8B.3 # Damage survey of the Greensburg, KS tornado

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1. Introduction

On the evening of May 4, 2007, a large and violent tornado struck the town of Greensburg, KS (Fig. 1). Approximately 95 percent of the town was destroyed including more than 500 homes and dozens of businesses. Eleven people died. Detailed ground and aerial damage surveys were conducted by three independent teams within days after the tornado and a consensus of damage intensity and implied peak wind speed and direction maps were produced using the Enhanced Fujita (EF)-scale, a scale adopted by the National Weather Service in 2007. Peak implied wind speeds were 92 ms^{-1} near the center of the tornado path, making this the first EF-5 rated tornado using the new EF-Scale.

This paper will present our findings in studying residential damage. We also studied the performance of manufactured housing with respect to residences. Correlations were made between the degree of building damage and the performance of vehicles in order to provide information on whether vehicles should be incorporated as a damage indicator in future revisions of the EF-scale. A plot of tree fall and utility pole damage revealed the broad scale rotation of this tornado.

We also studied, in detail, tornado damage to specific buildings such as the Greensburg High School, Delmer Day Elementary School, and the Kiowa County Memorial Hospital. We discovered weak points in the construction of these buildings that made them more susceptible to catastrophic failure in the tornado. The concept of “hinge lines” will be discussed in the hope that damage surveyors will recognize these fatal flaws in masonry buildings which can lead to the collapse of such buildings and inadvertently higher EF-ratings.

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Figure 1. Lightning illuminates the Greensburg, Kansas Tornado. Image courtesy of Melanie Metz.

2. Damage Survey

Ground damage surveys were performed within five days after the tornado to include those by McCarthy et al. (2007). The aerial survey was delayed to the fifth day due to recovery operations that restricted airspace as well as the occurrence of severe weather on May 5 and 6th. Tornadic supercells tracked within a few miles of Greensburg on both days. Heavy equipment had already cleared the streets by the end of the third day. The Federal Emergency Management Agency (FEMA, 2007) also conducted an independent study of the tornado damage.

According to Umscheid and Lemon (2008), the tornado traveled 46km and was on the ground for 65 minutes (Fig. 2). Average path width was 1.8 km with a maximum path width being 2.8 km. Total damage area covered nearly 86 km^2. The tornado initially touched down in Comanche County and traveled north-northeast into Kiowa County then gradually turned to the north-northwest when it struck Greensburg. The tornado traveled through the middle of town destroying the downtown business district and damaging or destroying more than 500 homes. The High School, Elementary School, and Hospital also were heavily damaged.

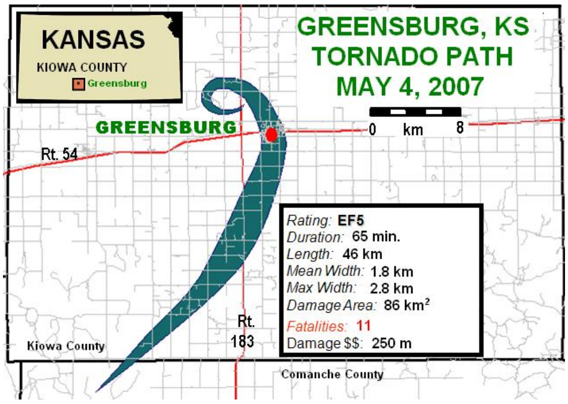

Figure 2. Damage path of the Greensburg, KS tornado. Courtesy of Umscheid and Lemon (2008).

2.1 Wood-framed housing

EF-scale numbers were assigned to 662 homes based on increasing severity of the damage (Fig. 3). Degrees of damage (DOD) descriptions were followed in accordance with those developed by the Wind Science and Engineering Center (2006). Homes were rated EF-0 if they had some damage to their roof coverings and/or lost some of their vinyl or metal siding (DOD=2). A rating of EF-1 was assigned to those homes that lost most of their roof covering and/or had minor structural damage to the roof such as displaced gable ends or loss of some roof decking (DOD=4). Homes were rated EF-2 if they had lost most of their roof structure but the walls remained standing (DOD=6). A rating of EF-3 was given to homes that lost most of their walls (DOD=8). An EF-4 rating was given to those homes that had all walls down and a pile of debris remaining on their foundation (DOD=9). EF-5 ratings were given to anchored homes that were swept clean from their foundations (DOD=10).

