Damage Survey of the Mayfield, KY Tornado: 10 December 2021

Timothy P. Marshall[1], Zachary B. Wienhoff[1], Brian E. Smith[2], and Christine L. Wielgos[2]
[1]Haag Engineering Company
[2]NOAA/NWS

1. INTRODUCTION

On December 10, 2021, a tornado outbreak occurred in the southern U.S. with more than 70 tornadoes reported. The worst hit areas were northeast Arkansas, western Tennessee, western Kentucky, and southern Illinois. This paper will concentrate on the damage in western Kentucky, particularly the towns of Mayfield and Dawson Springs where the most severe damage occurred. A detailed damage survey was conducted in the days following this event and the National Weather Service rated this tornado EF 4 on the Enhanced Fujita (EF) Scale. Various degrees of damage (DoD) were assigned to different damage indicators (DIs) in accordance with the 2006 EF-scale (WERC, 2006).

The EF-scale was adopted by the NWS in 2007 and is utilized to rate the severity of tornado damage. The NWS utilizes the damage assessment toolkit (DAT) to record and plot specific locations of the damage. Their mission includes determining the path length, path width, and most intense damage for each tornado.

Currently, the EF-scale is being updated and developed into a standard as a joint project by the American Society of Civil Engineers (ASCE), Structural Engineers Institute (SEI) and the American Meteorological Society (AMS). Additions to the EF-scale will include explanations of typical, stronger than typical, and weaker than typical resistance levels for each DI. The number of DoDs will be expanded, and the estimated failure wind speeds will be adjusted accordingly. There also will be a commentary and additional DoD photographs for each DI. The standard is expected to be published in the next few years.

The tornado which struck Mayfield and Dawson Springs, Kentucky occurred at night and was a large wedge-type. Refer to Figure 1.

*_Corresponding author address:_ Timothy P. Marshall, Haag Engineering Co., 4949 W. Royal Lane, Irving, TX 75063. Email: timpmarshall@cs.com

Fig. 1. Nighttime wedge tornado illuminated by lightning between Bremen and Sacramento, KY. Image by Eddie Knight.

2. TRACK OVERVIEW

The tornado that traveled through Mayfield and Dawson Springs, Kentucky initially developed in extreme northwest Tennessee, in Obion County, around 2049 UTC (8:49 pm CST), about 3.4 km (2.12 mi) south of the Kentucky state line. The tornado then continued through eleven counties in western Kentucky ending around 2345 UTC (11:45 pm CST) at Rough River Dam State Park in Grayson County, Kentucky. The total path length of this tornado was 267 km (165.7 mi) with a maximum path width of 1.8 km (1.13 mi). Unfortunately, 57 people lost their lives from this tornado and more than 500 people were injured.

This long-track tornado was part of a family of tornadoes produced by a supercell that developed near Jonesboro, AR and ended near the Kentucky-Ohio state line. The supercell which produced this family of tornadoes has been dubbed "The Quad State Tornadic Supercell" as it traveled through portions of four states. The storm lasted more than 11 hours and traveled about 966 km (600 mi). The storm had an average forward speed of 27 m/s (60 mph). Refer to Figure 2.

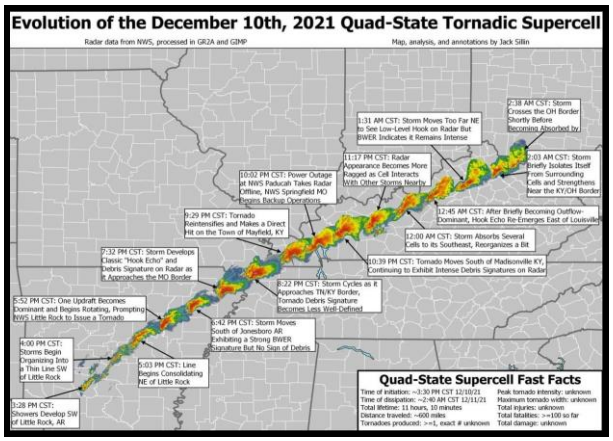

Fig. 2. Track of the supercell which produced the long-tracked tornado that went through Mayfield and Dawson Springs, KY. Source: NOAA.

3. MAYFIELD DAMAGE SURVEY

The tornado entered Mayfield from the southwest and traveled through an industrial area destroying several metal buildings including the Candle Factory where workers were making candles for the Christmas Holiday. Rescue workers indicated that at least nine workers died as the metal building collapsed. There was a small "tornado shelter" but it also collapsed killing three people. The tornado next struck a series of steel grain bins unroofing several of them that were filled with grain. Then, the tornado struck the Mayfield Garden Apartments where several buildings sustained roof damage and one building lost the roof and a portion of the top story. The tornado continued northeast and entered a residential area where it toppled a large steel water tower.

As the tornado entered downtown Mayfield, it destroyed many old brick low-rise buildings and church buildings. We examined in detail the First Baptist Church, First Christian Church, First Presbyterian Church, and First United Methodist Church as the updated EF-scale will be including church buildings as a new DI. Then, the tornado struck the courthouse toppling the domed clock tower and collapsed the top story. Across the street, north of the courthouse, was a one-story fire station that lost its roof and communications tower. The tornado continued through an older residential community before impacting the Mayfield Manor Apartments on the northeast side of town, where one building was destroyed. To the east of these apartments was the Mayfield Health and Rehabilitation Center which lost a portion of its roof and a few exterior walls. Across the street to the south of this facility was the Windhaven Apartments which consisted of 12, one- and two-story wood-framed structures. One apartment building lost its roof while the remaining buildings sustained partial roof damage.

