605 PM CST.
  CEDAR HILL...GLENN HEIGHTS...RED OAK AND CEDAR HILL STATE PARK
  AROUND 610 PM CST.
  DESOTO AND DUNCANVILLE AROUND 615 PM CST.
  LANCASTER AROUND 620 PM CST.
  HUTCHINS AND COCKRELL HILL AROUND 625 PM CST.
  HIGHLAND PARK AROUND 635 PM CST.
  MESQUITE AND UNIVERSITY PARK AROUND 640 PM CST.
  GARLAND AROUND 645 PM CST.
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Fig. 10. Tornado Warning issued by FWD for the MOG and SGR tornado.

The immediate need around 0000 UTC (6 PM) was for information about the MOG tornado. There were numerous reports of torandic circulation on media, social media, and noted on radar. Numerous spotters were watching the storm and relaying information back to FWD and others. At 0005 UTC (6:05 PM) an NWSChat message was relayed about the: *"significant threat of a tornado now for Glenn Heights, Ovilla, Desoto, Lancaster"*. Spotters still reported tornado on the ground with this storm (NWSChat Logs). The vaild tornado warning was upadated at 0007 UTC (6:07 PM) to mention: *"a confirmed large and extremely dangerous tornado was located Ovilla...or near Glenn Heights."* The MOG tornado continued to move northeast and dissipated before the warning expired.

While the tornado warning issued at 0001 UTC (6:01 PM) included the portions of eastern and northeastern Dallas County, including areas of Garland and Rowlett, the MOG tornado parent storm moved in a generally north direction, towards downtown Dallas and University Park. The tornado threat diminished as the storm moved away from a favorable enviornement, but the proximity to downtown and a large population center received considerable attention. A new updraft developed to the southeast of this parent storm around 0020 UTC (6:20 PM). As this storm intensified, a new tornado warning was issued for areas in northeast Dallas County, and parts of Collin and Rockwall Counties at 0039 UTC (6:39 PM) to account for the different motion of the newer supercell thunderstorm (Fig. 11).

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BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE FORT WORTH TX
639 PM CST SAT DEC 26 2015

THE NATIONAL WEATHER SERVICE IN FORT WORTH HAS ISSUED A

* TORNADO WARNING FOR...
  SOUTHERN COLLIN COUNTY IN NORTH CENTRAL TEXAS...
  NORTHEASTERN DALLAS COUNTY IN NORTH CENTRAL TEXAS...
  WESTERN ROCKWALL COUNTY IN NORTH CENTRAL TEXAS...

* UNTIL 730 PM CST

* AT 638 PM CST...A SEVERE THUNDERSTORM CAPABLE OF PRODUCING A
  TORNADO WAS LOCATED NEAR BALCH SPRINGS...MOVING NORTH AT 45 MPH.

  HAZARD...TORNADO AND QUARTER SIZE HAIL.

  SOURCE...RADAR INDICATED ROTATION.

  IMPACT...FLYING DEBRIS WILL BE DANGEROUS TO THOSE CAUGHT WITHOUT
           SHELTER. MOBILE HOMES WILL BE DAMAGED OR DESTROYED.
           DAMAGE TO ROOFS...WINDOWS AND VEHICLES WILL OCCUR.  TREE
DAMAGE IS LIKELY. THERE ARE TWO STORMS CAPABLE OF PRODUCING
TORNADOES. ONE JUST SOUTHEAST OF DOWNTOWN DALLAS... ONE NEAR BALCH
SPRINGS. BOTH STORMS ARE EXTREMELY DANGEROUS AND MOVING NORTHEAST.

* THIS DANGEROUS STORM WILL BE NEAR...
  SUNNYVALE AROUND 645 PM CST.
  DALLAS...GARLAND...RICHARDSON...ROWLETT...ROCKWALL AND SACHSE
  AROUND 700 PM CST.
  MURPHY AROUND 705 PM CST.
  WYLIE...LUCAS AND PARKER AROUND 710 PM CST.
  FAIRVIEW AROUND 715 PM CST.
  FARMERSVILLE AROUND 725 PM CST.
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Fig. 11. Tornado Warning issued by FWD for the SGR tornado.

