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1. INTRODUCTION

On 22 May 2011, a large and destructive tornado traveled through southern portions of Joplin, MO, a city of approximately 50,000 people (Fig. 1). According to the Storm Data (2011), the tornado killed 158 people and injured more than 1000. Total property damage exceeded two billion dollars. The extent of damage was staggering. According to the City of Joplin (2012), the tornado generated three million cubic yards of debris. There were 4,000 water leaks including 25 ruptured fire service lines. More than 20,000 people were left without power. According to the Missouri Public Service Commission (MPSC, 2011), the tornado damaged or destroyed 4,000 service poles, 1,500 transformers, 110 miles of line, and one substation.

In the week following the tornado, the authors conducted aerial and ground surveys of the damage path. Surveying the damage was a challenge due to the large numbers of damaged and destroyed buildings (about 8,500 structures) as well as the rapid clean-up response. The team rated the tornado EF-5, the highest number on the Enhanced Fujita Scale (EF), with maximum winds exceeding 89 m s^{-1} (200 mph). This was the first EF-5 tornado in southwest Missouri since records have been kept for such events.

This paper will present our findings from the damage survey and discuss how we implemented the EF-scale to rate the damage and estimate failure wind speeds. There were a variety of building types or damage indicators (DIs) which we evaluated utilizing the EF scale (WISE, 2006). These DIs included residences (DI 2), apartments (DI 5), small retail buildings (DI 8), small professional buildings (DI 9), strip malls (DI 10), large isolated retail buildings (DI 12), an automobile showroom (DI 13), automobile service buildings (DI 14), elementary schools (DI 15), a high school (DI 16), a few low-rise buildings (DI 17), an institutional building (DI 20), several metal buildings (DI 21), service station canopies (DI 22), electrical transmission lines (DI 24), free-standing towers (DI 25), free-standing light poles (DI 26), and trees (DIs 27 and 28). We determined the degree of damage (DOD) and failure wind speed for each DI.

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Figure 1. Large, rain-wrapped tornado in Joplin, MO. Photograph courtesy of Jeff Piotrowski.

2. TRACK OVERVIEW

We generated a series of maps from our damage survey and appended them to this paper. We found NOAA Aerial Imagery to be quite helpful. These high quality images were taken during aerial reconnaissance within days after the event and preserved the damage scene. Google Earth and Streets had pre-storm images of the buildings which helped us identify damaged buildings after the tornado. A review of radar imagery from the National Weather Service Forecast Office in Springfield, MO (KSGF) revealed the unique evolution of this storm and helped provide a timeline of the storm track.

The tornado developed just southwest of Joplin around 2234 UTC on 22 May 2011 and moved east. Large trees blew down about a half mile southwest of the intersection of JJ Highway and West 32nd Street (Newton Road). The tornado then entered a subdivision near the intersection of Country Club Drive and West 32nd Street and caused up to EF-3 damage. Several roofs blew off homes and exterior walls were removed. We observed a spiral ring of downed trees along South Day Road which indicated there was a brief, stationary vortex. A cell phone tower collapsed within the ring of downed trees. Storm chaser videos show the tornado began as a multi-vortex and quickly grew into a giant, wedge-shaped tornado.

The tornado crossed Iron Gates Road and entered another subdivision causing up to EF-3 damage along Sunset and South Kelly Drive. The damage path at this location had widened to 400 m across. EF-4 damage began along and east of South Winfield Avenue where homes were flattened. Many large trees fell in this established neighborhood. The Elks Lodge off West 26th Street collapsed, killing five people.

Around 2240 UTC, the tornado approached the Medical District. The tornado flattened several one and two-story professional office buildings along West 26th and 27th Streets. It was at this location, along South Adele Avenue, that the tornado produced the first EF-5 damage. Besides the extreme damage to buildings, there were missing manhole covers, lofted concrete parking curbs, and tossed vehicles. Some vehicles were thrown more than 100 m. The tornado crossed McClelland Boulevard and struck St. Johns Hospital. This multi-story, steel and reinforced concrete structure was located just south of the tornado core. The hospital experienced extreme south and west winds that blew through the building causing extensive interior and exterior damage. Six people in the hospital reportedly lost their lives. It was at this point the tornado attained a maximum width of 1650 m. EF-1 damage extended 700 m wide. Radar analyses indicated the tornado became rain wrapped as the forward flank downdraft (FFD) from a storm to the south merged into the mesocyclone of the Joplin storm (Fig.2).

The tornado continued east-northeast along West 26th Street striking the Greenbriar Nursing Home. This one-story, wood-framed structure was completely destroyed resulting in the deaths of 20 patients. The tornado then crossed South Moffet Avenue striking St. Mary's Church. Roofs over the sanctuary and classrooms collapsed, and the adjacent parsonage was destroyed. The roof also collapsed at the nearby Irving Elementary School. The tornado reduced an electrical substation at 26th and Pearl Street to a heap of twisted steel. The tornado then crossed Main Street between West 21st and West 27th Streets destroying several commercial businesses including a bowling alley.