One of the biggest challenges in conducting the damage survey was the length of the tornado track (128 miles through the Paducah NWS County warning area) and the fact that clean-up began almost immediately. Within a matter of hours, heavy equipment had cleared the streets of downed trees and power lines in Mayfield. People boarded up broken windows and installed blue tarps on roofs. Thus, details regarding building failures were perishable. Because of the rapid cleanup response, damage survey teams were limited in their selection of which buildings to study in detail. Our goal for this paper was to sample as many different DIs as possible and include church buildings and the water tower as these DIs will be included in the updated version of the EF-scale. Refer to Figure 3. Google Street View and Google historical imagery were invaluable as they showed what the buildings looked like prior to the tornado.

3.1 Barns and Outbuildings (DI 1)

Many rural barns and outbuildings were destroyed by this tornado. According to the 2006 EF-scale, total destruction of a barn or outbuilding has an expected failure wind speed of 50 m/s (112 mph). One such example of a destroyed outbuilding was a one-story, wood post and frame structure at 514 West Walnut Street in Mayfield. Refer to Figures 4 and Table 1. Walls were built with 15 x 15 cm (6 x 6 in) wood posts spaced 3.7 to 4.8 m (12 to 16 ft) apart. The gable roof was wood trusses. The entire building was clad with metal panels. Four roll-up doors were located on the north side of this building. The building was completely destroyed, and posts were snapped off at the concrete floor slab. Such an open post and frame type building would have little resistance to strong winds. It is important to note this was not a metal building system (MBS) as they have interior steel framing.

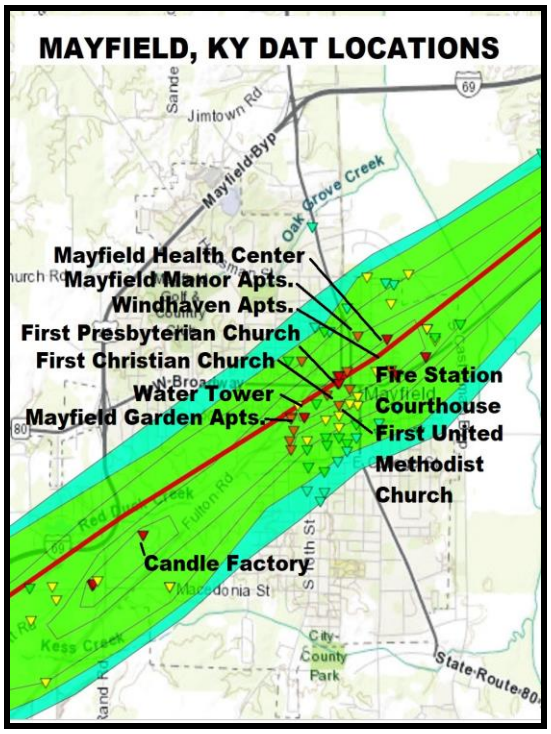

Fig. 3. DAT locations along with some of the specific buildings selected for detailed examination in Mayfield, Kentucky.

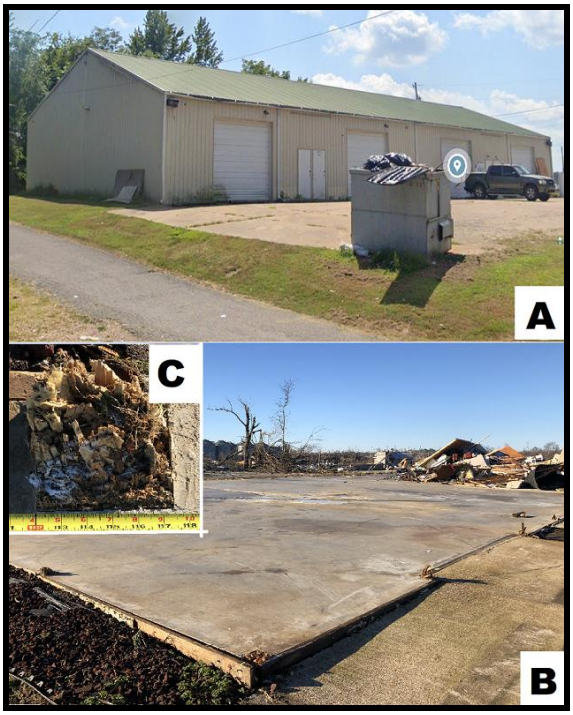

Fig. 4. Wood post and frame building in Mayfield, Kentucky: A) Google Street View of front (north) elevation before the tornado, B) building view after the tornado, and C) wood post snapped at foundation.

Table 1. DoDs for barns and outbuildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	62	53	78
2	Loss of wood or metal roof panels	74	61	91
3	Collapse of doors	83	68	102
4	Major loss of roof panels	90	78	110
5	Uplift or collapse of roof structure	93	77	114
6	Collapse of walls	97	81	119
7	Overturning or sliding of entire structure	99	83	118
8	Total destruction of building	112	94	131

* Degree of damage

3.2 One- and two-story residences (DI 2)

Hundreds of homes were damaged by the tornado. There were basically two types of wood-framed homes: those that were clad with siding and those that clad with brick masonry. The typical home was a one-story, wood-framed structure built on a pier and beam foundation. The foundation was built with concrete masonry units (CMUs). These buildings were essentially not anchored and susceptible to sliding off their foundations as noted with the residence at 314 S. 11th Street in Mayfield. Refer to Figure 5.