We encountered 53 homes that slid off their block foundations (Fig. 4). These homes were rated EF-2 or assigned an EF number of the adjacent home that did not slide off its foundation. In addition, about one dozen homes were not rated as homeowners already had cleared the debris from their foundations.

The results of our house to house survey are presented in Table 1 and plotted in Figure 5. EF-0 damage occurred to 194 homes. These homes were located on the periphery of the damage track, along the east and west edges of town. EF-1 damage occurred to 74 homes, while 177 homes had EF-2 damage. It was found that homes were more apt to lose their entire roof rather than a portion of the roof by a factor of more than 2 to 1. We found approximately the same number of EF-3 and EF-4 damaged homes. Only seven homes were found with EF-5 damage.

Figure 3. Examples of EF-scale damage ratings to homes in Greensburg, KS.

Figure 4. Example showing a home that was "swept clean" from its foundation that was rated EF-2 based the removal of its roof. Note vehicle remained within the destroyed garage.

As expected, the degree of damage to homes was more severe on the east side of the tornado track than on the west side. However, the variability in EF-scale ratings was greater on the west side of the tornado track (Fig. 6).

TABLE 1
EF-SCALE RATINGS TO HOUSING

EF rating	East*	West*	Homes	Percent
EF0	53	141	194	29
EF1	48	26	74	11
EF2	112	65	177	27
EF3	67	37	104	16
EF4	52	54	106	16
EF5	5	2	7	1
TOTAL	**337**	**325**	**662**	**100**

*East or west of the convergence center.

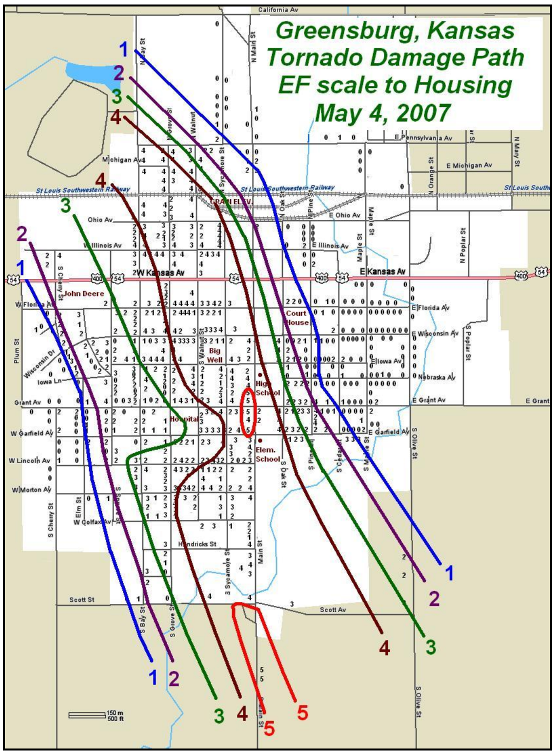

Figure 5. Plot of EF-scale damage to housing, with contours. Considerable smoothing had to be done to draw the contours given the large variability in housing performance.

