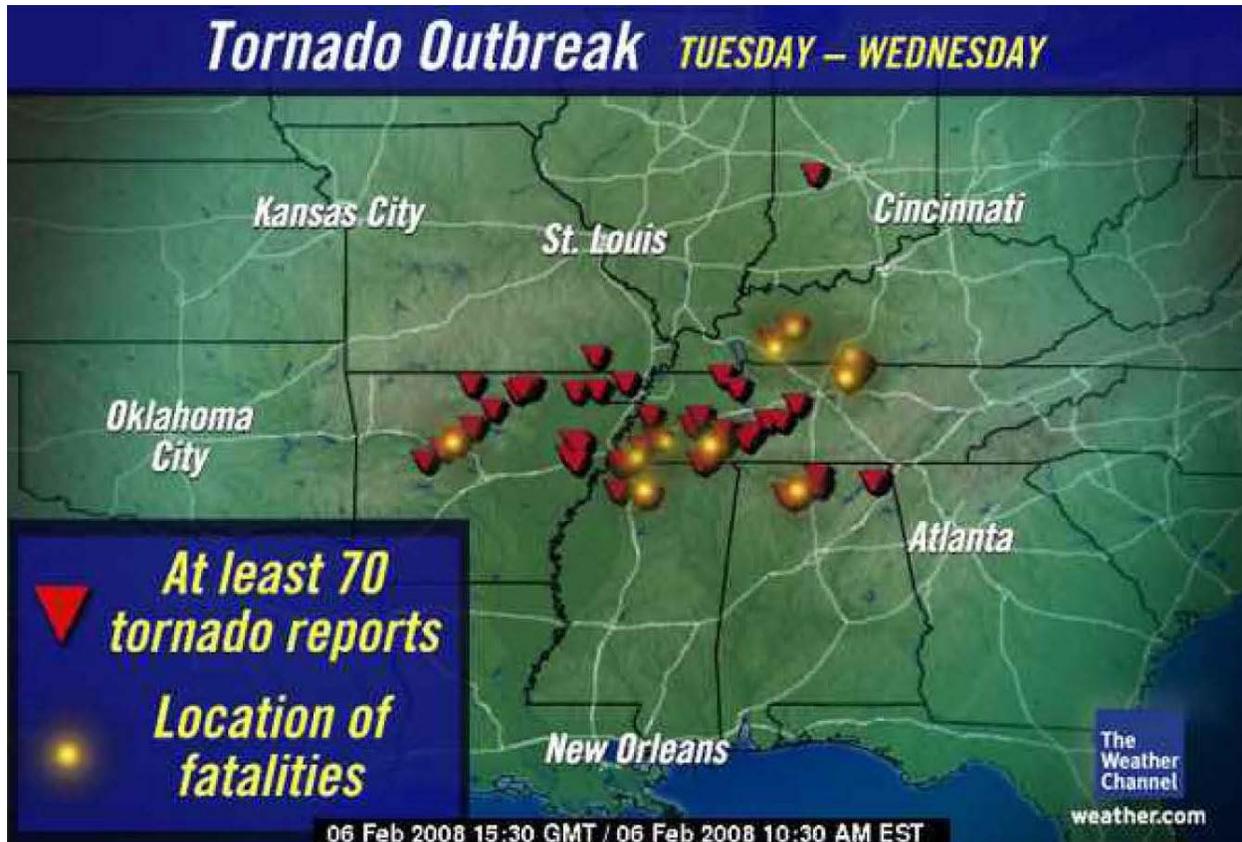


Tornado Damage Documentation – Using the EF-Scale

Super Tuesday Tornadoes
Alabama, Arkansas, Kentucky & Tennessee
February 5 & 6, 2008



PhotoCredit: The Weather Channel

August 2, 2010

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FOREWORD

In 1971, Dr. T. Theodore Fujita introduced a research paper titled, *Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity*. The paper categorized tornadoes by intensity and area, with a scale divided into six categories:

- F0 (Gale)
- F1 (Weak)
- F2 (Strong)
- F3 (Severe)
- F4 (Devastating)
- F5 (Incredible)

Dr. Fujita's goals in his research in developing the F-Scale were:

- Categorize each tornado by its intensity and its area
- Associate wind speed ranges with each category of tornado

However, over the years, the F-Scale has revealed weaknesses and misuses:

- It was based on cursory description of damage.
- There was no recognition in difference in construction.
- Was difficult to apply with no Damage Indicators (differentiation between construction types).
- Was based on the worst damage.
- Overestimated wind speeds for category greater than F3.
- Was too reliant on associated wind speeds.
- Oversimplified the damage.
- Did not recognize weak structures.