Fig.5. Typical wood-framed home: A) Google Street view before the tornado, B) building view after the tornado, and C) close-up view showing lack of attachment to the foundation.

As noted in the 2006 EF-scale document, unanchored homes swept off their foundations are DoD 5 and have an estimated failure windspeed of 54 m/s (121 mph). Thus, we assigned this failure wind speed to this home. Refer to Table 2.

Generally, homes clad with brick masonry were heavier and had more wind resistance. The home at 219 E. North Street in Mayfield was a two-story, wood-framed structure clad with painted brick masonry. This home was built on a brick masonry foundation. Tornadic winds removed the roof and second story exterior walls leaving interior walls remaining. Damage was equivalent to DoD 8 for the top story with an estimated failure windspeed of 68 m/s (152 mph). Refer to Figure 6 and Table 2.

Fig. 6. Two-story wood-framed residence clad with brick masonry: A) Google Street View before the tornado and B) view of house after the tornado.

Table 2. DoDs for residences.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	53	80
2	Loss of roof covering material (<20%), gutters and/or awning; loss of vinyl or metal siding	79	63	97
3	Broken glass in doors and windows	96	79	114
4	Uplift of roof deck and loss of significant roof covering material (>20%); collapse of chimney; garage doors collapse inward; failure of porch or carport	97	81	116
5	Entire house shifts off foundation	121	103	141
6	Large sections of roof structure removed; most walls remain standing	122	104	142
7	Exterior walls collapsed	132	113	153
8	Most walls collapsed, except small interior rooms	152	127	178
9	All walls	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	165	220

* DOD is degree of damage

3.3 Apartments (DI 5)

Several apartment buildings were damaged or destroyed by the tornado in Mayfield. These buildings were mostly one and two-story, wood-framed structures built on concrete foundations. Exterior walls were brick masonry, painted wood siding, or exterior insulation and finish system (EIFS).

The Mayfield Garden Apartments consisted of 10, two-story buildings, and a one-story office building. Buildings were rectangular in plan, being oriented either north-south or east-west. The exterior walls were clad with brick masonry. Roofs were gable type covered with asphalt shingles.

The apartment buildings experienced the strongest winds from the south. Buildings oriented north-south sustained damage to their south-facing gable ends including loss of roof shingles and decking along the south rakes. East-west oriented buildings were broadsided by the tornadic winds.

An east-west oriented building sustained the most severe damage. Refer to Figure 7. This building lost its roof which extended over a second-story walkway. Steel posts supported the roof overhang. Each steel post had a welded plate at the top with a hole where a lag screw was installed into the roof structure. Wind became trapped under the walkway roof which added additional uplift to the roof structure. As the beams lifted, screws at the top of each post pulled out of the roof structure leaving the lag screws on top of the posts. This roof overhang faced south and "caught" the strong, south winds, whereas other east-west oriented buildings had overhangs leeward to the wind, so they did not catch the wind.

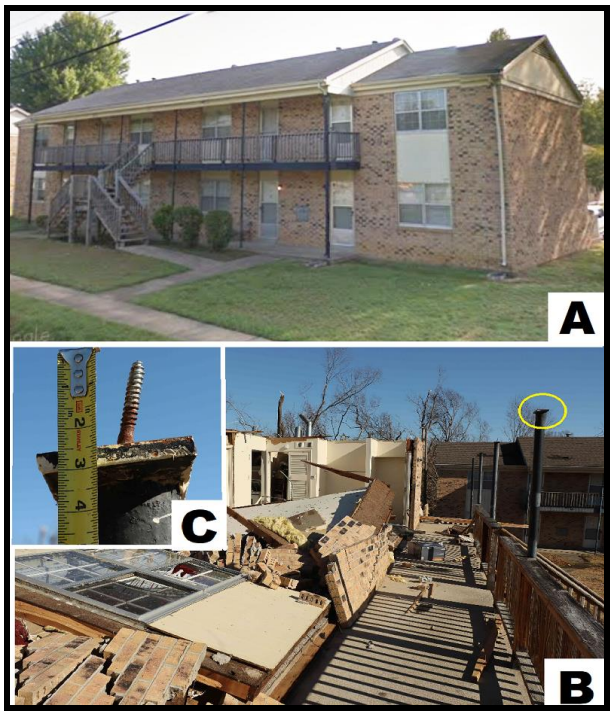

Fig. 7. Two-story apartment building at Mayfield Garden Apartments: A) Google Street View before the tornado, B) loss of roof and overhang after the tornado, and C) close-up view of lag screw left at the top of the steel post along the walkway.

Second story wall bottom plates were straight nailed to the floor. Nails pulled out of the floor as the walls toppled about their bases once the roof was removed. Damage to this apartment building was consistent with DoD 5 in the 2006 EF-scale with estimated failure wind speeds of 71 m/s (158 mph). Refer to Table 3.

Table 3. DoDs for apartment buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	76	63	95
2	Loss of roof covering (<20%)	99	82	121
3	Uplift of roof decking; significant loss of roof covering (>20%)	124	107	146
4	Uplift or collapse of roof structure leaving most walls standing	138	120	158
5	Most top story walls collapsed	158	138	184
6	Almost total destruction of top two stories	180	155	205

* DOD is degree of damage

The Windhaven Apartments were located in northeast Mayfield. There were 5, one-story buildings constructed on concrete slab foundations. Buildings were rectangular in plan and oriented either north-south or east-west. Walls were cold-formed steel studs. Exterior wall bottom plates were bolted to concrete slabs foundations, while interior wall bottom plates were nailed to the slabs. Roof framing consisted of cold-formed steel trusses.