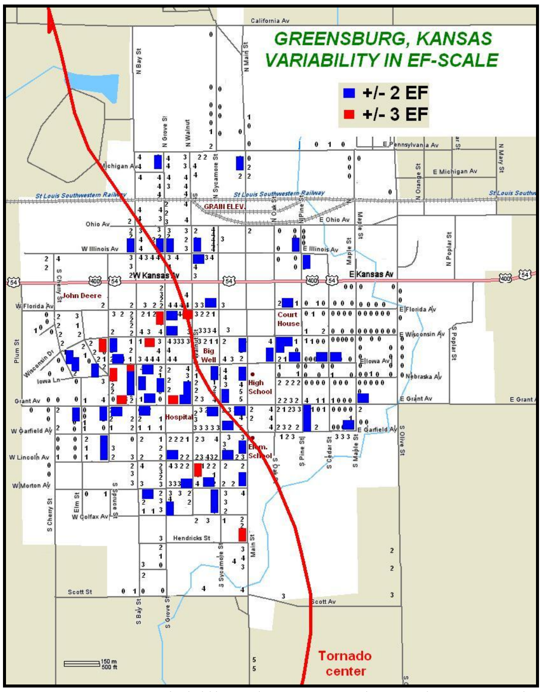

Figure 6. Variability in EF-scale ratings. Blue boxes indicated a difference of two in adjacent homes and red boxes indicate a difference of three.

We checked to see how well homes at street corners performed in comparison to neighboring homes. There were 245 homes on street corners. We found 68 corner homes performed better, 65 performed worse, and the remaining 112 homes performed the same as neighboring homes. Thus, homes on street corners had no better/worse chance of suffering the same degree of damage as neighboring homes that were not on street corners.

2.2 Manufactured housing

There were 39 manufactured homes within the damage path. Manufactured homes consisted of wood-framed structures mounted on steel undercarriages. There were 11 double-wide manufactured homes and 28 single-wide homes. Manufactured homes were rated EF-0 if they had some loss of roof shingles or decking (DOD 1 and 2). An EF-1 rating was assigned to homes that had shifted or rolled off their foundations or lost their roofs (DOD 3 to 5). Homes that were completely destroyed (i.e. all walls down) were rated EF-2 (DOD ≥ 6).

In general, the manufactured homes performed poorly in the tornado winds regardless of the size of the home. Refer to Table 2. Unanchored manufactured homes were common and these homes rolled, vaulted, or were lofted. A total of 28 manufactured homes, or 72 percent, were destroyed and as such, provided no occupant protection. By comparison, only 17 percent of "permanent" homes had been damaged in Greensburg to the point where they provided no occupant protection. Many of the destroyed manufactured homes were adjacent to "permanent" homes that only experienced EF-0 to EF-2 damage (Fig. 7). In certain instances, the steel frames from the manufactured homes were lofted downwind and struck other buildings. This finding underscores the importance that manufactured homes are not safe havens in tornadoes.

TABLE 2
EF-SCALE RATINGS TO MANUFACTURED HOUSING

EF rating	Singlewide	Doublewide	Percent
EF0	6	2	20
EF1	2	1	8
EF2	20	8	72
TOTAL	**28**	**11**	**100**

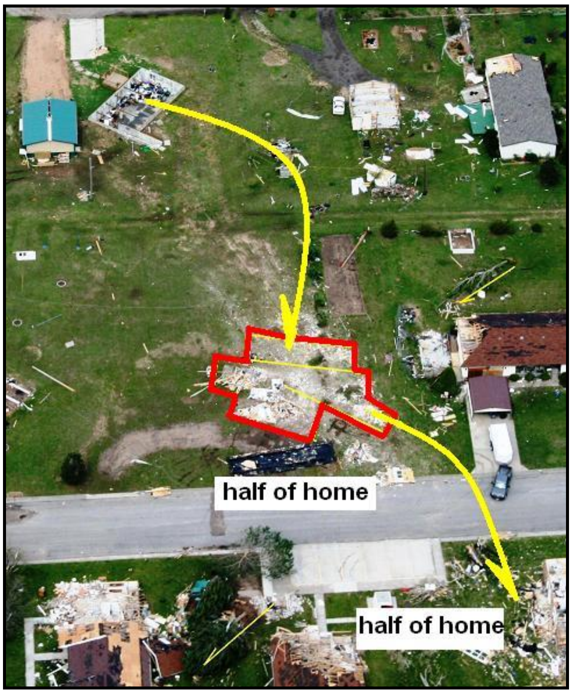

Figure 7. Lofting of unanchored, double wide manufactured home in area where residences experienced only EF-0 to EF-2 damage.