The tornado continued through a densely populated residential area causing EF-4 damage to hundreds of houses before striking the Joplin High School and adjacent Franklin Technology Center. Portions of the High School and the entire Franklin Technology Center collapsed. The tornado then crossed Indiana Avenue and destroyed two churches: Harmony Heights Baptist Church and the Church of Jesus Christ. Three deaths occurred at the Harmony Heights Baptist Church. The tornado moved east along West 20th Street and caused considerable damage to the Dillon's Food Store. This one-and one-half story steel-framed structure partially collapsed. Adjacent to the food store was the two-story

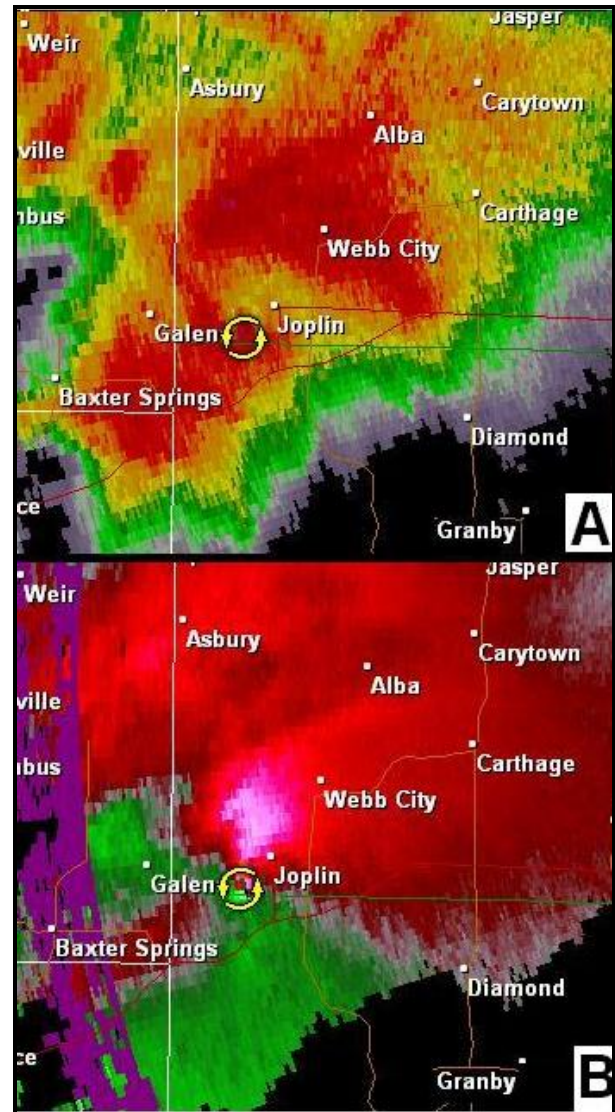


Figure 2. Radar images of the tornadic supercell over Joplin, MO at 2239 UTC: a) reflectivity and b) radial velocity. The curved arrows indicate the location of the mesocyclone.

Hampshire Terrace Apartments. The tornado removed the second stories on all ten buildings. After destroying hundreds more homes, the tornado crossed Range Line Road near 20th Street and destroyed a strip shopping mall, several automobile service stations, the Home Depot, Academy Sports, and Walmart along with numerous other commercial businesses. Twenty deaths occurred inside the buildings or in the parking lots of these businesses. Semi trucks and cargo containers on the east (back) side of the Walmart store traveled more than 400 m to the southeast and were deposited in the debris of the Pepsi warehouse building. The tornado continued to move eastward along and south of 20th Street destroying numerous metal buildings. Windrowing of debris occurred in an

open field west of South Duquesne Road; the debris included pieces of vehicles and large storage containers. From that point, the tornado began to weaken and struck the Joplin East Middle School. The gymnasium and auditorium collapsed, but the main school structure remained intact. The tornado moved southeast causing EF-4 damage to many residences before crossing Interstate 44, exiting the city around 2253 UTC. The majority of the damage and loss of life during the first twenty minutes of the tornado as it cut a path of destruction that extended 10 km through Joplin. East of Joplin, the tornado continued to weaken and narrow in open country as it traveled another 20 km, ending at 2312 UTC about 8 km northeast of Granby, Missouri.

3. DAMAGE INDICATORS

3.1 Residences (DI 2)

The vast majority of buildings damaged by the Joplin tornado were residences. We determined the degree of damage (DOD) for each residence using the EF-scale. For a residence to be assigned an EF-5 rating, it must be “well-constructed” and swept clean from its foundation.

The definition of a well-constructed house can vary among individual damage surveyors. We defined a well-constructed house as one that had a continuous load path of straps and anchors from the roof to the ground, without weak connections in the horizontal or vertical planes. Most homes in the tornado path had pier and beam foundations constructed with poured concrete, stacked CMU, or rock masonry. Wood sill plates rested on top of the foundations but rarely were attached to them (Fig. 3). In a few instances, anchor bolts connected the sill plates to grouted joints in the masonry. Regardless, such connections had little lateral strength, and the bolts broke out of the masonry. Homes on these perimeter foundations failed to provide safe shelter against such a violent tornado.

Floor joists were supported by the sill plates, and we found many instances where the floor joists were not attached to the sill plates. Such homes were prone to sliding off their foundations (Fig. 4). The EF-scale lists the expected failure wind speed as 54 m s^{-1} (121 mph) for homes that slide off their foundations. However, we adjusted the failure wind speeds based on other DODs to the house (i.e. extent of roof damage) and/or the DODs of adjacent buildings that remained on their foundations.



Figure 3. Floor platform supported by a rock masonry foundation.