There was roof shingle and decking damage to four of the apartment buildings, but one apartment building was partially removed down to the concrete slab foundation. Close examination revealed that the anchor bolts remained intact around foundation perimeter. Wall bottom plates had pulled through the anchor bolts. The anchor bolts were properly installed with nuts and washers; the nuts were tightened properly.

Building debris was scattered to the north indicating the strongest winds were from the south. This apartment building was oriented east-west, and there was a parking lot to the south. We surmise that the open fetch of the adjacent parking lot likely allowed higher wind speeds while other buildings were blocked by trees or other buildings to the south. Refer to Figure 8.

Damage to this building was consistent with DoD 6 with estimated failure wind speeds around 80 m/s (180 mph). Interestingly, a Ford Fusion car was moved from the parking lot onto the concrete slab where the building had been.

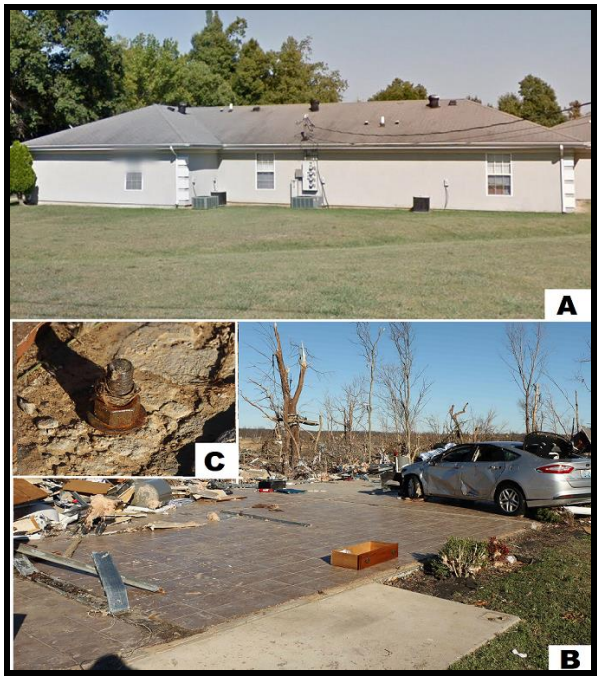

Fig. 8. Windhaven Apartment building: A) Google Street View before the tornado, B) destroyed building after the tornado, and C) close-up view of anchor bolt which remained in the concrete slab foundation.

We also examined damage at the Dawson Village Apartments in Dawson Springs, Kentucky where there were 6, two-story, wood-framed structures built on concrete slab foundations. The exterior walls were a combination of painted wood siding and brick masonry. Gable roofs were wood-framed and covered with asphalt shingles. One building had collapsed leaving a pile of debris on the foundation. Some debris also was transported east into the parking lot.

Close examination revealed that the first story wall bottom plates had been bolted to CMU half blocks set around the perimeter of the concrete slab foundation. Wall plate connections failed as these blocks rotated away from the concrete slab foundation. Refer to Figure 9. This type of foundation connection was inherently weak to resist lateral wind loads. As a result, we rated this building at the lower bound of DoD 6 with estimated failure wind speeds of 69 m/s (155 mph).

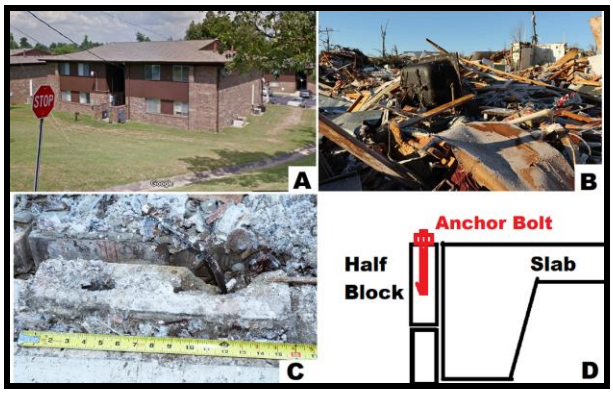

Fig. 9. Wood-framed building at the Dawson Village Apartments: A) Google Street View of the building before the tornado, B) pile of debris on the foundation after the tornado, C) CMU half block with anchor bolt broken out of the block, and D) cross section detail of the foundation.

3.4 Small Professional Buildings (DI 9)

There were several small retail buildings that were damaged or destroyed by the tornado, especially near downtown Mayfield. These buildings were one- or two-stories and constructed of load bearing brick masonry with wood floors and roof platforms. Large windows extended across the front of these buildings on the lowest levels.

We inspected the Good News Shop, a one-story wood and masonry structure near downtown Mayfield. The west loadbearing masonry wall collapsed resulting in the collapse of the wood roof structure. Damage to this building was equivalent to DoD 8 on the 2006 EF-scale with expected failure wind speeds of 64 m/s (144 mph). This failure wind speed was likely too high as the large maple tree west of the building remained intact indicating failure wind speeds were probably closer to 45 m/s (100 mph). Refer to Figure 10 and Table 4.