2.3 Trees and Utility Poles

We plotted damage vectors of 155 downed trees and utility poles which revealed the broad cyclonic wind flow of the tornado (Fig. 8). A sharp convergence line was found oriented southeast-to-northwest extending through the middle of town. Most trees and utility poles were toppled to the west or northwest east of the convergence line whereas most trees and utility poles were toppled to the east and southeast west of the convergence line. Trees with large branches broken were rated EF-0 (DOD=2), trees uprooted or snapped were rated EF-1 (DOD 3 and 4), and trees that were debarked with only stubs of the trunks remaining were rated EF-2 (DOD=5). Many trees near the center convergence line were debarked and lost their largest branches leaving trunk stubs.

A comparison between tree damage and residential damage revealed that significant tree damage (i.e. broken branches, uprooting) occurred when homes only sustain EF-0 damage. We found debarked trees adjacent to homes at all EF-scale levels with the greatest number of debarked trees occurring near homes with EF-4 ratings. Refer to Table 3. Out of 634 trees surveyed, 244 (38%) trees had their branches removed and trunks were reduced to stubs. Severed branches became part of the flying debris which impacted homes and vehicles.

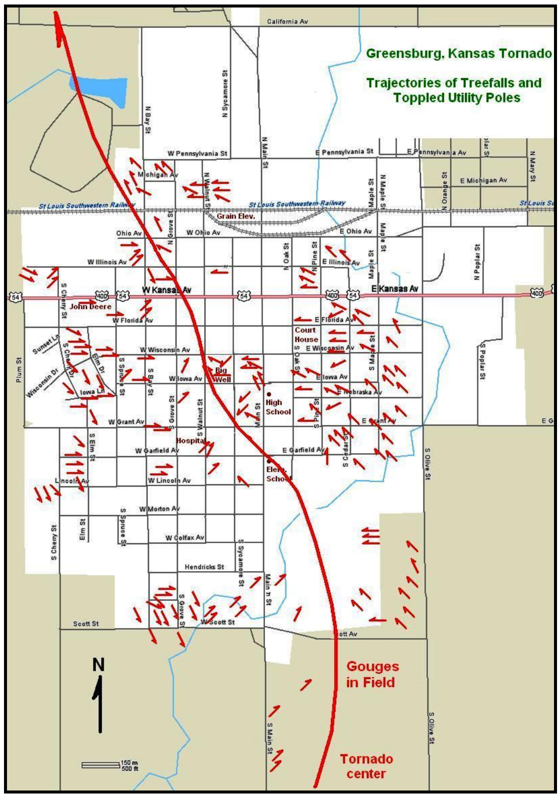

Figure 8. A plot of damage vectors of 155 downed trees and utility poles.

TABLE 3
COMPARISION OF TREE DAMAGE TO RESIDENTIAL DAMAGE

EF-rating of nearest house	EF<0 Leaves removed	EF-0 Large branches broken	EF-1 Tree uprooted	EF-2 Tree stub
EF 0	81	68	31	18
EF 1	4	35	29	31
EF 2	6	68	15	59
EF 3	0	22	4	52
EF 4	0	22	4	80
EF 5	0	1	0	4
TOTAL	**91**	**216**	**83**	**244**

2.4 Vehicles

A total of 370 cars and "light" trucks were found within the damage path. Most of these vehicles had been parked adjacent to homes or along streets while other vehicles had been parked in garages. We compared the degree of damage of residences to whether vehicles had moved or not. Refer to Table 4.

Surprisingly, 166 vehicles, or 45 percent, had not moved even when homes sustained EF-4 damage. However, the vast majority of vehicles had been breached by flying debris and would not have been safe shelters. Significant movement did occur in the remaining 204 vehicles, of which 48 vehicles were rolled, tumbled, or lofted. Most vehicles that moved were adjacent to homes that were rated EF-2 or greater while most vehicles that were lofted, tumbled, or rolled were adjacent to homes that were rated EF-3 or greater.