Once the damage from the tornadoes had occurred and warnings expired for the day, attention turned to logistics of damage surveys. While some information had been received on the night of the 26th, the damage surveys would begin on the 27th and all indications showed the surveys would take several days. National Weather Service teams at FWD began to assemble the necessary teams as early as the 26th, finalizing teams on the morning of the 27th. Two teams were assembled to address the storm which received the most media coverage, the damage and fatalities in Garland and Rowlett.

Early in the morning of the 27th, the emergency managers for the affected areas were called in order to receive permission to take a look at the damage. Most of the areas damaged were blocked off to traffic, and entry into the damaged area was limited. The emergency managers coordinated access into the damage areas with help from law enforcement and/or fire officials. Not only would these escorts assure safety, they allowed access into areas and were able to identify what areas had remained undisturbed since the damage occurred.

5. USE OF SOCIAL MEDIA

The FWD utilized three social media platforms for communicating the ongoing threat during the 26 December 26 2015 outbreak: NWSChat (an instant messaging program that connects NWS personnel, broadcast media, and emergency management officials), Twitter, and Facebook. From the time the cell which spawned the MOG tornado was identified around 2130 UTC (4:30 PM) to shortly after the SGR tornado lifted at 0105 UTC (7:05 PM), there were at least 160 documented instances of FWD communicating to the broadcast media and emergency management. These documented instances were solely communications about the MOG tornado, SGR tornado, and cell that developed east of the MOG tornado (which eventually moved into Dallas County). The 160 documented instances of communications did not include those of other thunderstorms ongoing during this time. It also did not include the number of communications that occurred both leading up to and after this timeframe.

The most used social media platform for communication between FWD, the broadcast media, and the emergency managers during this time was NWSChat. Twitter was the second most used platform, followed by Facebook. (Note: Archival settings for Facebook Business accounts, such as FWD's, limit or filter the posts that users are able to access and the numbers in this analysis may not be truly representative of Facebook usage by FWD during the event.) Thus, only 2 posts were identified from FWD that fit the constraints of this analysis (Figs. 12 and 13.) NWSChat was used to provide real-time information to broadcast media and emergency managers from FWD, while also serving as a collection point for situational awareness of impacts from storms from communities around the Dallas/Fort Worth Metroplex. FWD used both Twitter and Facebook to provide brief updates about warning information and thunderstorm trends, in addition to relaying storm reports as they were received by the forecast office.

Fig. 12. Tweet sent by FWD during the SGR tornado.

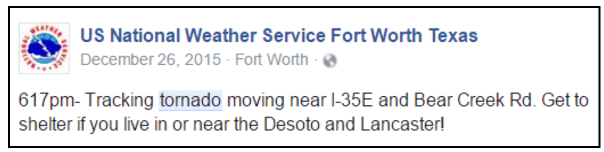

Fig. 13. Facebook post sent by FWD during the MOG tornado.

NWSChat usage showed relative spikes when tornado warnings were issued, while Twitter usage showed an initial spike with the first tornado warning for the MOG tornado, and a secondary, but broader spike with subsequent warnings (Fig. 14). NWSChat's largest spikes in usage appear to come as the MOG tornado approaches Dallas County, which stem from increased media interest in a tornado approaching a county with almost 2.5 million residents. With limited posts available for Facebook, there was not enough information to show trends in Facebook usage through this outbreak.

In addition, to the spikes in social media usage, there are two notable minima in usage that occur before both the MOG and SGR tornadoes. This is likely due to FWD forecaster discussions or collaboration preceding issuance of these warnings. Outside of these minima, overall social media usage was more during the MOG and SGR tornadoes by FWD than before the tornadoes.

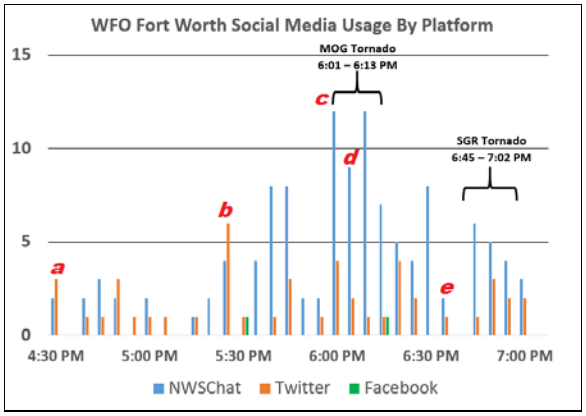

Fig. 14. Graph showing the number of social media posts by platform between 2130 UTC (4:30 PM) on 26 December 2015 and 0105 UTC (7:05PM) on 27 December 2015. Posts are grouped in 5 minute increments. At time a), the MOG storm became a supercell, b), the first tornado warning was issued for the MOG storm which included Ellis and Johnson Counties, c), the second tornado warning was issued for the MOG storm to include Dallas and Ellis Counties, d), the MOG warning was updated to include a large and extremely dangerous tornado near Ovilla, and e) the first tornado warning was issued for the SGR storm which included Collin, Dallas, and Rockwall Counties.