To address these issues and shortcomings of the F-Scale, research engineers from Texas Tech University's Wind Science and Engineering Research Center, along with over forty professionals from the engineering and meteorological communities, participated in a forum and expert elicitations to develop the *Enhance Fujita Scale (EF-Scale)*. With a directive to continue to support and maintain the original tornado database, the EF-Scale offers the following improvements:

- Enhances description of damage with examples and photos, including structures and vegetation.
- Assigns wind speed estimates based on level of damage.
- EF Scale assignment is based on more than one structure, if available.
- Develops a PC-based expert system.
- Develops training materials.
- Maintains current tornado database.

- Requires surveys to include data related to path width, basis for damage assignment, latitude/longitude of the path, and survey team names and hours spent in survey.

The EF-Scale utilizes 28 Damage Indicators (DI), and with each Indicator there are Degrees of Damage (DOD) that are associated with an expected estimate of wind speed; a lower boundary of wind speed; and an upper boundary of wind speed that could produce the observed damage. Photographs are included in the EF-Scale to assist the investigator.[1]

The Super Tuesday Tornadoes were the second major storm outbreak, since the February 2007 Storms in Central Florida, to be investigated by Texas Tech Researchers using this new EF-Scale system.

Acknowledgements: Thanks are due to Kishor C. Mehta, P.E., Ph.D., Wind Science and Engineering Research Center (WISE), Professor rtd., for his technical review; and Ms. Amber Reynolds, IGERT Fellow (NSQ FT Grant #0221688), Ph.D. Candidate, for her field assistance and contributions to this report.

Opinions expressed in this report are solely those of the senior author and not necessarily those of the Wind Science and Engineering Research Center, Texas Tech University or the National Science Foundation.

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- Oklahoma and Kansas 1998, tornadoes (member of FEMA MAT Team)
- Tuscaloosa, Alabama 2000, tornado
- Happy, Texas 2002, tornado
- Ohio 2002 tornadoes
- Southwest Missouri and Oklahoma City tornadoes, 2003
- Hurricane Ivan, Pensacola, Florida in September, 2004
- Hurricane Katrina, 2005 (member of FEMA MAT Team)
- Evansville, Indiana 2005 Tornado
- Florida Tornadoes, 2007
- The Super Tuesday Outbreak - Tennessee tornadoes, 2008
- Hurricane Ike, 2008 (member of FEMA MAT Team)

His work further includes collaboration with FEMA in the writing of FEMA 320: *Taking Shelter from the Storm*, FEMA 361: *Design and Construction Guidance for Community Shelters*, and FEMA 342: *Building Performance Assessment Report of Midwest Tornadoes of May 3, 1999*, co-authorship of FEMA Publication 549: *Hurricane Katrina in the Gulf Coast, Observations, Recommendations, and Technical Guidance*, co-authorship of FEMA Publication 757: *Hurricane Ike in Texas and Louisiana*, and co-authorship of the 2008 updates to FEMA 320 and FEMA 361.

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ABSTRACT

On February 5, 2008, when voters in 24 U.S. states were voting in the Super Tuesday Presidential Primary Elections, a massive storm system containing numerous supercells and 87 reported tornadoes raked across nine states producing 57 fatalities in the states of Arkansas, Alabama, Tennessee, and Kentucky. It was the deadliest outbreak in both Tennessee and Kentucky since the 1974 Super Outbreak. According to the National Weather Service (NWS), the outbreak tornado Watches and Warnings averaged 17 minutes. Fifty-four deaths were residential-related with 36 of those occurring in manufactured housing. Three deaths were recorded to have occurred in a Memphis commercial building. No “Safe Places” (hardened safe rooms) were found at the death scenes, though eight deaths occurred where hardened shelters were available within ½ mile or less. The NWS interviews found a general ambivalence of the public with regard to the anticipated severity of a winter tornado.

Most all of the deaths and destruction were related to residential structures and occurred during the night in generally forested areas. Residential structures routinely fail at lower wind speeds than professionally designed structures that include safety factors. The emphasis of this investigation was therefore directed at damaged commercial structures with the expectations of finding different types of buildings (Damage Indicators and Degrees of Damage per the EF Scale). Two specific storms were studied, the EF-2 that struck northeast Mississippi and southwest Memphis, and the EF-4 storm that struck Jackson, Tennessee. In the EF-2 tornado, three large tilt-up concrete warehouses, a large shopping mall, and a large airplane hangar were studied. Excepting the shopping mall (which is believed to have been on the periphery of the tornado) damage to the other buildings was exceptional and led the investigators to believe that damage was the result of wind speeds in excess of an EF-2 tornado.