Figure 4. Homes swept clean from their pier and beam foundations. Note the vehicles remained.

We rated a total of 7191 homes using the EF-scale using NOAA Aerial Imagery, Google Earth and Streets, and our own survey images. Detailed maps sections of the Joplin tornado are appended to this paper. In general, we rated homes EF-0 if they lost less than 20 percent of their roof coverings or lost siding (DOD=2). We rated homes EF-1 if they lost most of their roof coverings or had minor structural damage to the roof such as missing gable ends (DOD=4). Homes were rated EF-2 if they lost most of their roof structure but the walls remained standing (DOD=6). A rating of EF-3 was assigned to homes that lost most of their walls (DOD=8). An EF-4 rating was given to those homes which had all walls down with only a pile of debris remaining on their foundations (DOD=9). An EF-5 rating was given to those homes that were swept clean of their concrete slab foundations. Unanchored homes that slid off their foundations were rated according to the extent of damage they sustained above floor level, or were based on the DOD to adjacent homes. The default rating for a sliding home was DOD

6, with failure wind speeds estimated to be 54 m s^{-1} (121 mph). We identified 12 homes that slid off their foundations. A total of 22 homes sustained EF-5 damage (Fig. 5).



Figure 5. A row of homes swept clean from their concrete slab foundations were assigned EF-5 ratings.

Overall, this tornado was remarkably consistent in its damage intensity in Joplin except at the very beginning and end of the track where winds noticeably weaker. The EF-1, 2, 3, 4, 5 damage paths were up to 700, 600, 500, 400 and 100 m wide, respectively.

Table 1 summarizes the numbers of damaged homes by EF-scale. The majority of homes in the tornado path were rated EF-0. This damage was due primarily to inflow winds. The number of homes rated EF-1 through EF-4 ranged between 7 and 9 percent of the total homes affected, for each category. The similar percentages of damaged homes were attributed to the uniform width of the damage track. We found a steady increase or consistent gradient of damage toward the tornado core with a wide area (about 400 m) of EF-4 damage or greater.

TABLE 1
SUMMARY OF DAMAGE TO RESIDENCES
IN THE JOPLIN TORNADO

EF-scale	Houses
0	>5000
1	507
2	642
3	509
4	511
5	22
Total	7191

3.2 Apartments (DI 5)

There were several apartment complexes in the path of the Joplin tornado. One of the most devastated apartment complexes was the Hampshire Terrace Apartments located off 20th Avenue. There were ten, two-story, wood-framed apartment buildings and a one-story office building. First story exterior wall coverings were brick veneer. Second story exterior walls were stucco and painted wood boards (Tudor style).

The tornado passed directly over the apartment complex and removed the top stories from all ten buildings (Figs. 6 and 7.) Walls were straight-nailed into the second story floors and toppled when the roof structure was removed. The straight-nailed connections simply pulled out of the floors as the walls rotated.

The expected failure wind speeds for destruction of the top story of an apartment building (DOD 5) was determined to be 71 m s^{-1} (158 mph) or EF-3.



Figure 6. Aerial image of the Hampshire Terrace Apartments looking south. The tornado blew away the second story units. Workers already had cleared most of the debris from the streets.



Figure 7. Ground view of one of the apartment buildings at Hampshire Terrace.

3.3 Small retail building (DI 8)

The Joplin tornado destroyed a number of small retail buildings. One such building was the Walgreens Drug Store on Range Line Road. This building was a one-story structure oriented east-west. North and south CMU walls were load-bearing, supporting steel trusses. East and west walls were non load-bearing. Windows extended along north and west sides of the building; the front entrance had a large glass wall atrium that faced northwest. Green painted metal awnings extended over the windows and entry door.

The building was located just south of the tornado core and encountered strong south and west winds. The non load-bearing west wall was pushed inward, rotating about the base of the wall. Positive internal pressures helped push the top of the north load-bearing wall outward, and the roof collapsed (Fig. 8).

Per the EF-scale, the building reached DOD 7, but the building was not totally destroyed (DOD 8). Thus, we estimated the failure wind speed to be 61 m s^{-1} (138 mph), or EF-3.



Figure 8. North elevation of the Walgreens Drug Store: a) before and b) after the tornado.

3.4 Small Professional Building (DI 9)

There were several small professional buildings destroyed by the tornado, especially around St. Johns Hospital. One such building was the office building at the intersection of West 27th Street and South Cunningham Road. This split-level building (one story on the west elevation and two stories on the east) was rectangular in plan and oriented north-south; the front of the building faced west. The first story was constructed with load bearing CMU walls that supported a concrete floor slab. The second story was conventional wood-framing. Wall bottom plates were bolted to the floor slab, and wall studs were straight-nailed to the top and bottom wall plates. The building had hip type roof framing.

The core of the tornado struck the building removing the roof and entire top story leaving portions of the second story floor slab exposed to the weather (Fig. 9). The DOD of this building was between 8 and 9, indicating an expected failure wind speed of about 67 m s^{-1} (150 mph) or EF-3.