6. DAMAGE SURVEY

Damage survey teams coordinated with local emergency management officials and law enforcement to quickly determine the overall tornado path length, width, and intensity. Teams surveyed the most intense damage first to determine the highest EF rating. Team members exited their vehicles in several areas to examine the damage first-hand. We paid particular attention to roof-to-wall and wall-to-foundation connections. Unfortunately, high winds and heavy rains days after the tornadoes slowed damage survey efforts.

Google Street View was an important tool in determining what buildings looked like before the tornado, especially when buildings had EF3 and greater damage. Information like number of stories, type of roof, location of large windows, and size/orientation of the garage were quickly determined using Google Street View (Fig. 15). Marshall et al. (2014) found Google Streets helpful in the analysis of the Mayflower-Vilonia tornado.

Fig. 15. View of a house taken (a) prior to the tornado using Google Street View and (b) after the tornado during our survey. Such images were helpful in determining various building characteristics.

Two sources of aerial imagery were utilized to conduct building-by-building damage assessments. The Dallas Morning News (DMN, 2016) and City of Garland (COG, 2016) conducted independent flyovers just after the storm. Aircraft flew only few hundred meters above ground and persons obtained high quality video which proved invaluable for this study (Fig. 16). Aerial surveys provided quick overall views of the tornado paths since team members could not visit the site of each damaged building. Aerial surveys also provided important information where damaged buildings had been mechanically removed from the site prior to our inspection.

Fig. 16. Example of high quality aerial imagery used in this study. Source: City of Garland.

We supplemented our aerial analyses with high quality, amateur drone video (ADV, 2016) posted on the Internet. Drones were able to get much closer to buildings than manned aircraft, and we could see more detail regarding how structures were constructed. However, manned aircraft could cover more ground than drones.

EF ratings were assigned to each damaged building, and numbers were plotted on Google Maps (Fig. 17). These maps also had outlines of buildings, making it easier to identify them in relation to trees and outbuildings. We also toggled between satellite images and road maps to verify locations of buildings, trees, and outbuildings. Similar damage survey techniques were done by Marshall et al. (2012) during the analysis of three Oklahoma tornadoes.

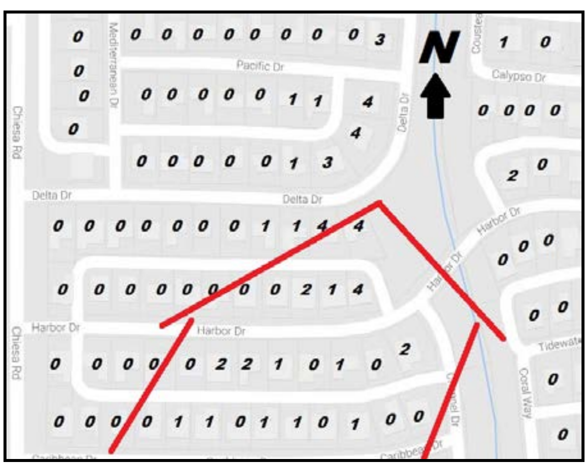

Fig. 17. EF scale ratings to buildings by block. The red arrow indicates direction of the SGR tornado.

6a. The MOG tornado path

The MOG tornado first touched down just northeast of Midway Regional Airport near Midlothian, Texas in Ellis County and traveled north-northeast. This was a rural area with several open fields bordered by trees. Damage was limited to tree branches and roof shingles on rural houses. Damage intensity increased as the tornado crossed Longbranch Road. A few manufactured homes were flipped and destroyed along Daniel and Spring Branch Roads, and were assigned EF2 ratings.

The tornado continued into a subdivision with large estate homes on large lots. Tornadic winds removed roofs and outside walls on several two-story homes (EF3 damage) along Black Champ Road, Cross Creek Court, and Walker Court. The width of the most intense damage path was quite narrow, being only one or two houses wide.