The EF-4 tornado first struck Union University on the north side of I-40 in Jackson, Tennessee. The damage was minimal at the new academic buildings, but progressed to devastate the lightly constructed, apartment style residence hall buildings. As the storm exited the campus, it produced significant damage to a two-story bank building. The end of the major damage concluded at an assisted living center, a total path length of 2 miles. The assisted living center was a light, wood-frame building consisting of multiple wings of varying dates of construction. One wing was destroyed by the storm, and other portions of the buildings exhibited roofing and cladding damage. Through the use of the new Enhance Fujita Scale, the researchers were able to associate wind speeds to each area of damage based upon the new Damage Indicators (DI) and related Degrees of Damage (DOD). The academic buildings and the bank building were much easier to associate damage to a moderate tornado wind speed. However, considering the resistance and safety margins of residential construction, it is believed that the storm descended upon the University campus producing EF-2 damage at the academic buildings, produced EF-4 damage upon touch-down at the University residential complex, then began to lift producing EF-2 damage, and finally dissipated as an EF-1.

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1.0 The Event

On Tuesday, February 5, 2008, the Nation was focused on the Super Tuesday Presidential Primary Elections being held in 24 U.S. states. The outcome of these primaries would ultimately determine the eventual Democratic Presidential Candidate, either Barack Obama or Hillary Clinton. Though the primaries would prove to be nation changing, the 87 tornadoes that were produced by the supercell on the Super Tuesday Outbreak affected nine states, and produced 57 fatalities in the States of Alabama, Arkansas, Tennessee, and Kentucky. All fatalities were caused by storms rated from EF-2 to EF-4. Five EF-4 tornadoes were recorded in this event: two in Alabama, one in Arkansas, and two in Tennessee. "It was the deadliest outbreak in both Tennessee and Kentucky since the 1974 Super Outbreak." [2] Most of the deaths occurred at nighttime in rural and residential areas shadowed by forests. Thirty-six of those residential deaths occurred in manufactured housing. As a part of their *Service Assessment Report*, the National Weather Service (NWS) determined that all areas of these states experiencing tornadoes were covered by Watches and Warnings with an average lead time of 17 minutes, which upon investigation seemed adequate. As a part of their research and assessment, they determined that many fatalities occurred as the result of either not seeking shelter or not having a "Safe Place" or a hardened shelter. Eight separate deaths occurred when hardened shelters were within 100 yards to ½ mile away. [3] The *Service Assessment Report* attributed the number of fatalities to the following:

- Sixty-three percent of the fatalities occurred in manufactured homes.
- Most of the fatalities occurred at night.
- Most of the areas affected by the deadly tornadoes were heavily forested.
- Many people interviewed acknowledged that they minimized the threat of this early February outbreak because of their perception that it was outside the "traditional" tornado season.
- Over 50 percent of the people interviewed indicated it was too early in the year for tornadoes and, as a result, minimized the threat. [3]

The storm system produced several destructive tornadoes in heavily populated areas, most notably in the Memphis metropolitan area, an EF-2, and in Jackson, Tennessee, an EF-4. [2]. Since residential structures routinely fail at lower wind speeds than professionally designed structures, the emphasis of the investigation was directed at damaged commercial structures with the expectation of finding different types of buildings. It is the destruction to commercial buildings in these two metropolitan areas that was the subject of this investigation. The damage documentation of the destruction produced by these tornadoes was evaluated using the newly adopted *Enhanced Fujita Scale* that associates the construction type and building types of 28 Damage Indicators (DI). Each DI has numerous Degrees of Damage (DOD), with each DOD in each DI category given an expected estimate of wind speed, a lower bound of wind speed, and an upper bound of wind speed. [4] **Figures 1.1 through 1.3** were extracted from the NWS training session *Lesson 1: Introducing the Enhanced Fujita Scale*. [5] **Figure 1.1** tabulates the 28 Damage Indicators; **Figure 1.2** shows an example of Degrees of Damage for a Single Family Residence; and **Figure 1.3** correlates the EF Scale wind speeds with the original Fujita Scale speeds. This report does not contain all types of construction, nor does it contain examples of all

degrees of damage. However, this storm report will provide additional examples of degrees of damage which can be included in the EF Scale Report. Building types [Damage Indicators (DI)] and associated levels of damage [Degree of Damage (DOD)] are used in this report and are identified in the EF Scale Report.[4]