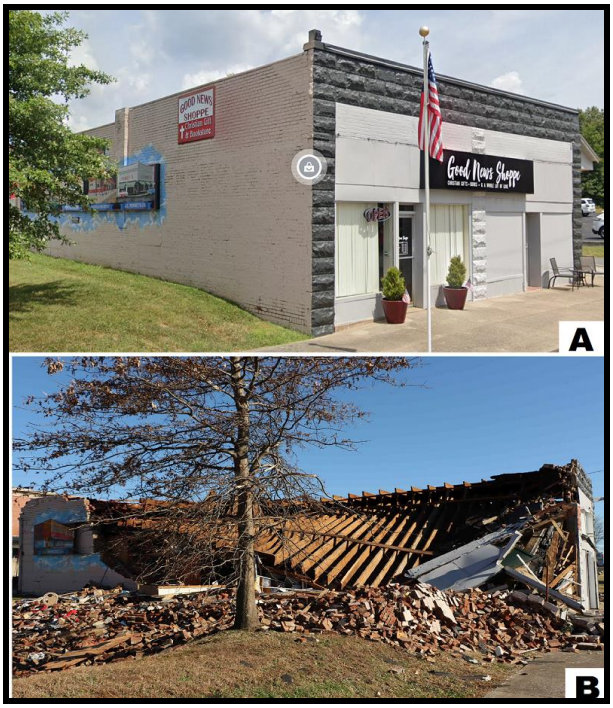

Fig. 10. The Good News Shop in downtown Mayfield: A) Google Street View of the building before the tornado, and B) collapse of the loadbearing west wall from the tornado.

Table 4. DoDs for small professional buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	65	54	81
2	Loss of roof covering (<20%)	78	65	98
3	Broken windows, including clear story windows or skylights	89	74	107
4	Exterior doors fail	100	82	118
5	Uplift of roof decking; significant loss of roof covering (>20%); loss of rooftop HVAC equipment	100	84	117
6	Collapsed façade or parapet walls	103	85	123
7	Uplift or collapse of entire roof structure	124	105	145
8	Collapse of exterior walls; closely spaced interior walls remain standing	144	123	165
9	Total destruction of entire building	157	148	200

* DOD is degree of damage

Midstate's Glass Company building was a two-story, rectangular structure oriented north-south located in downtown Mayfield. The building had loadbearing masonry perimeter walls with wood floor and roof joists. Large windows extended across the front of the building on the first story, which faced north. This building completely collapsed during the tornado into a pile of rubble. Damage was equivalent to DoD 9 in the 2006 EF-scale with expected failure wind speeds of 70 m/s (157 mph). Refer to Figure 11 and Table 4.

Fig. 11. Midstate's Glass Company building: A) Google Street View before the tornado, and B) complete collapse of building from the tornado.

3.5 Large Isolated Retail Buildings (DI 12)

The Pilgrims Pride North plant sustained damage from the tornado. This was a large, isolated retail building (LIRB) located southwest of downtown Mayfield. The building was constructed with precast, concrete wall panels and double tee, concrete roof beams. The tornado passed to the east of the building subjecting it to strong west winds. Two wall panels on the east side of the building fell outward causing the supporting double tee roof beams to collapse. Close examination revealed each wall panel was secured to the concrete foundation with two anchor bolts. Each wall panel had a pair of L-shaped, steel embeds with a hole to receive the threaded bolt stems to be tightened with nuts and washers. Anchor bolts broke in tension leaving cup-cone fractures on the bolt stems. The L-shaped steel embeds were not bent and remained intact in each wall panel. Refer to Figure 12.

Damage to the building was equivalent to DoD 6 in the 2006 EF-scale with estimated failure wind speeds of 61 m/s (137 mph). Refer to Table 5. However, since only two wall panels had failed, the failure wind speed was likely lower. There were two steel light poles near the building that toppled. This would yield a DoD of 3 in DI 26 with an estimated failure wind speed of 53 m/s (118 mph).

One deficiency in the 2006 EF-scale is that is does not give a percentage of wall damage. Specifically, DoD 6 is used when one wall panel collapses or most wall panels fail. This deficiency will be corrected with the new EF-scale.

Fig. 12. Pilgrims Pride building: A) Google Street View before the tornado, B) loss of two wall panels from the tornado, C) closer view of the base of the toppled wall panel, D) steel bracket embed remained intact on the wall panel, E) broken anchor bolt in the foundation.

Table 5. DoDs for Large Isolated Retail Buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	68	57	83
2	Loss of roof covering (<20%)	81	68	103
3	Uplift of some roof decking; significant loss of roofing material (>20%); loss of rooftop HVAC	103	87	123
4	Long roof spans collapsed downward	122	103	144
5	Uplift and removal of roof structure	134	114	157
6	Inward or outward collapse of exterior walls	137	118	158
7	Complete destruction of all or a large section of the building	173	147	201

* DOD is degree of damage

3.6 Metal Building System (DI 21)

The most famous building failure in this tornado was the Candle Factory located in southwest Mayfield. This large, steel-framed, metal clad factory was filled with employees making candles when the tornado struck. Unfortunately, nine people were killed including three who took cover in a "storm shelter". Other employees were burned by hot wax when certain tanks ruptured. The building was constructed with tapered steel columns bolted to the concrete foundation and the roof was supported by tapered, structural steel beams.

The tornado traveled directly over the building subjecting it to strong east and south winds. The roof was uplifted, and steel columns collapsed in succession, failing where they were bolted to concrete foundation. Anchor bolts broke while column base plates bent, and successive bays fell like dominoes. Refer to Figures 13 and 14.