The tornado then struck a second subdivision along Meghann Lane and Mary Court, causing up to EF3 damage to various two-story homes. Several automobiles, pickup trucks, and sport utility vehicles (SUV) were shifted, rolled, or tossed. A few large homes under construction had collapsed along Rex Court.

The tornado then crossed Red Oak Creek, traveling through rural parts of Ovilla, Texas. Numerous trees along the creek were uprooted and snapped. Damage to homes was relatively minor, primarily limited to EF1 damage to roof coverings and garages.

The tornado then crossed Ovilla Road, toppling masonry walls at the Ovilla Road Church of the Nazarene, leaving the roof intact. Certain perimeter walls toppled at the nearby Donald T. Shields Elementary School. Internal pressure helped remove a portion of the built-up roof and steel roof deck. Several unanchored heating, ventilation, and air conditioning (HVAC) units were tossed from the roof and deposited in fields north of the school. A chain link fence north of the school was rolled up into a ball. Next, the tornado removed metal cladding from the roof and walls on the Harvest of Praise Ministry Church on Hampton Road, leaving the steel-frame structure intact.

The tornado strengthened as it crossed Craddock Lane causing up to EF3 damage to several homes along Trishia Lane, Mesa Wood Drive, and Mesa Drive. Several two-story homes collapsed, leaving piles of debris on their concrete slab foundations. Construction problems involved some homes where perimeter walls were nailed to their concrete foundations instead of being secured with anchor bolts, nuts, and washers. Cut nails provided little resistance and easily pulled out of the concrete slabs as walls overturned. Double-timber power poles were snapped just east of this subdivision.

As the tornado crossed Bear Creek road, it clipped the southeast corner of the Glenn Heights Mobile Home Park. Several manufactured homes shifted off their supports or flipped. The tornado maintained EF3 damage intensity as it struck four homes along Cascade Drive before passing through Meadow Creek Park. However, none of the tall steel-reinforced concrete light standards in the park were moved or toppled. The tornado weakened quickly, ending prior to Parkerville Road. In all, more than 100 homes and 20 manufactured homes were damaged or destroyed as a result of the MOG tornado.

6b. The SGR tornado path

The SGR tornado first touched down north of U.S. Highway 80 in Sunnyvale, Texas and moved north-northeast. Damage initially was limited to toppled trees and removed roof shingles on houses. The tornado intensified as it traveled through Plantation Place, tossing several recreational vehicles (RVs); some RVs were blown into a shallow pond. The tornado crossed between large, steel electrical transmission lines leaving the steel towers and lines undamaged.

Next, the tornado traveled through a subdivision in Garland, Texas causing up to EF3 damage. The most severe damage was a few houses wide. The tornado maintained this width and intensity as it crossed Bobtown Road and entered a second subdivision. The first EF4 damage occurred along Crestpoint Lane where all walls toppled on two, single-story and one, two-story home, leaving a pile of debris in their back yards. The tornado then crossed Locust Grove Road, destroying two rows of steel storage lockers at G. T. Storage and Marine and damaging a third building. Considerable damage was done to the adjacent Landmark at Lake Village West Apartments along the frontage road to Interstate-30. Large, wood roof trusses were removed and some top story walls collapsed on these two and three-story buildings. The tornado then tossed several vehicles from Interstate 30 reportedly killing 9 people.

The tornado continued across the west arm of Lake Ray Hubbard entering Rowlett along Windjammer Way. More than a dozen lakefront homes along the bluff sustained up to EF4 damage. Several two-story homes collapsed, and debris scattered to the northeast. The tornado damage path was widest at this point, about 500 m. One EF4 damaged home had an above ground storm shelter. Nine people sought refuge in the shelter and escaped injury. A partially below ground shelter in the same neighborhood saved 12 people.

The tornado damage path narrowed to about 200m wide by the time it crossed Chiesa Road and weakened during the next kilometer, causing EF2 damage. Then, the tornado intensified again, causing up to EF4 damage to four homes along Delta Drive.