28 Damage Indicatorsq ftor EF-Scale		
DI No.	Damage Indicator (DI)	<i>Use</i>
1	Small Barns or Farm Outbuildings (SBO)	<i>Residential</i>
2	One – Two-Family Residences (FR12)	
3	Manufactured Home – Single Wide (MHSW)	
4	Manufactured Home – Double Wide (MHDW)	
5	Apartments, Condos, Townhouses [3 stories or less] (ACT)	
6	Motel (M)	<i>Commercial & Retail Structures</i>
7	Masonry Apartment or Motel Building (MAM)	
8	Small Retail Building [Fast Food Restaurant] (SRB)	
9	Small Professional Building [Doctor’s Office, Branch Bank] (SPB)	
10	Strip Mall (SM)	
11	Large Shopping Mall (LSM)	
12	Large, Isolated Retail Building [K-Mart, WalMart] (LIRB)	
13	Automobile Showroom (ASR)	
14	Automobile Service Building (ASB)	<i>Schools</i>
15	Elementary School [Single Story; Interior or Exterior Hallways] (ES)	
16	Junior or Senior High School (JHSH)	<i>Professional Buildings</i>
17	Low-Rise building [1-4 Stories] (LRB)	
18	Mid-Rise building [5-20 Stories] (MRB)	
19	High-Rise Building [More than 20 Stories] (HRB)	
20	Institutional Building [Hospital, Government or University] (IB)	<i>Metal Buildings & Canopies</i>
21	Metal Building Systems (MBS)	
22	Service Station Canopy (SSC)	
23	Warehouse Building [Tilt-up Walls, or Heavy Timber Const] (WHB)	<i>Towers/Poles</i>
24	Transmission Line Towers (TLT)	
25	Free-Standing Towers (FST)	
26	Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)	<i>Vegetation</i>
27	Trees: Hardwood (TH)	
28	Trees: Softwood (TS)	

Figure 1.1. EF Scale 28 Damage Indicators.[5]

DOD to Wind Speed to EF-Scale

DOD	Damage Description – Framed House	EXP	LB	UB
1	Threshold of visible damage	63	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 or outward; failure of porch or carport	97	81	116
5	Entire house shifts of 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 collapsed	170	142	198
10	Destruction of engineered and/or well constructed residence; slab swept clean	200	162	220



Expected wind 97 mph

Figure 1.2. Example, EF Scale Degree of Damage Single Family Residence (FR12) [5]

F-Scale Converted to EF-Scale

F Scale	Wind Speed	EF-Scale	Wind Speed
F0	45-78	EF0	65-85
F1	79-117	EF1	86-109
F2	118-161	EF2	110-137
F3	162-209	EF3	138-167
F4	210-261	EF4	168-199
F5	262-317	EF5	200-234

Wind speeds in mph, 3-second gust

Figure 1.3. F-Scale to EF-Scale Conversion Table.[5]

2.0 SYNOPTIC ENVIRONMENT for the Super Tuesday Tornado Outbreak

Atmospheric conditions in the outbreak region prior to the outbreak reflected an unstable environment conducive to the formation of severe storms. A powerful, low-pressure system and cold front at the surface provided a lifting mechanism to initiate the storms. **Figure 2.1** shows a surface analysis from the early morning hours of February 6, 2008. The area ahead of the cold front shows the contrast of a warm, moist airmass from the Gulf of Mexico. Overnight, the unusually high temperatures and dew points remained which allowed for instability in the atmosphere to continue. Aloft, a split in the jet stream (see **Figure 2.2**) over the middle South created enhanced, upper-level diffluence which provided sustenance for long-lived supercell thunderstorms once they were initiated.[3] **Figure 2.3** shows an absolute vorticity maximum at 500 mb located over central Oklahoma which suggests large levels of rotation in the middle of the atmosphere near the location of the outbreak. This model output is also verified by actual observations at the surface (**Figure 2.1**) and 300 mb (**Figure 2.2**). In Tennessee, winds at the surface were from the south; however, at 300 mb, 90 knot (104 mph) winds were from the west southwest, which shows strong wind shear in the atmosphere.

The combination of moisture, a source of lift, and wind shear created an environment conducive to the formation of tornadic supercells, focused around Memphis, Tennessee, on the afternoon of the outbreak. The supercell that produced damage at the Memphis International Airport and nearby warehouses continued to propagate northeast, where it continued to strengthen in intensity. **Figure 2.4** shows a radar composite of the same supercell that hit Jackson, Tennessee, later in the evening.

The ‘Super Tuesday’ outbreak produced 87 tornadoes that crossed six states including Mississippi, Arkansas, Tennessee, Alabama, Kentucky, and Missouri, with 57 fatalities recorded in all but Mississippi and Missouri. **Figure 2.5** shows approximate tornado tracks based on radar imagery and storm reports as well as the number of fatalities by state.