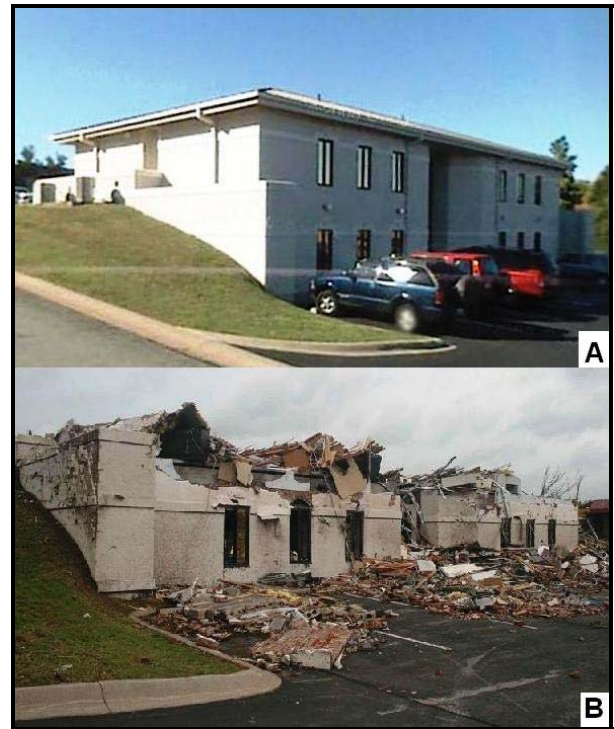


Figure 9. Southeast elevation of the professional building: a) before and b) after the tornado. Strong winds removed the second story wood framing.

3.5 Strip Mall (DI 10)

The Joplin tornado destroyed several strip shopping malls. One of the largest strip malls affected was the Bel-Aire Plaza Shopping Center located at the intersection of 20th Avenue and Range Line Road. This large steel-framed structure was oriented north-south; the front of the building faced east. Exterior walls were covered with an exterior insulating finish system (EIFS).

The core of the tornado passed directly over the building, pushing the west walls inward and removing the steel roof deck. The window wall along the front of the building blew outward (Fig. 10). Light standards in the parking lot fell over and wood power poles were snapped near their bases. According to the EF-scale, the DOD was between 8 and 9 indicating failure wind speeds were about 67 m s^{-1} (150 mph) or EF-3.



Figure 10. Front (east) elevation of the Bel-Aire Plaza Shopping Center. Tornadoic winds toppled the back (west) walls and removed the steel roof decking.

3.7 Large Isolated Retail Building (DI 12)

There were several large, isolated retail buildings damaged or destroyed by the tornado. These “big box” structures were located along Range Line Road and included Walmart, Academy Sports, and Home Depot. Damage to the Walmart store was discussed by Marshall (2012), and will not be repeated here.

The Home Depot building was a two-story, steel-framed structure constructed on a concrete slab foundation. The building was rectangular in plan and oriented north-south; the front faced west. Square tube columns were bolted into the concrete slab and supported the roof girders. Open web steel joists spanned between the girders, and the steel deck supported a membrane type roof covering. Exterior walls were precast concrete panels 31 cm (12 in.) thick. The panels were attached to each other with steel bars that were welded to steel plates already imbedded in the panels. Pockets at the top of the wall panels supported the ends of the roof joists. The ends of the joists were welded to steel plates imbedded in the pockets.

The core of the tornado passed just north of the Home Depot building. Thus, the building experienced strong south and west winds. South and west wall panels fell inward, and east wall panels fell outward. North wall panels remained upright. Bases of the wall panels were attached to the concrete slab with welded plates. The welds broke causing the panels to tip over. Welds also broke where the ends of the joists were attached to the plates in the wall pockets. Thus, the wall panels broke free from the steel frame (Figs. 11 and 12).

The interior steel-frame collapsed as the square tube columns buckled. Some column base plates rotated and pulled the steel anchor bolts out of the slab. In other instances, steel anchor bolts were sheared off. Some girders fell onto steel stacks in the store. Other girders blew into an open field east of the store (Fig. 13). A car from the parking lot was deposited inside the building.

According to the EF-scale, the expected value for the complete destruction of a large section of an LIRB building is 77 m s^{-1} (173 mph) or EF-4. These large buildings have the same basic design wind speed requirement as residences, a 40 m s^{-1} (90 mph) three-second gust wind. The rebuilt store now has a storm shelter.



Figure 11. Aerial images of the Home Depot: a) before and b) after the tornado looking north. The superstructure collapsed when the wall panels toppled and the interior steel columns buckled.



Figure 12. Base of a tubular steel column that failed when the anchor bolts pulled out of the concrete slab. Inset view (a) is a closer image.



Figure 13. Toppled wall panels on the east side of the Home Depot building. Inset view (a) is a close up of a wall pocket where welds failed that attached the ends of the steel roof joists.

3.8 Auto Showroom – (DI 13)

Only one automobile showroom was struck by the tornado. This building contained Frank Fletcher Toyota-Nissan and was located along Range Line Road. The building was a one-story, steel-framed structure constructed on a concrete foundation; the front of the building faced west. Windows extended around three sides (north, west, and east) of the building.

The building was located at the south end of the tornado damage path, and received the strongest winds from the west. Flying debris broke most of the windows around the building and many of the acoustical tiles fell from the suspended ceiling over the showroom (Fig. 14). No roof panels blew off. We determined the DOD to this building was 3 with a failure wind speed of 39 m s^{-1} (87 mph) or EF-1. Vehicles remained in the parking lot but had sustained significant damage from impact by flying debris.