After crossing Schrade Road, the tornado struck a mobile home park tossing and destroying several homes. Flying debris struck a large water tower for the City of Rowlett. A steel undercarriage from a mobile home bent one of the horizontal girts between the tower legs. However, the water tower remained upright. Nearby homes on concrete slab foundations sustained up to EF4 damage. The tornado continued through another subdivision causing up to EF4 damage then weakened slightly to EF3 as it crossed Highway 66. The tornado dissipated over Lake Ray Hubbard. In all, more than 1000 homes and 20 manufactured homes were damaged as a result of the SGR tornado.

6c. Wood-framed houses (DI=2)

About 95 percent of structures damaged by the tornadoes were wood-framed houses. A total of 189 homes were assigned EF ratings in the MOG tornado, and 1202 homes were assigned EF ratings in the SGR tornado. In all, 891 homes sustained EF0 damage, 234 homes EF1 damage, 151 homes EF2 damage, 94 homes

EF3 damage, and 21 homes EF4 damage. Refer to Table 1.

TABLE 1
EF-SCALE DAMAGE RATINGS TO HOUSES

EF rating	MOG tornado	SGR tornado	Total
0	125	766	891
1	22	212	234
2	21	130	151
3	21	73	94
4		21	21
Total	189	1202	1391

Most of the damaged homes had bottom wall plates bolted to concrete foundations. However, some bolt installations lacked nuts and washers. (Fig. 18). The nut is an important component as it secures the bottom wall plate to the foundation. The washer is also important as it helps spread lateral and overturning loads. Thus, it was no surprise that unattached walls toppled more easily than walls that were properly bolted and secured with nuts and washers.

In other instances, cut nails were utilized to secure perimeter wall plates to the foundations. Such nails extended only about 1 to 1.2 cm into the concrete. As these walls overturned, the nails either pulled out leaving divots in the concrete surfaces or pulled through the wall bottom plates remaining embedded in the foundations (Fig. 19). Poor connections sometimes led to complete collapse of homes. The size of the home and/or location did not affect the quality of construction. Large, expensive homes had the same connection problems as smaller homes. When such connection problems were encountered, EF ratings were adjusted downward or defaulted to the value of another DI nearby.

Prevatt et al. (2015) also conducted a detailed ground survey of the SGR tornado photographing the damage from more than 700 homes. Their study indicated that if the SGR tornado had occurred 30 years ago, only 876 homes would have been exposed to the tornado as opposed to the 2,250 that were exposed in 2015.

Fig. 18. This toppled wall was not attached properly. Note the absence of nuts and washers on the bolts (red circles). The inset image is a closer view of an anchor bolt missing the nut and washer.

Fig. 19. This home collapsed due to poor attachment of perimeter walls to the concrete slab foundation. Inset images show cut nails and divots left in the foundation.

Many two-story homes lost second story walls. Typically, second story walls were straight-nailed to the wood floor. Usually, there was one nail installed in the wall bottom plate between each stud. The nails usually did not extend into the floor joists. As a result, second story walls were prone to overturning as the nails pulled out of the floor. This action was similar to using a claw hammer to remove nails from wood (Fig. 20). We also noticed that two-story homes sustained more roof structure damage than adjacent one-story homes. One reason was that two-story homes were higher above the ground and experienced stronger winds. Rafters lifted off the wall top plates as toe-nailed connections pulled apart.

Fig. 20. Removal of the second story wall occurred when straight nails in the wall bottom plates (yellow arrows) pulled out of the floor (circled).

Certain exterior walls had built-in "hinges" that failed during the tornado. Such walls had minimal overlap between the doubled top plates. As a result, walls bent inward or outward depending on wind direction. Long walls in garages and living rooms were particularly prone to this type of failure (Fig. 21).

Fig. 21. A "hinge" (arrow) formed when joints aligned in the double top plate. Inset image shows close up view of the "hinge".

Marshall and McDonald (1982) found that homes with attached garages were more likely to sustain greater damage than homes without attached garages, especially when garage doors faced the wind. As garage doors buckle inward, wind pressures increase inside the structure creating additional uplift on the roof and outward pressures on the walls. Eventually, either the roof or wall(s) failed. Leeward garage doors were frequently blown outward due to internal pressure created when winds breached the windward sides of homes (Figs. 22 and 23).

Fig. 22. Collapse of the garage roof after a loadbearing side wall toppled. Wind pressure blew in the garage door.

Fig. 23. Examples of (a) inward and (b) outward wind pressure-caused failures of garage doors.