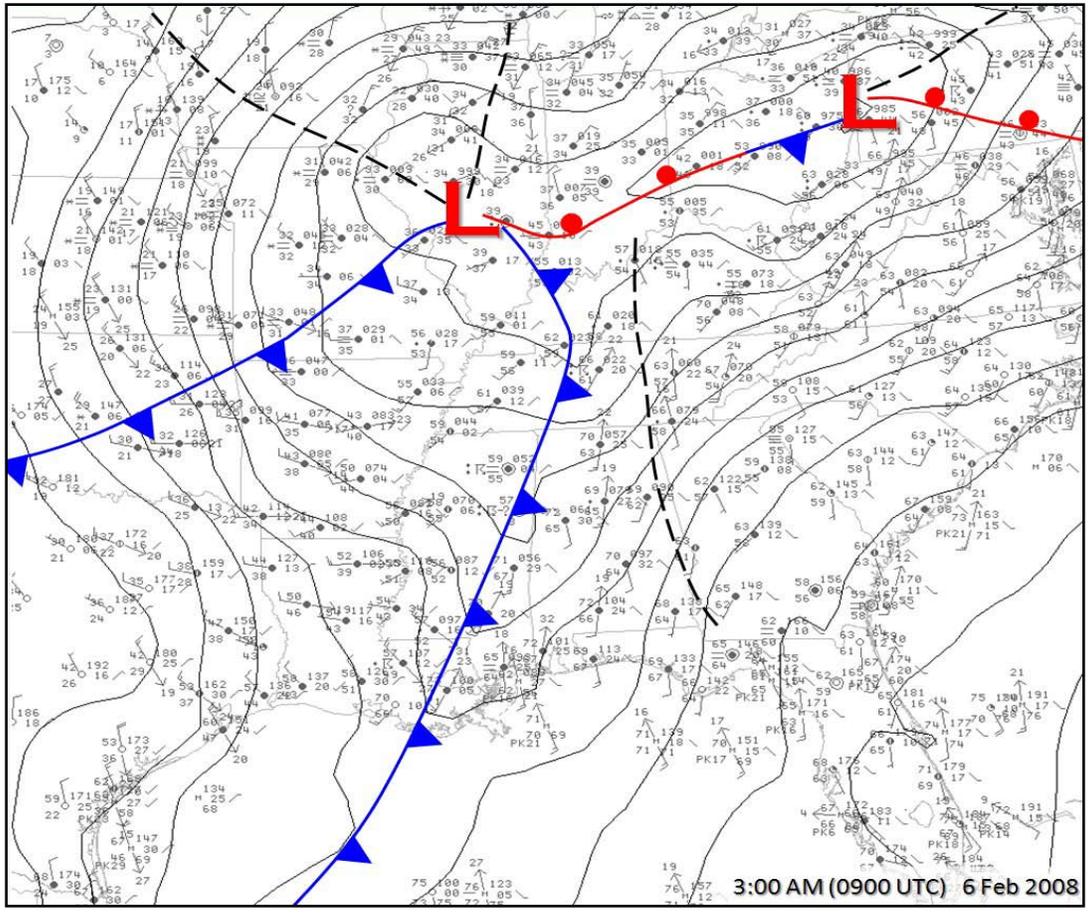


Figure 2.1. A surface map at 0900 UTC, 6 February 2008 (3 AM CST), shows a cold front moving into northwest Alabama, along with 60+ degree dew points ahead of the front .[6]