Figure 14. The front (west) elevation of the Fletcher Toyota-Nissan showroom. Flying debris broke the glass windows, and the suspended acoustical tile ceiling fell. This auto showroom was on the south edge of the tornado damage path.

3.9 Auto Service Building (DI 14)

There were a few automobile service buildings destroyed by the tornado. The most severe damage occurred to the Pennzoil Oil Change and to the adjacent Goodyear buildings located at the intersection of Range Line Road and West 20th Street. These one-story structures had load bearing CMU walls and interior steel framing. Roof structures were comprised of steel joists and steel decking.

The core of the tornado passed directly over these buildings, causing them to collapse, reaching the maximum DOD of 8 (Fig. 15). Thus, we estimated the failure wind speeds to be about 72 m s^{-1} (160 mph) or EF-3.



Figure 15. The center of the tornado passed directly over the Pennzoil Oil Change facility causing complete collapse of the building.

3.10 Elementary School (DI 15)

There were three elementary schools that were damaged by the Joplin tornado. One such building was the Joplin East Middle School located on the east end of the tornado damage path. Strong winds had collapsed the gymnasium and auditorium (Figs. 16 through 19).

The Joplin East Middle School was constructed in 2009. Perimeter and interior walls were vertically-stacked CMU, including the walls of an auditorium at the southeast corner of the school. All four walls in the auditorium were load-bearing. The north and south walls supported curved, steel roof trusses. The CMU walls were approximately 10m (33 ft) tall.

The center of the tornado passed just south of the school. Strong west winds and positive internal pressure caused the auditorium east wall to fall toward the east and the south wall to fall toward the south, resulting in collapse of the entire roof structure. Remaining CMU walls in the school remained intact. Close examination of the toppled CMU walls in the auditorium revealed that rebar extending out of the foundation pulled out of grouted cells at the bases of the walls, and vertical rebar in the walls pulled apart.

According to the EF scale, the expected value for the collapse of the roof structure for an Elementary School building (DOD 7) would be 56 m s^{-1} (125 mph) with an upper bound of 66 m s^{-1} (148 mph) and lower bound of 48 m s^{-1} (108 mph). Given that collapses were limited to the two longest spans in the school, and that there was little lateral strength in the large walls, the authors believe the failure wind speeds were around 56 m s^{-1} (125 mph) or EF-2.



Figure 16. Aerial view of the East Joplin Middle School: (a) before and (b) after the tornado. The yellow box outlines the damaged gymnasium and the red box outlines the collapsed auditorium.



Figure 17. West wall in the gymnasium fell inward. The precast wall panels were attached poorly to each other and were not attached to the foundation.



Figure 18. Roof on the auditorium collapsed when the south and east masonry walls failed.



Figure 19. Base of the east auditorium wall showing foundation rebar (red boxes) bent to the east. This wall had little resistance to lateral wind pressures.

3.11 High School (DI 16)

The Joplin High School was comprised of several types of interconnected buildings. The original school building was a cast-in-place, steel-reinforced concrete structure with exterior, non load-bearing “fill-in” CMU walls, as well as non load-bearing interior CMU partition walls. Later additions had steel framing. The gymnasium and auditorium were located at the south end of the school complex and were constructed with CMU interior and brick exterior walls. North and south walls of the gymnasium and auditorium were load-bearing, while east and west walls were not.

The High School was on the north end of the damage path and experienced the strongest winds from the north and east. A portion of the exterior north CMU wall and several interior partition walls fell into the second story hallway. This could have been tragic had these hallways been occupied during the tornado (Figs. 20 through 22). There was extensive damage to the roof covering and removal of the roof decking. The gymnasium building collapsed. Steel girders fell when the steel reinforced pilasters failed, and the tall, non-load bearing west wall blew outward.

According to the EF scale, the expected value for complete collapse of tall masonry walls at a gymnasium (DOD 7) would be 51 m s^{-1} (114 mph) with collapse of exterior walls in the top floor being 62 m s^{-1} (139 mph). The authors selected the higher wind speed which is at the lower end of EF-3.

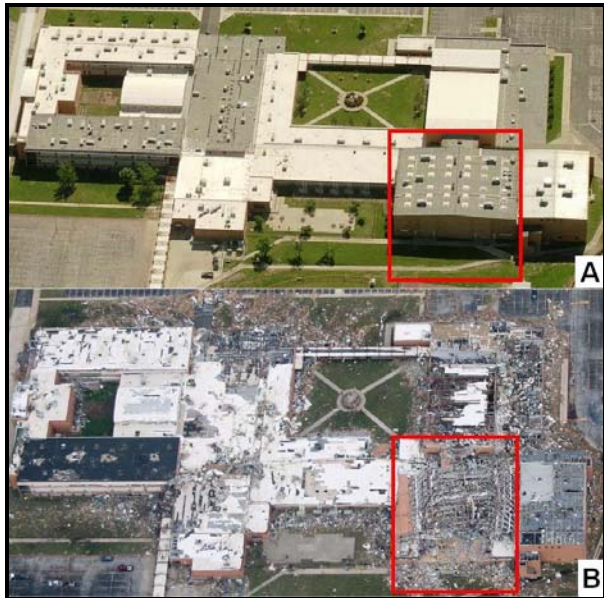


Figure 20. Aerial images of the Joplin High School looking east: (a) before and (b) after the tornado. The gymnasium (red box) collapsed.