6*d. Manufactured homes (DI=3)*

The two tornadoes damaged or destroyed about 40 manufactured homes. These homes were supported on steel undercarriages elevated by loosely stacked concrete masonry units (CMUs). Homes usually were strapped to auger type anchors that extended 0.8 m into the ground. Each anchor had two tilted discs welded to a steel rod. Failure of manufactured homes occurred when the straps broke or the anchors pulled out of the ground. Manufactured homes were rolled or lofted usually leaving nearby vehicles and anchored porches untouched (Fig. 24).

Fig. 24. This double-wide manufactured home vaulted into the background before the pickup truck rolled into the space where the home had been.

6e. Wood-framed apartments (DI = 5).

The Landmark at Lake Village West Apartments sustained considerable damage from the SGR tornado. This complex consisted of 14 two- and three-story wood-framed structures constructed on concrete slab foundations. Exterior walls were clad with a combination of painted wood siding and brick veneer.

The southwestern-most building sustained the greatest damage with the removal of the roof and most second story walls, a DoD of 5. Expected wind speeds for this level of damage was 71 m/s or EF3 (Fig. 25). Eight buildings lost portions of their roof structures consistent with DoD 4. Expected wind speeds for this level of damage was 62 m/s or the borderline between EF2 and EF3. Roofs were comprised of long and slender manufactured wood trusses with steel gang-nailed connector plates. Remaining buildings sustained some loss of roof decking and significant damage to the roof coverings, and were assigned a DoD of 3. Expected wind speeds for this level of damage was 55 m/s or EF2.

Fig. 25. Damage to three apartment buildings at the Landmark at Lake Village West. Much of the top floor was removed on the southern-most (left) building. Source: ADV.

Many vehicles were moved or shifted in the parking lot. One vehicle was found upside down in the alley between two apartment buildings (Fig. 26). Movement of vehicles occurred throughout the damage path when EF2 or greater damage was found to adjacent buildings.

Fig. 26. Roofs removed from the Landmark at Lake Village West Apartments. Several vehicles also were moved with one being flipped (circled). Source: ADV.

6f. Elementary School (DI=15)

The Donald T. Shields Elementary School sustained moderate damage by the MOG tornado. The school was constructed in 2008 and finished in 2009. Exterior walls consisted of brick veneer and cold-formed, galvanized steel studs. This wall assembly was designed to be attached to the steel frame with powder-actuated fasteners and plates. The tornado toppled several non-load bearing walls, exposing classrooms, and revealing connection details (Fig. 27). Our close inspection revealed that none of the toppled walls were attached to the steel frame. No fasteners had penetrated the steel beams or columns (Fig. 28). Windows and blinds remained intact on the toppled walls, indicating the walls failed at relatively low wind speeds. Bases of the walls were nailed to the concrete slab foundation. However, nails penetrated only 1 cm into the concrete. Small divots were left in the concrete where nails had pulled out. Such walls had little lateral or overturning resistance. Given poor attachment of the walls, team members used the lower bound wind speed for DoD 8 of 62 m/s which led to an EF2 rating. However, failure wind speeds probably were below this lower bound value, so team members looked at other DoDs at the school.

Breach of the school building led to increased internal pressure and uplift of a small section of steel roof decking and damage to the built-up roof. Several unanchored air conditioners were removed from the roof and deposited north of the school (Fig. 29). Damage to the roof and HVAC equipment was consistent with a DoD of 5 where the expected wind speed of 45 m/s. This led to an EF1 damage rating for the school which seemed more reasonable.

Fig. 27. School walls fell outward during the tornado leaving the steel-frame intact. Close examination (see inset) revealed that nails attached the bottoms of the walls to the concrete foundation and walls were not attached to the steel frame.

Fig. 28. Bracket on perimeter wall stud was never attached to the steel frame. Bracket fasteners should have penetrated structural steel (finger pointing) at the Donald T. Shields school.

Fig. 29. Unanchored HVAC equipment was blown off the school roof.

6g. Churches

Two churches sustained damage by the MOG tornado. Churches currently do not have assigned DIs in the EF scale so DIs had to be selected from other building types.

The Ovilla Road Church of the Nazarene was located just southwest of the Shields Elementary School. This one-story, wood-framed church was similar in construction to a residence except for the sanctuary on the east end of the building. The sanctuary had a vaulted ceiling supported by curved glulam (glue laminated wood) beam-columns bolted to steel brackets and anchored to the concrete slab. A wood frame wall extended around the perimeter of the sanctuary, and wall bottom plates were nailed to the concrete slab.