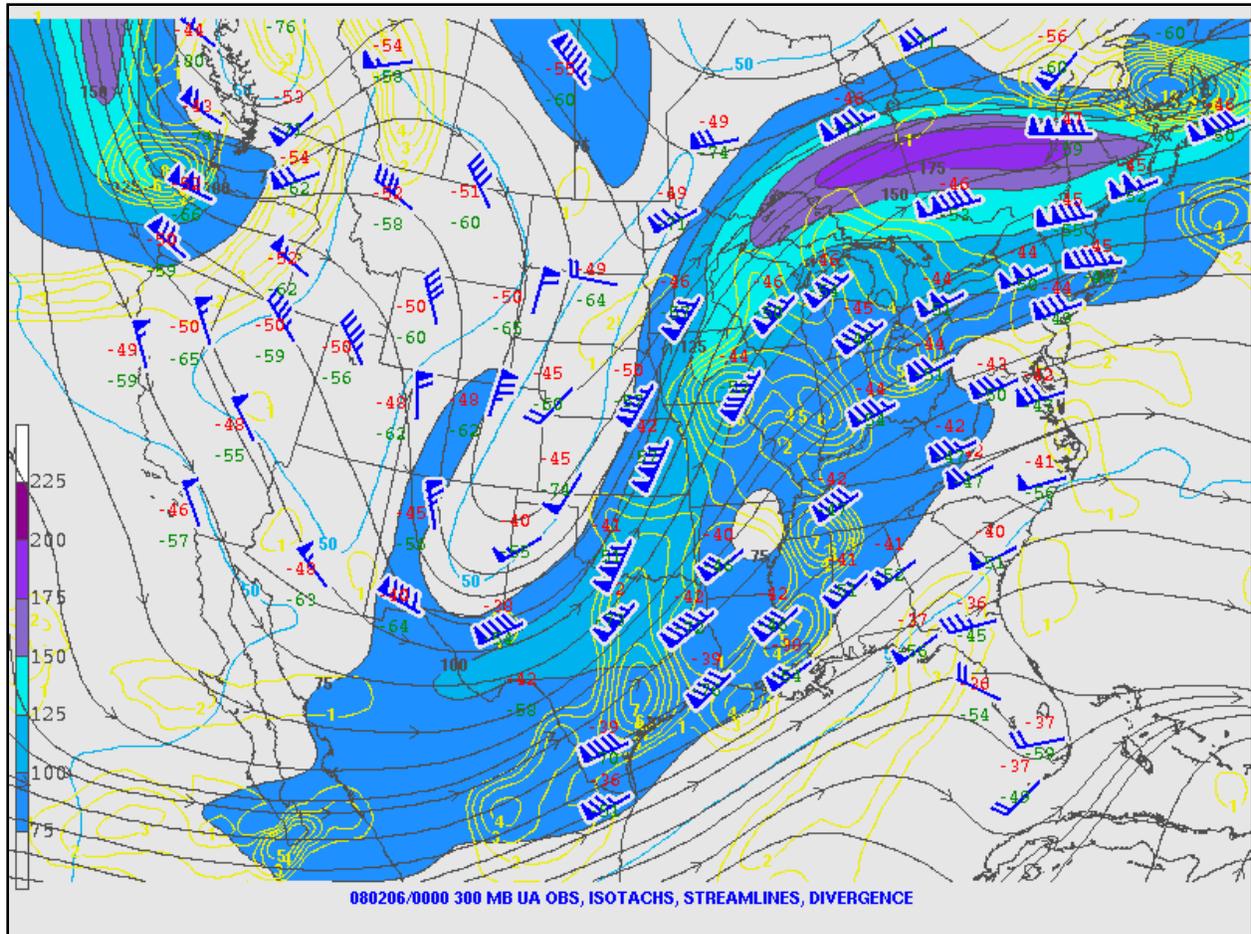


Figure 2.2. A 300 mb pressure map showing wind speeds, streamlines, and contoured divergence for the United States at 0000 UTC 6, February 2008 (6:00 PM CST 5 February 2008). Note the split in the jet stream to the west of Tennessee.[7]