Figure 21. Collapse of second story CMU walls at the Joplin High School: (a) north hallway and (b) center hallway.



Figure 22. Collapse of CMU walls at the Joplin High School Gymnasium: (a) overall view looking east, and (b) close-up of the non load-bearing west which fell inward.

3.13 Low Rise Building (DI 17)

There were two low-rise buildings impacted by the Joplin tornado. The most severe damage occurred to the Ozark Center for Autism. This three-story building was a poured-in-place, steel-reinforced concrete frame with a flat roof slab. The main building was rectangular in plan and oriented north-south. A one-story steel-framed structure extended from the northeast corner of the main building. Exterior walls were covered with painted metal panels.

The building was located on the northern edge of the tornado path and experienced strong north and west winds. Windows on these elevations blew inward, and the windows on opposite elevations blew outward. Most of the metal facade was damaged or removed. However, the steel-reinforced concrete frame was not damaged (Fig. 23).

According to the EF-scale, the expected value for such a building to sustain significant damage to exterior walls and some interior walls (DOD 7) is 64 m s^{-1} (143 mph) or EF-3. The Federal Emergency Management Agency (FEMA, 2012) reached a similar conclusion.

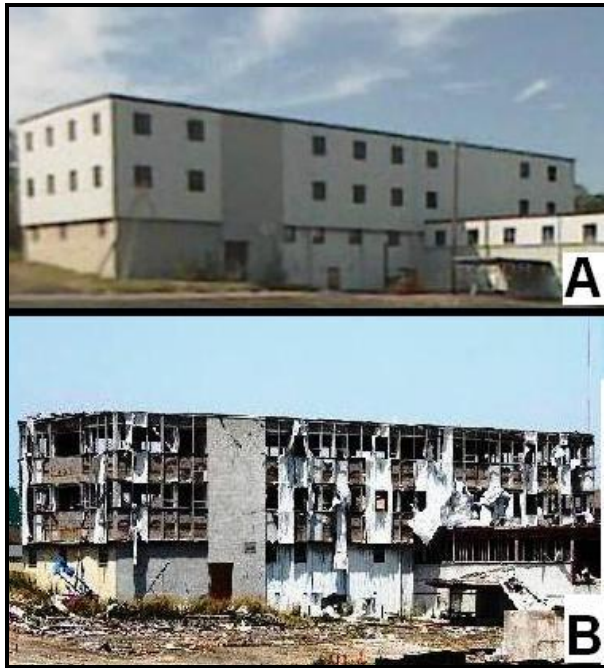


Figure 23. Southeast elevation views of the Ozark Center for Autism building: a) before and b) after the tornado.

3.14 Institutional Building (DI 20)

The only institutional building struck by the tornado was St. Johns Hospital. This large building complex consisted of steel-reinforced, cast-in-place concrete frames and steel-framed structures with cast-in-place concrete floors. The building exterior included window walls and concrete spandrels. Penthouses were steel-framed structures.

St. Johns Hospital was located just south of the tornado core and experienced strong south and west winds. Windows on these elevations blew into the hospital whereas windows on opposite elevations blew outward. Flying debris traveled through the hospital corridors and caused many injuries and six deaths. Built-up and single-ply roof coverings blew off. However, both concrete and steel framing remained intact. Many vehicles impacted each other in the parking lot, and some concrete parking curbs were shifted or removed (Figs 24 through 27).

According to the EF-scale, the expected value for damaged curtain walls or wall cladding (DOD 7) is 59 m s^{-1} (131 mph). However, there was no uplift of the roof deck (DOD 8 and 9), so failure wind speeds at the hospital were likely less than 64 m s^{-1} (142 mph), or within the EF-3 range.



Figure 24. Northwest elevation view of St. Johns Hospital. The steel-framed structure remained intact. Cars were tossed around and crashed into each other in the parking lot.



Figure 25. Loss of window glass on the north elevation of St. Johns Hospital.



Figure 26. View inside the lobby of St. Johns Hospital. The two-story atrium floor was covered with broken glass.

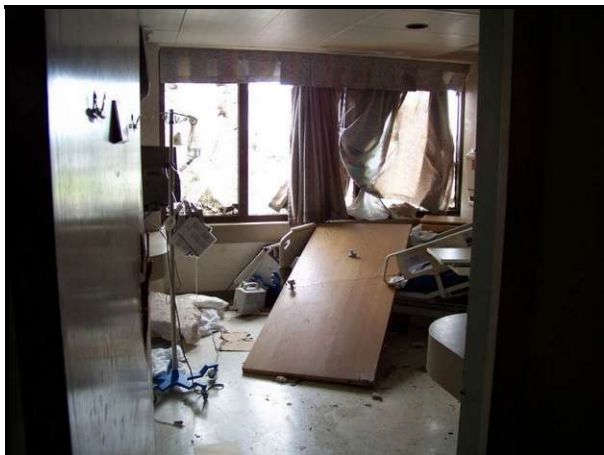


Figure 27. Damage to a patient room adjacent to an exterior wall.

3.15 Metal Building System (DI 21)

There were several metal buildings destroyed by the Joplin tornado, particularly on the east side of town in the Industrial district. Among the damaged metal buildings inspected was the Cummins Equipment building located just off 20th Avenue, east of Range Line Road.