Frame walls toppled during the tornado but the glulam beam-columns remained undamaged (Fig. 30). Nails either pulled out with the wall plates, leaving small divots in the perimeter of the concrete slab, or the wall plates split around the fastener leaving the fasteners still embedded in the concrete foundation. Outside the sanctuary, there was little roof damage to remaining portions of the church. We selected the residential DI=2 for this church, and given the poor attachment of the failed frame wall, we used the lower bound wind speed for DoD=7 of 51 m/s yielding an EF2 rating. However, minimal damage to the roof covering suggested a wind speed closer to DoD=4 or 43 m/s, yielding an EF1 rating.

Fig. 30. Sanctuary frame walls collapsed at the Ovilla Road Church of the Nazarene but the glulam frame remained upright. Bottom wall plates on the frame walls were poorly attached with concrete nails.

The Harvest of Praise Ministry Church was located northeast of the Shields Elementary School. This two-story, steel-framed structure with gable roof was clad with metal R-type panels. The panels were secured to underlying framing with sheet metal screws that had neoprene washers. Steel columns were bolted to the concrete slab. Brick veneer extended around lower portions of the building. The church was rectangular in plan with the long dimension oriented east-west. A carport extended from the front (east) side of the church.

Much of the metal cladding was torn away from the roof during the tornado, and brick veneer walls fell. Both east and west gable ends collapsed, but the main steel frame, including the roof structure, remained intact (Fig. 31). This church building was a metal building system (MBS) which is DI=21. The level of damage to this building was consistent with DoD=3 with an expected wind speed of 42 m/s or an EF1 rating.

Fig. 31. Wall and roof cladding were removed from the steel frame at the Harvest of Praise Ministry Church. However, the steel frame, carport, and parking signs remained intact.

6h. Shelters

Two storm shelters were found in the tornado damage path in Rowlett, Texas. One shelter was constructed above ground in the southwest corner of a residence on Windjammer Way. It had steel-reinforced CMU walls with a four-inch thick concrete slab roof. A heavy steel door was mounted in a steel frame attached to the east side of the shelter. Nine people reportedly sought refuge inside the shelter before the house was destroyed, and all escaped injury (Fig. 32). We rated the damage level to the house at EF4.

A neighboring home along Lake Ray Hubbard had a prefabricated concrete shelter installed partially below grade. Twelve people (and their pets) reportedly sought refuge in this shelter and all escaped injury (Fig. 33) The damage level to this house was EF1.

6i. Vehicles

Many vehicles were tossed, rolled, or thrown during both tornadoes where residential damage was EF2 or greater. Marius et al. (2016) conducted a comprehensive study of vehicle movements in tornadoes and found similar results. One SUV traveled more than 100 m from a garage on Glenloch Drive and ended up in an open field. About a dozen gouge marks were found in the ground leading from the destroyed garage, indicating the vehicle rolled and tumbled. Another SUV was lofted and found in the back yard of a home with EF2 damage (Figs. 34 and 35).

Fig. 32. This above ground shelter was all that remained after the tornado. Nine people took refuge inside the shelter and escaped injury.

Fig. 33. A partially below ground concrete shelter where 12 people reportedly survived in Rowlett. Image by the Dallas Morning News.

Fig. 34. This flipped SUV end up in the back yard of a home that sustained EF2 damage.

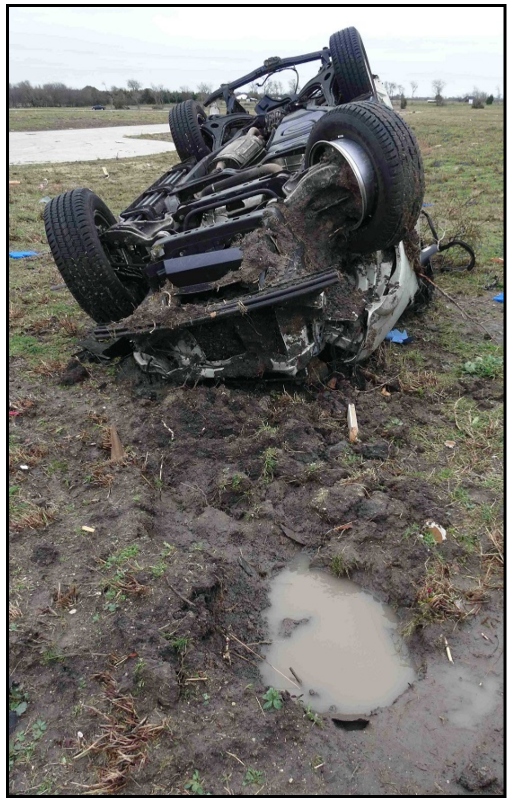

Fig. 35. This SUV tumbled more than 100 m leaving about a dozen impact marks in the ground.