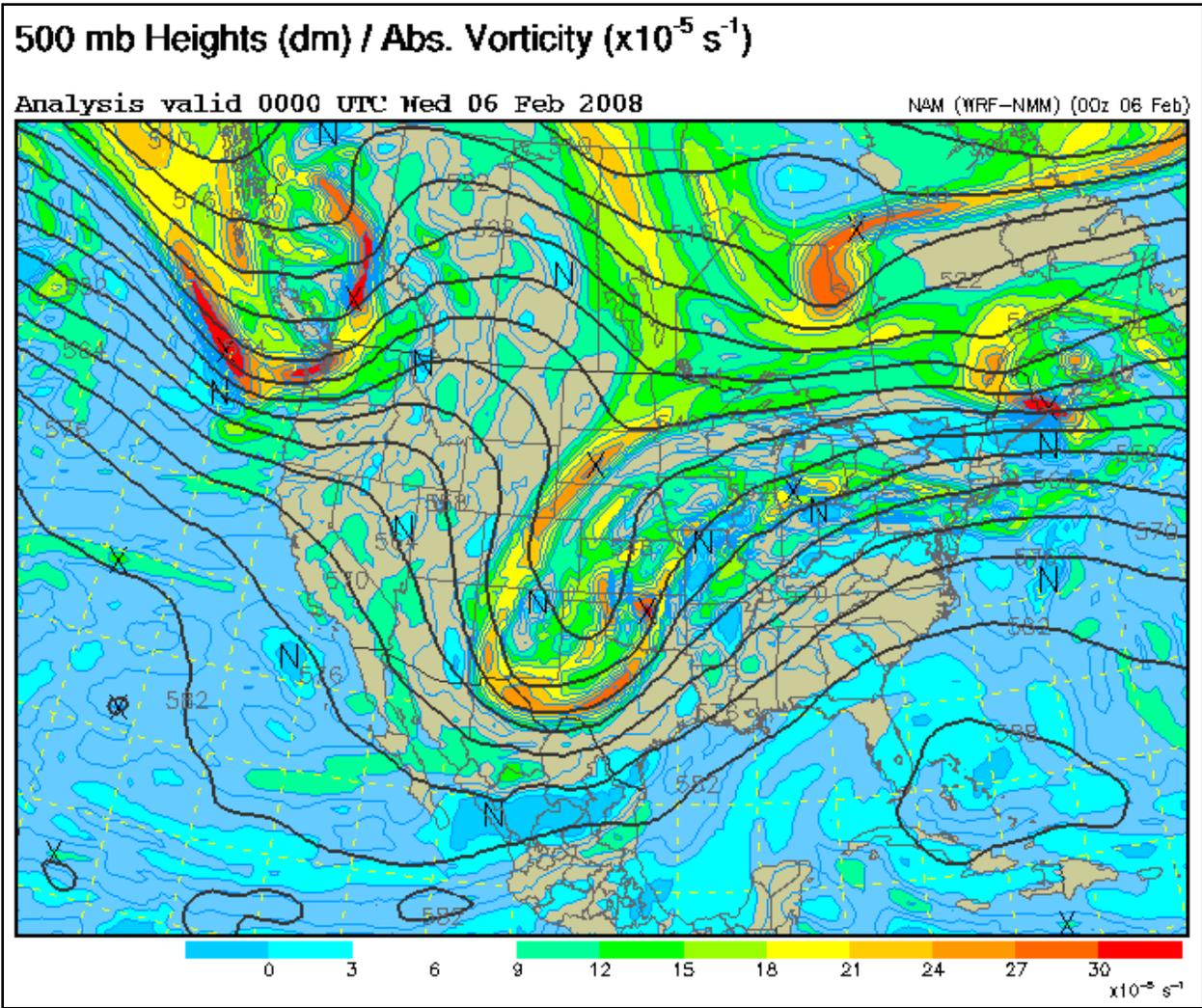


Figure 2.3. An Eta model 500 mb pressure map showing heights (in decameters) and contours of absolute vorticity. Note the absolute vorticity maximum over central Oklahoma.[7]

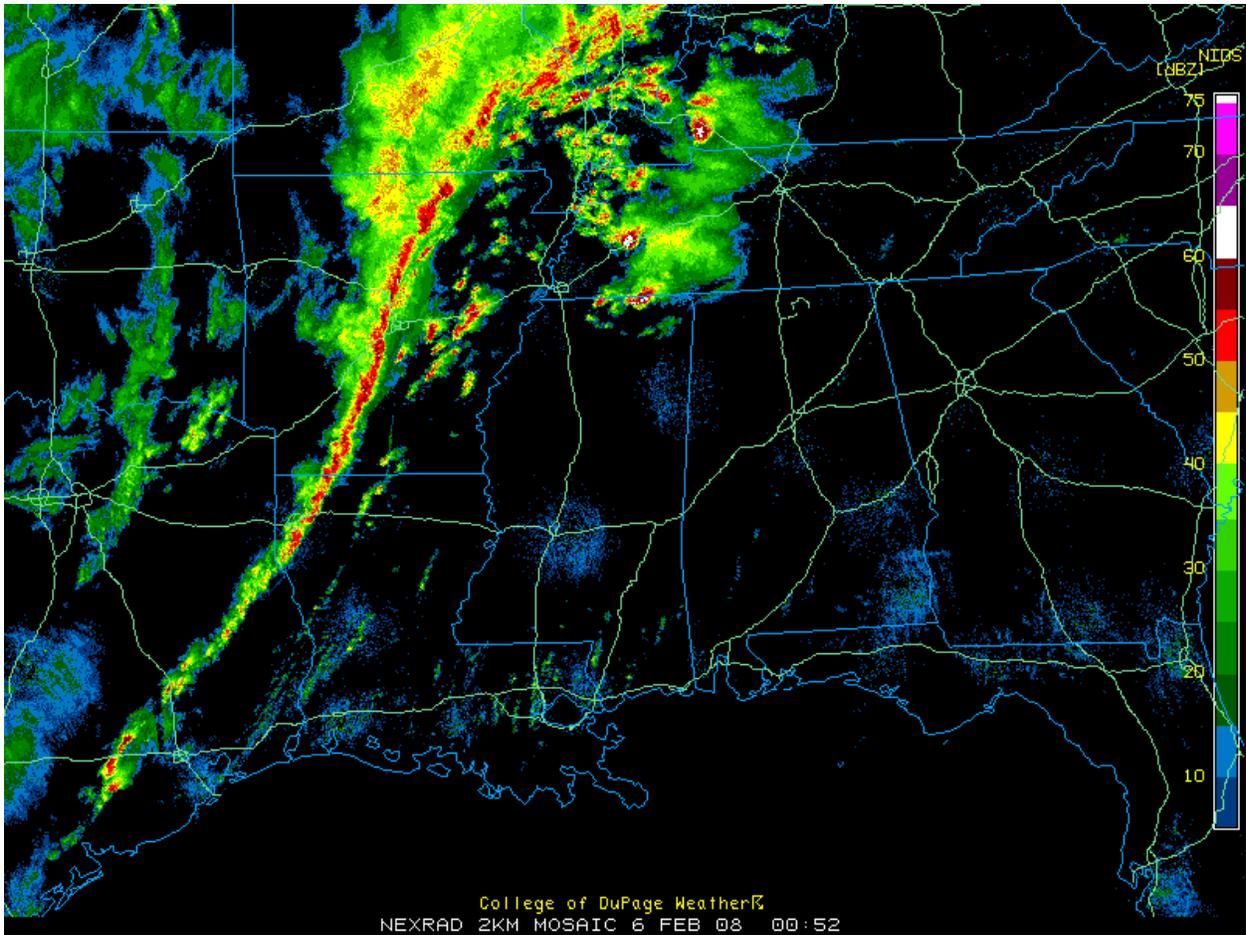


Figure 2.4. A radar composite of the southern Mississippi Valley at 0052 UTC, 6 February 2008 (6:52 PM CST, 5 February 2008). The supercell of interest is the one with 60 dBZ reflectivity crossing I-40 in western Tennessee, where the city of Jackson was hit.[8]