This building was a one-story, steel-framed structure constructed on a concrete foundation. Exterior, non load-bearing curtain walls were stacked CMUs. The long dimension of the building was oriented north-south. Large overhead bay doors faced east, and there was an array of windows on the south side of the building.

The building was in the center of the tornado damage path and collapsed completely (Fig. 28). South and west walls fell into the building, while north and east walls fell outward. There was no anchorage of the CMU walls to the roof structure or foundation.

The DOD for a destroyed metal building is 8 which puts the expected value failure wind speed at approximately 70 m s^{-1} (155 mph) or EF-3.



Figure 28. Southeast elevation of the Cummins Equipment building: a) before and b) after the tornado. This steel-framed structure had non load-bearing CMU curtain walls that collapsed during the tornado.

3.16 Service Station Canopy (DI 22)

There were five service station canopies destroyed by the Joplin tornado. Two gas stations were along Range Line Road, another was on West 20th Street, and two more were on McClelland Avenue.

Damage to the canopies ranged from the removal of the metal cladding to toppling of the steel columns (Fig. 29). Destroyed canopies were assigned a DOD of 6, and had expected value failure wind speeds of about 59 m s^{-1} (133 mph) or EF-2. In some instances, actual wind speeds were higher than that needed to fail the canopies as noted by the DOD for the adjacent store. For example, the Fastrip gas station in front of the Walmart collapsed (Fig. 30). This small retail building had a DOD between 7 and 8 yielding a failure wind speed of about 67 m s^{-1} (150 mph).



Figure 29. Collapse of a service station canopy in the Joplin tornado.



Figure 30. Collapse of a store with gas station canopy in front of the Walmart.

3.17 Electrical Transmission Lines (DI 24)

According to the Missouri Public Service Commission (MPSC, 2011), the tornado damaged or destroyed 4,000 service poles, 1,500 transformers, 110 miles of line, and one substation, leaving about 20,000 customers without electricity after the Joplin tornado. Most of the lost poles were wood, and there were approximately 130 tapered steel poles damaged or destroyed by the tornado. These tapered steel poles extended from the main substation located at 26th and Pearl Streets (Fig. 31). This intersection happened to be in the center of the tornado. According to the EF-scale, wood poles are expected to break at wind speeds around 53 m s^{-1} (118 mph) while steel poles bend or break at about 62 m s^{-1} (138 mph).



Figure 31. Damage to a tall, tapered steel pole that had supported power lines from the substation.

3.18 Free Standing Towers (DI 25)

The tornado damaged or destroyed ten cell phone towers. Cell phone towers were single, tapered, steel poles or triangular (cross section), latticed, steel towers. These towers ranged in height from 60 to 100 m.

Two cell phone towers collapsed at the Plaza Apartments, just east of the Walmart. One tower was a single pole while the adjacent tower was triangular tower. Both towers fell toward the north before the tornado arrived. The core of the tornado then passed to the south. The triangular tower struck one of the apartment buildings and penetrated into the first story (Fig. 32). According to the EF-scale, the expected failure wind speed for cell phone towers is 59 m s^{-1} (133 mph) or EF-2. The loss of cell phone service greatly affected rescue operations.



Figure 32. Cell phone tower toppled into one of the apartment buildings at the Plaza Apartments.

3.18 Free Standing Light Poles (DI 26)

Many large parking lots had free standing light standards that were bent or broken during the tornado. These parking lots were at St. Johns Hospital, Bowling Alley, High School, Bel-Aire Shopping Center, Walmart, and Academy Sports. Winds blew from the direction opposite the direction the poles were pointing. According to the EF-scale, the expected wind speed necessary to bend a free standing light pole is 46 m s^{-1} (102 mph). We found that failure wind speeds of the adjacent buildings typically were higher than that of the damaged light poles.



Figure 33. A light pole bent to the south in the High School parking lot.

3.20 Trees (DIs 27 and 28)

The Joplin tornado destroyed thousands of trees. Many trees were uprooted or had trunks snapped. Trees were debarked and shredded by flying debris (Fig. 34). The direction of the toppled trees (from base to tree top) indicated the direction from which the wind blew at the moment of failure. Near the beginning of the tornado path, we found a spiral pattern of tree falls where there was a brief, stationary vortex (Fig. 35).



Figure 34. Debarked trees near the center of the tornado path in an EF-4/5 area southeast of the High School.



Figure 35. A spiral pattern of downed trees (yellow arrows) caused by a stationary sub-vortex near the beginning of the Joplin MO Tornado. A latticed, steel, cell tower (outlined in red) fell to the northeast.

4. NON DAMAGE INDICATORS

There were several non-damage indicators that indicated the strength of this tornado. Many vehicles tumbled and rolled long distances; pavement was scoured; parking curbs were lofted; and manhole covers were missing. Such non-DIs were difficult to assign a failure wind speed but were considered in conjunction with nearby DIs.

4.1 Vehicles

The Joplin tornado damaged or destroyed thousands of vehicles. Many vehicles had broken windows and dents in body metal due to flying debris. Vehicles were moved or rolled in EF-3 or greater areas, and a number of vehicles became airborne. Vehicles were piled up in the parking lots of St. Johns Hospital, Walmart, and Academy Sports. There were two locations where we observed regions of high velocity impacts. A truck was wrapped around a tree in a field just east of the St. Johns Hospital. The steel frame of the truck was bent around the tree to form the letter “U” (Fig. 36). A four door vehicle, reportedly parked in front of the Walmart, traveled at a high rate of speed toward the southeast on the back side of the tornado, and struck a tree. The frame was bent around the tree like the letter “U” such that the front of the vehicle was almost touching the back of the vehicle (Fig. 37). Blacktop pavement was removed in a parking lot west of the Home Depot. However, the pavement was an overlay that had cracked and contained loose pieces prior to the tornado.