Tanker trucks parked along the north and east sides of the building toppled to the north and ruptured causing hot wax to flow into ravines north of the building. Vehicles in the parking lot were tossed into a field to the east of the building on the back side of the tornado. At least one vehicle was lofted with all sides being crushed.

According to the 2006 EF-scale for DI 21, total destruction of the building would have an estimated failure wind speed of 69 m/s (155 mph). Refer to Table 6.

Fig 13. The Candle Factory in Mayfield: A) Google Street View before the tornado, and B) complete collapse of the building by the tornado.

Table 6. DoDs for metal building systems.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	67	54	83
2	Inward or outward collapsed of overhead doors	89	75	108
3	Metal roof or wall panels pulled from the building	95	78	120
4	Column anchorage failed	117	96	135
5	Buckling of roof purlins	118	95	138
6	Failure of X-braces in the lateral load resisting system	138	118	158
7	Progressive collapse of rigid frames	143	120	168
8	Total destruction of building	155	132	178

* DOD is degree of damage

Fig. 14. Collapse of the Candle Factory building: A) pile of steel debris on the foundation with support column in foreground, and B) closer view showing bent base plate on column where it had been bolted.

3.7 Warehouse Buildings (DI 23)

Myers Flooring Store was a warehouse type building in downtown Mayfield. The building was a one- and one-half story steel-framed structure with brick masonry perimeter walls and bowstring-shaped, steel roof trusses. The roof trusses were bolted to steel columns which in turn were bolted to the concrete foundation. Exterior walls were brick masonry. There was a large array of windows on the northeast, east, and south sides of the building along with roll up doors. These windows and doors failed from strong east and south winds resulting in a rapid increase in internal wind pressure which uplifted and collapsed the roof. Most of the debris remained in place on the foundation. Bolted connections were sheared apart between the bowstring roof trusses and tops of the columns as well as where the columns were secured to the foundation. Refer to Figure 15.

According to the 2006 EF-scale DI 23, total destruction of a large portion of a warehouse

building (DoD 7) has an expected failure wind speed of 71m/s (158 mph). Refer to Table 7.

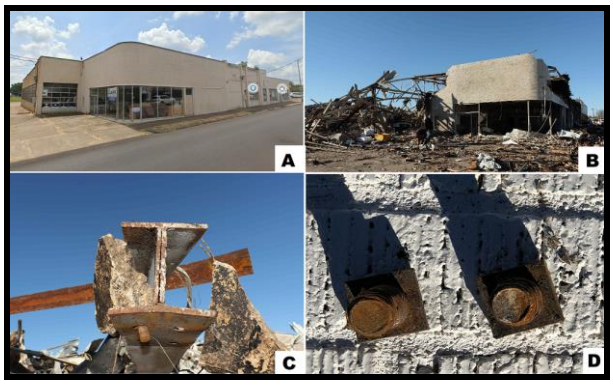

Fig. 15. Myers Flooring Store: A) Google Street View before the tornado, B) Collapse of the roof and walls from the tornado, C) Sheared bolted connection where the bowstring truss was attached to the top of the columns, and D) closer view of sheared bolts.

Table 7. DoDs for Warehouse Buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	68	55	83
2	Loss of roofing material (<20%)	83	69	105
3	Inward or outward collapse of overhead doors	88	75	107
4	Uplift of roof deck; significant loss of roofing material (>20%); loss of rooftop HVAC equipment	103	88	122
5	Collapse of other non-bearing exterior walls	114	93	126
6	Collapse of pre-cast concrete tilt-up panels	124	102	144
7	Total destruction of a large section of building or entire building	158	131	186

* DOD is degree of damage

3.8 Electrical Transmission Systems (DI 24)

As expected, there was extensive damage to wood utility poles throughout the tornado path. Common failures were snapped poles at or near the ground. Some poles were rotted while others were not rotted. Damage to wood utility poles was consistent with DoD 4 in DI 24 with expected failure wind speeds of 53 m/s (118 mph). Refer to Figure 16 and Table 8.

Fig. 16. Broken wood power pole.

Table 8. DoDs for Electrical Transmission Systems

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	83	70	98
2	Broken wood cross member	99	80	114
3	Wood poles leaning	108	85	130
4	Broken wood poles	118	98	142
5	Broken or bent steel or concrete poles	138	115	149
6	Collapsed metal truss towers	141	116	165

* DOD is degree of damage

3.9 Free-standing Towers (DI 25)

There was a tapered, three-legged, steel truss communications tower at the main fire station. This tower was about 30 m (100 ft) tall and comprised of 3, 8 cm (3 in) wide steel legs spaced 1.8 m (6 ft) apart at the ground. Each leg was secured to a base plate with 4 anchor bolts.

Strong south winds from the tornado toppled the tower to the north partly blocking the street north of the fire station. Close examination of the base of the tower revealed that two legs were torn away leaving base plates anchored to the foundation while the third leg broke the anchor bolts; the base plate was still attached to the leg. Refer to Figure 17.

According to the 2006 EF-scale DI 25, a collapsed tower has an estimated failure wind speed of 59 m/s (133 mph). Refer to Table 9.