6j. Oddities

One of the most unusual items found was a fence post that was pulled out of the ground, flipped over, and stuck back into the ground (Fig. 36). This occurred at the Shields Elementary School. The fence post had been part of a cyclone fence that had been blown away during the tornado.

We also found a piece of steel that had pierced the front panel on a pickup truck. The steel piece appeared to have been from an outbuilding such as a carport (Fig. 37).

A plastic child's seat penetrated a wood-fiber siding panel on an east-facing gable end (Fig. 38). The siding was relatively soft and easily penetrated.

Wood projectiles were common in both tornadoes. Boards up to 4m long were found stuck into the ground downwind of residential areas (Fig. 39). Some boards punctured roofs and brick masonry.

Fig. 36. Fence post was removed then driven upside down into the ground near Shields Elementary School.

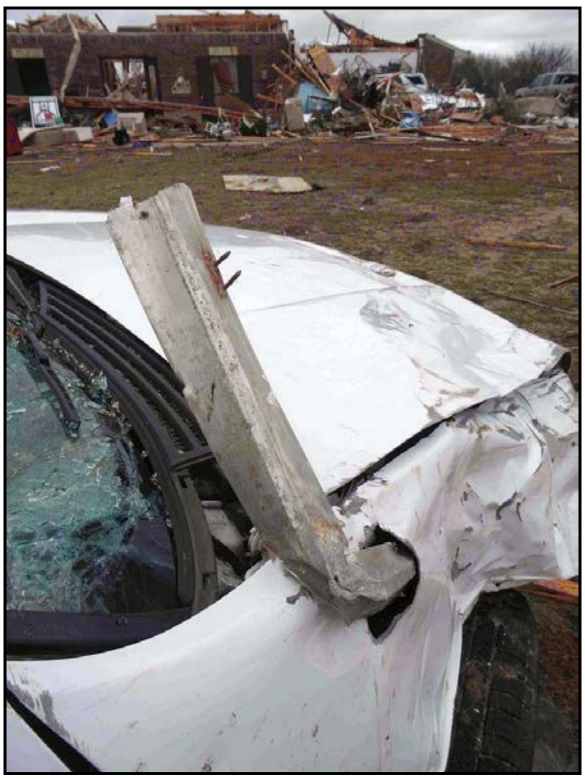

Fig. 37. Portion of a metal post that pierced the front panel on a vehicle.

Fig. 38. Childs plastic seat impaled wood-fiber siding on a gable end.

Fig. 39. One of several long boards sticking out of ground after the tornado.

We found sections of cyclone fencing rolled up into ribbons or balls by both tornadoes (Fig. 40). This occurred as portions of fencing became detached and rotated or pivoted around anchored sections.

Fig. 40. Chain link fences rolled up into balls.

7. Summary

A damage survey team from FWD conducted detail damage assessments of the tornadoes that occurred on December 26, 2015. One tornado traveled from Midlothian to Ovilla to Glenn Heights and had a maximum damaging rating of EF3. The second tornado (from a different supercell) traveled from Sunnyvale to Garland to Rowlett and had a maximum damage rating of EF4. Not surprisingly, the survey team found that both tornadoes exploited weak links in building connections which sometimes led to more severe building damage. Thus, we adjusted EF ratings downward where we encountered poor construction. Problems in the quality of building construction have been identified in numerous other damage surveys in various parts of the country. Thus, damage surveyors need to be able to quickly recognize weak links or fatal flaws in buildings while trying to rate damage intensity.

Not much new was learned from this survey. Buildings behaved the same way as observed previously. There were a few new projectile items that can be added to our list such as the upside-down fence post and the flying child seat. The purpose of this survey was to document the event. It is hoped that future updates of the EF scale will include a DI with DoDs for churches.

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