Figure 36. Truck frame wrapped around the base of a tree just east of the St. Johns Hospital.



Figure 37. Four-door vehicle bent into a U-shape around a tree just south of the Walmart building.

4.2 Parking Curbs

There were a number of parking curbs moved, rolled, and lofted during the Joplin tornado. These parking curbs had been in the parking lots at St. Johns Hospital and in front of the professional buildings west of the hospital. The parking curbs were precast concrete planks that contained two rebar extending horizontally. Parking curbs had tapered tops and flat bottoms and were two sizes. The smaller curbs were 1.9 m (6 ft.) long and weighed 113 kg (250 lbs.). The larger curbs were 2.5 m (8 ft.) long and weighed 150 kg (330 lbs.). Both curb types had pairs of holes which extended through them for anchoring. Steel rebar (dowels) were driven through the holes into the ground to hold the parking curbs in place.

The tornado removed several parking curbs and tossed them up to 20 m away (Figs. 38 and 39). In some instances, the rebar remained anchored in the parking lot but was bent in the direction the curb had moved. Removal of the parking curbs demonstrated how strong tornado winds extend down to just above the ground.



Figure 38. Removed concrete curbs (thrown westward) in a parking lot of a professional building just west of St. Johns Hospital.



Figure 39. Parking curb found in the crawl space of a destroyed home. The curb traveled 20 m.

4.3 Miscellaneous

There were a number of oddities found in the damage of the Joplin tornado. A piece of wood was driven through a concrete curb (Fig. 40), cardboard was driven through EIFS siding at the High School, and a steel lawn chair was imbedded in the EIFS siding at Academy Sports. Steel manhole covers were missing. A 5 m long 2 x 10 board had penetrated a partition wall in the principal's office at the High School (Fig. 41). A picture remained unaffected on an adjacent bookshelf. The board had traveled horizontally through a small window in a high speed east wind. A child's play set, made of hard plastic, remained virtually intact within an EF-4/EF-5 area of destroyed houses, uprooted trees, and broken light poles in Cunningham Park (Fig. 42).



Figure 40. Wood splinter driven through a concrete curb.

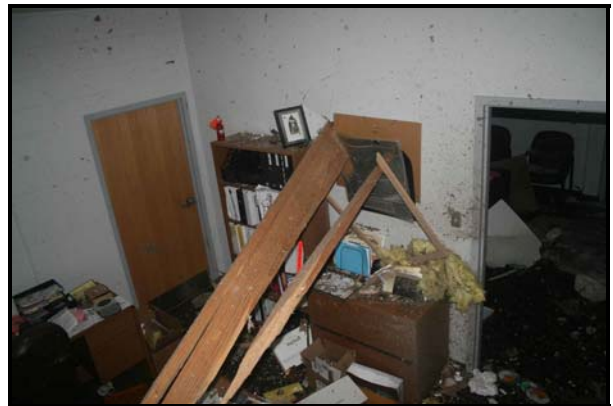


Figure 41. A large wood board penetrated a small window and partition wall in the principal's office at the High School. Note a picture remained upright on the adjacent book case.



Figure 42. Child's play set was left virtually untouched in the middle of an EF-4/EF-5 area at Cunningham Park. Note the snapped steel pole in the foreground.

5. SUMMARY

The Joplin tornado was the largest and most destructive tornado in recorded history in southwest Missouri. The tornado developed at the southwest edge of Joplin and cut a path of destruction that extended 10 km through the city and up to 1650 m wide. East of Joplin, the tornado weakened and narrowed in open country, and traveled another 20 km before lifting about 8 km northeast of Granby, Missouri.

The authors conducted aerial and ground surveys immediately after the tornado. Various building types were evaluated to determine a range of failure wind speeds and overall damage intensity of the tornado. We examined sample DIs utilizing the EF-scale. Based on our damage survey, we rated the tornado EF-5, the highest number on the EF-scale with maximum winds exceeding 89 m s^{-1} (200 mph). There were 22 (out of 7191) homes which sustained EF-5 level damage. Each home was swept clean from their concrete slab foundation. The tornado destroyed unanchored homes on pier and beam foundations well before EF-5 level winds were reached. The number of homes rated EF-1 through EF-4 ranged between 7 and 9 percent of the total homes affected, for each category. There were no other DIs where EF-5 level damage could be attained. Various non-DIs indicated high speed winds occurred just above ground level. These included movement and lofting of parking curbs and wood boards that penetrated the ground.

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MAP ATTACHMENTS

We have attached damage maps developed from our analysis of the Joplin tornado. Only that portion of the track that went through the city is shown. Houses were rated EF-0 to EF-5 per the EF-scale. Boxes around the numbers indicated where homes slid off their foundations. The maps are contoured EF-1 through EF-5 in color. Lines shown in blue are EF-1, purple EF-2, green EF-3, brown EF-4, and orange EF-5.