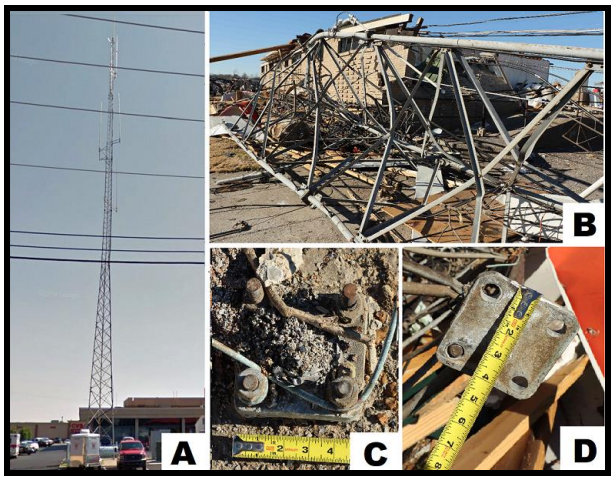

Fig. 17. Steel trussed communications tower at the Fire Station in Mayfield: A) Google Street image before the tornado, B) toppled tower after the tornado, C) leg tore at base plate, D) broken bolts with attached base plate.

Table 9. DoDs for free-standing towers.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	92	76	113
2	Collapsed cell-phone pole or tower	133	113	157
3	Collapsed micro-wave tower	136	116	160

* DOD is degree of damage

3.10 Light Poles (DI 26)

Free-standing, light poles and cantilevered traffic signals were damaged or toppled by the tornado. Those near the Pilgrims Pride facility were round, tapered steel poles that were about 12 m (40 ft) tall and 15 cm (6 in) at the base. Pole bases were welded to a square base plate and attached to concrete piers with four anchor bolts. Refer to Figure 18.

Strong east winds from the tornado toppled the poles to the west and they tore just above the welded joints. According to the 2006 EF-scale, toppled poles are DoD 3 in DI 26 with expected failure wind speeds of 53 m/s (118) mph. Refer to Table 10.

Fig. 18. A steel light pole tore at its base near Pilgrim Pride north building.

Table 10. DoDs for light poles.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	81	67	100
2	Bent pole	102	85	120
3	Collapsed pole	118	99	138

* DOD is degree of damage

3.11. Hardwood Trees (DI 27)

There were many hardwood and softwood trees damaged by the tornado. As an exemplar, we selected a group of hardwood trees in front of the Candle Factory. These trees were up to 15m (49 ft) and 30 cm (12 in) at the base. The large trees were stripped of leaves and branches by flying debris leaving only their main trunks. Damage to these trees was consistent with DoD 5 in DI 27 of the 2006 EF-scale with expected failure wind speeds of 65 m/s (145 mph). It is believed that multiple impacts of sheet metal debris from a nearby building aided in the removal of large tree branches and debarking of the trees. Refer to Figure 19 and Table 11.

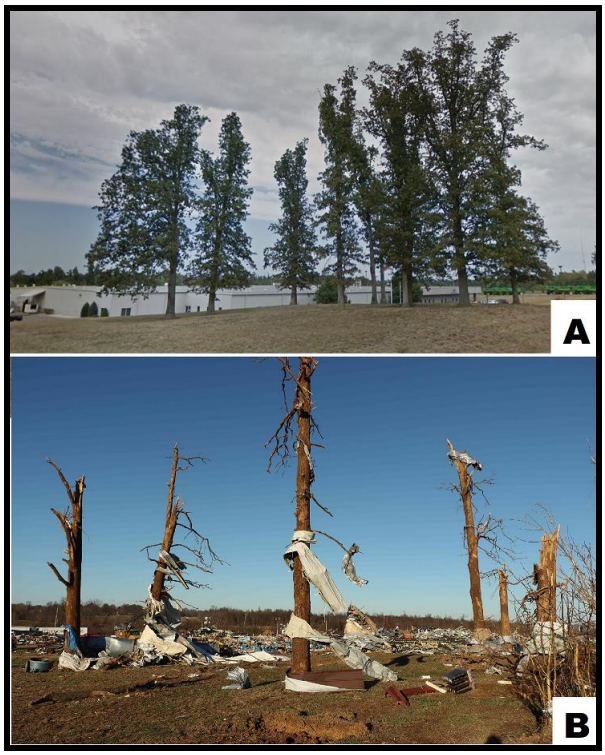

Fig. 19. Hardwood trees south of the Candle Factory: A) Google Street View before the tornado, and B) view of trees after the tornado.

Table 11. DoDs for hardwood trees.

DOD*	Damage description	EXP	LB	UB
1	Small limbs broken (up to 1" diameter)	60	48	72
2	Large branches broken (1"-3" diameter)	74	61	88
3	Trees uprooted	94	76	118
4	Trunks snapped	107	93	134
5	Trees debarked with only stubs of largest branches remaining	143	123	167

- DOD is degree of damage

3.12 Religious Buildings (new proposed DI)

There were several religious buildings in downtown Mayfield that were damaged or destroyed by this tornado. These buildings were studied in detail as religious buildings will be added to the updated version of the EF-scale.

The First Christian Church building was a large, two-story wood-framed structure with brick masonry exterior. A wood-framed domed roof extended over the sanctuary and was supported by multi-wythe brick masonry walls. There were two-story buildings containing classrooms and offices north and west of the sanctuary also with brick masonry exteriors.

Strong south and west winds passed directly over the church building as the tornado passed causing the domed roof to collapse into the sanctuary. Much of the second story was removed on the remaining church building, as well as the adjacent office and classroom buildings.

In the 2006 EF-scale, this building would be considered a low-rise building (DI 17) with DoD between 6 and 7. Estimated failure wind speeds to the church building and adjacent buildings would be around 76 m/s (170 mph). We note that winds in the tornado were likely higher. Refer to Figure 20 and Table 12.