TABLE 4
COMPARISION OF VEHICLE DAMAGE TO RESIDENTIAL DAMAGE

EF-rating of nearest house	No vehicle movement	Vehicle shifted laterally	Vehicle was rolled or lofted
EF 0	23	3	0
EF 1	17	15	3
EF 2	39	40	6
EF 3	22	37	14
EF 4	65	57	23
EF 5	0	4	2
TOTAL	**166 (45%)**	**156 (42%)**	**48 (13%)**

2.5 Greensburg High School

Greensburg High School consisted of several interconnecting buildings (Fig. 9). Walls were three wythes thick of unreinforced masonry. The main building was three stories with a one-story south wing. Roof structures were wood or steel. A steel-reinforced concrete structure and metal building extended from east side of the High School.

The High School was located about one block east of the convergence line and experienced the strongest winds from the south through east. Walls in the top story of the main building and south wing were broadsided by the strongest winds and collapsed to the west. The heavy masonry walls on the east side of the school fell inward into the classrooms whereas the west walls fell outward. Close examination revealed the walls failed about hinge lines that occurred at the level of the window sills (Figs. 10 and 11). The lack of columns with vertical steel reinforcement between the windows resulted in walls that lacked sufficient strength to resist lateral wind loads. Still, the degree of damage to the High School yielded an EF-4 rating.

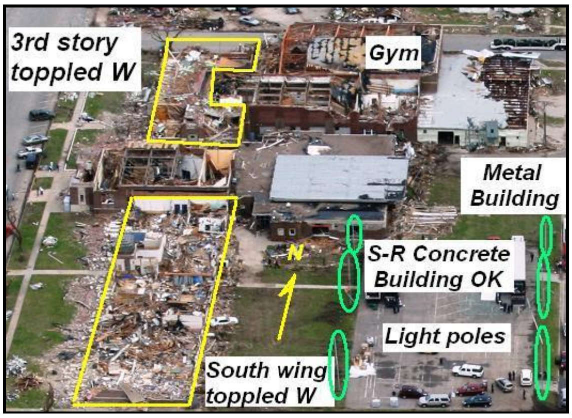

Figure 9. Aerial view of the Greensburg High School looking north. Unreinforced masonry walls collapsed (yellow outlines) to the west whereas the steel reinforced concrete building remained intact.

Figure 10. West wall of south wing fell outward rotating about the base of the windows. Red arrow indicates hinge line.

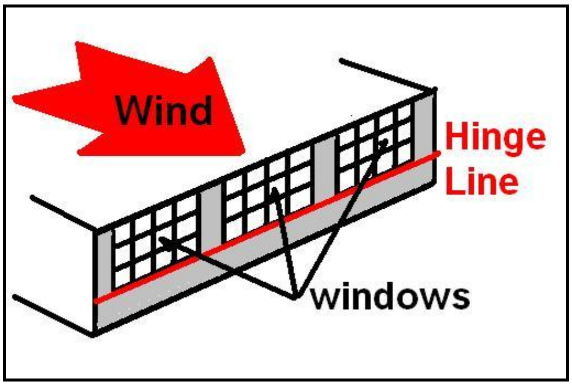

Figure 11. Illustration of how unreinforced masonry walls failed on schools. Walls rotated about hinge lines at the bases of the windows.

2.6 Delmer Day Elementary School

Delmer Day Elementary School consisted of four, single-story interconnected structures that were oriented north-south (Fig. 12). Walls were two wythes thick of unreinforced masonry. The east and south portion of the building had a wood framed roof structure consisting of glulam beams. The beams were attached to the top of the masonry walls with J-bolts. The north and west portions of the building had steel-framed roof structure. Open web steel joists were welded to a steel angle that was secured to a wooden top plate anchored to the tops of the masonry walls with J-bolts.

The school was located just east of the convergence line and experienced the strongest winds from the south through east. Just as with the High School, the east and west walls were broadsided by the strongest winds and collapsed to the west in the east and south buildings. The masonry walls on the east side of the school fell inward into the classrooms whereas the west walls fell outward. Close examination revealed the walls failed about hinge lines that occurred at the level of the window sills just like the High School (Fig. 13). The lack of columns with vertical steel reinforcement between the windows resulted in walls that lacked sufficient strength to resist lateral wind loads. Still, the degree of damage to the Elementary school yielded an EF-4 rating.

Figure 12. Aerial view of the Delmer Day Elementary School looking north. Unreinforced masonry walls (red outlines) collapsed to the west.

Figure 13. East wall of the South building toppled inward rotating about the base of the windows. Red arrow indicates hinge line.

2.7 Kiowa County Memorial Hospital

The Kiowa County Memorial Hospital consisted of four interconnected structures and a detached garage (Fig. 14). Walls were two wythes thick of masonry with vertical steel reinforcement at the wall corners. North, south, and west wings (including the detached garage) had steel-reinforced concrete bond beams located at the tops of the walls. Steel-reinforced concrete tee beams spanned these structures but were not anchored to the bond beams (Fig. 15). The remaining center and east wings had wood-framed roof structures.

Figure 14. Aerial view of the Kiowa County Memorial Hospital looking north. Moved cars are circled. A displaced concrete tee beam (red outline) and collapsed garage (yellow outline) are noted.

Figure 15. Wind removed a 4500 kg steel-reinforced concrete roof beam on the hospital.

The hospital was located about one block to the west of the convergence line and experienced the strongest winds from the west-southwest. Several vehicles in the parking lot were moved to the north. One of the concrete tee beams at the south end of the south wing was uplifted and deposited on a vehicle to the northeast. According to FEMA (2007), the beam weighed approximately 4500 kg. They calculated a wind velocity of 66 ms^{-1} to lift the beam. By comparison, the expected value for wind to uplift such a beam is 64 ms^{-1} according to the EF-scale. Damage to the hospital was indicative of an EF-3 rating.

3. SUMMARY

The tornado that struck Greensburg, Kansas was the first one rated EF-5 on the new Enhanced Fujita scale adopted by the National Weather Service in early 2007. This paper summarized the findings of three survey teams that conducted independent evaluations of the damage. It was found that tornado tracked through the middle of town and only the homes at the east and west edges of town were sustained little or no damage.

EF-scale ratings were assigned to 662 wood-framed houses. Building failures were typical to what has been observed in past tornadoes (i.e. Marshall, 2002). However, the variability in EF-scale ratings was greater on the west side of the tornado track than on the east side. Also, we found that homes on street corners had no better/worse chance of suffering the same degree of damage as neighboring homes that were not on street corners.

In general, unanchored manufactured homes performed poorly and were quite susceptible to being destroyed even in areas where residential damage was EF-0.

Analysis of fallen trees and poles provided damage vectors that revealed the broad cyclonic wind flow of the tornado. A comparison between tree damage and residential damage revealed that significant tree damage (i.e. broken branches, uprooting) occurred when homes only sustain EF-0 damage. Debarked trees were adjacent to homes at all EF-scale levels with the greatest number of debarked trees occurring near homes with EF-4 damage.

Our comparison of vehicle performance to residential damage indicated that 45 percent of vehicles remained even when residential damage was EF-4. However, these vehicles were breached by flying debris and offered no shelter for occupants. Also, most vehicles that moved were adjacent to homes that were rated EF-2 or greater while most vehicles that were lofted, tumbled, or rolled were adjacent to homes that were rated EF-3 or greater.

Specific study of the damage to the High School and Elementary School revealed weak points in the construction of unreinforced masonry walls. In particular, hinge lines formed at the bases of windows causing the walls to topple. Damage to these schools was characteristic of an EF-4 rating. Even the better built hospital sustained significant damage as roof components were not anchored. There was good correlation between the calculated wind load to lift the concrete roof beam and the EF rating.

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