Fig. 20. First Christian Church in Mayfield: A) Google Street View before the tornado, and B) collapsed domed roof and top story after the tornado.

Table 12. DoDs for low-rise buildings.

DOD*	Damage description	EXP	LB	UB
1	Threshold of visible damage	68	55	83
2	Loss of roof covering (<20%)	80	67	103
3	Uplift of metal roof decking at eaves and roof corners: significant loss of roofing material (>20%)	101	83	120
4	Broken glass in windows, entryways or atriums	101	83	122
5	Uplift of lightweight roof structure	133	114	157
6	Significant damage to exterior walls and some interior walls	143	122	167
7	Complete destruction of all or a large section of building	188	161	221

* DOD is degree of damage

The First Presbyterian Church was a rectangular-shaped building, oriented north-south, the front faced south. There was a steep roof over the sanctuary supported by A-shaped steel roof trusses. Roof trusses were bolted to steel plates

embedded into the top of the masonry walls. Six masonry buttresses provided lateral support to the walls and thrusting forces from the roof trusses. A three-story, masonry clock or bell tower was located at the southeast corner of the church building. To the north of the sanctuary was a two-story building that contained offices and classrooms. A large metal building was attached to the west side of the two-story building.

The building was struck with strong south and west winds as the center of the tornado passed causing the sanctuary to collapse to the north and east. Three of the six A-shaped steel roof trusses fell onto north 9th Street along with the east masonry wall. Debris remained in close proximity to the site. The bell tower also collapsed. The two-story building to the north of the sanctuary lost its top floor and the metal building also collapsed. Refer to Figure 21.

The current consensus of opinion by the ASCE/SEI/AMS committee is that a religious building with all walls collapsed with pile of debris on the foundation would have an estimated failure windspeed of at least 76 m/s (170 mph). The two-story building north of the sanctuary was considered a low-rise building and the damage, between DoD 6 and 7 in DI 17 in the 2006 EF-scale, would have similar failure windspeeds. Destruction of the metal building would have an estimated failure wind speed of 69 m/s (155 mph).

Fig. 21. First Presbyterian Church building in Mayfield: A) Google Street View before the tornado, and B) destroyed building after the tornado.

3.13 Water Tower (new proposed DI)

The Mayfield water tower was supported by 8 steel legs and had a tank capacity of 1900 kl (500,000 gal). Each leg was approximately 76 cm (30 in) in diameter and 1.3 cm (0.5 in) thick steel. Hexagonal base plates were welded to the bases of each leg and supported on concrete piers. Each base plate measured 103 cm (40.5 in) wide and 3.8 cm (1.5 in) thick and were bolted to the concrete footing with a pair of steel anchor rods 3.5 cm (1.375 in) in diameter. We studied this failed water tower in detail as water towers will be included in the updated version of the EF-scale.

High winds toppled the water tower to the northeast as the tornado passed. Anchor rods broke and, in some cases, were pulled upward as much as 76 cm (30 in) from the concrete piers. Refer to Figure 22.

The current consensus of opinion among the ASCE/SEI/AMS committee is that toppled water

towers would have an estimated failure wind speed of around 58 m/s (130 mph).

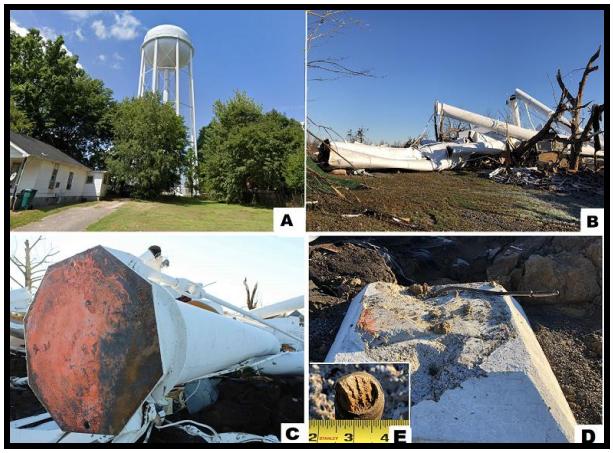

Fig. 22. Mayfield water tower: A) Google Street View before the tornado, and B) collapsed water tower after the tornado, C) hexagonal steel bottom plate of leg, D) broken anchor bolts and concrete pier cap, and E) cup-cone fracture of anchor bolt.

4. SUMMARY

A violent tornado struck Mayfield and Dawson Springs, KY on December 10, 2021, as part of a long-track tornado that began in extreme northwestern Tennessee and traveled through western Kentucky. Total path length was 267 km (165.7 miles). The forward speed of the tornado averaged 27 m/s (60 mph).

More than one dozen different DIs were studied in detail and DoDs chosen in order to estimate failure wind speeds in accordance with the 2006 EF-scale document. We also paid particular attention to damaged church buildings and the water tower as these items will be added as new DIs in the updated version of the EF-scale. The NWS rated this tornado as a high-end EF 4. The tornado damage rating might have been higher had more wind resistant structures been encountered. Also, the fast forward speed of the tornado had little "dwell" time of strong winds over a building and thus, the damage likely would have been more severe if the tornado were slower.

5. ACKNOWLEDGEMENTS

The author would like to thank Mr. C. S. Kirkpatrick for reviewing this paper.

6. REFERENCES

Wind Science and Engineering Center (WSEC), 2006: The Enhanced Fujita Scale, 111 pp. Available online at: https://www.spc.noaa.gov/efscale/ef-ttu.pdf