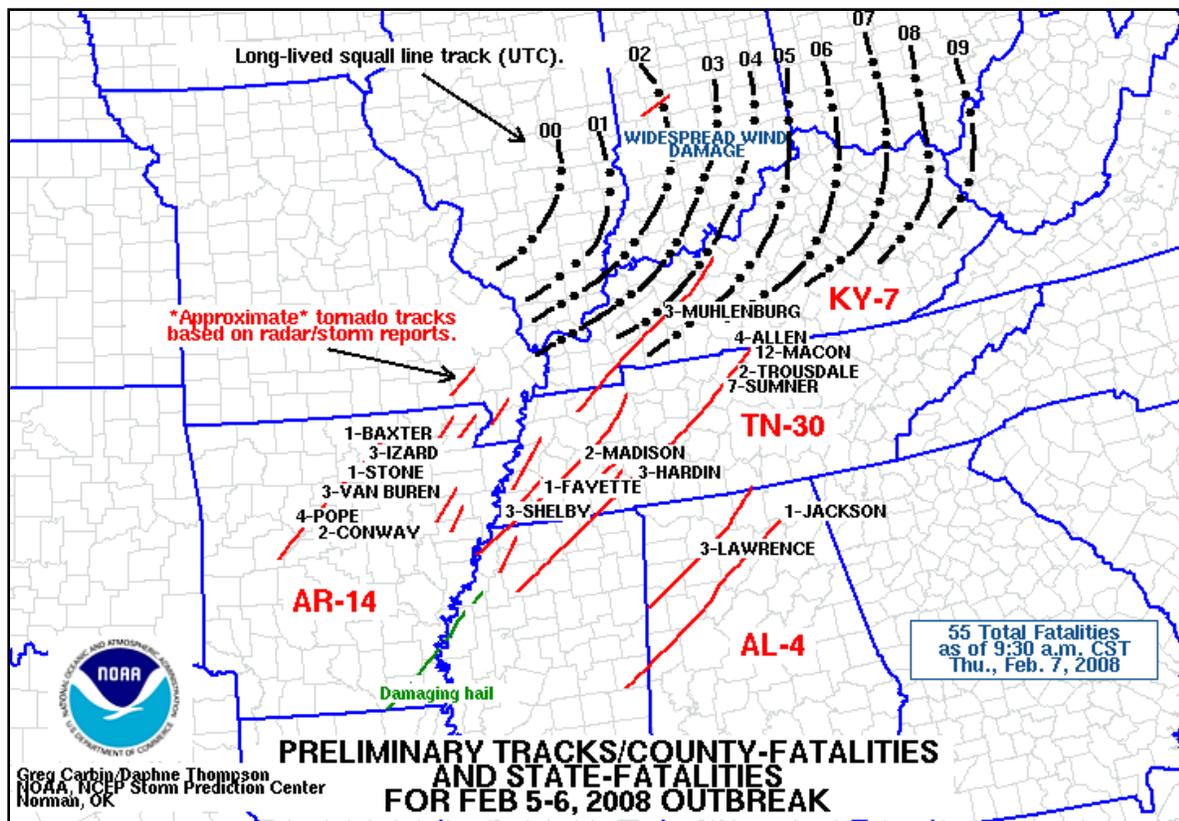


Figure 2.5. Preliminary tornado tracks and fatalities by state.[9]

3.0 METROPOLITAN MEMPHIS, TENNESSEE

Numerous tornadoes ranging in intensity from EF-2 to EF-4 struck the northeast portion of Mississippi and the southwest portion of Tennessee on the evening of February 5, 2008. When the supercell systems crossed the state line with Kentucky near Nashville, it left behind 31 fatalities and massive devastation (refer to **Figure 2.5**). Most of the fatalities in all the affected states were related to failures of residential structures. According to the National Weather Service (NWS), supercells began developing over northwest Mississippi near the town of Southaven where it destroyed two massive tilt-up concrete warehouses on Airport Industrial Drive and then crossed State Line Highway, and continued in a northeasterly direction destroying the large Southaven Distribution tilt-up concrete warehouses. The EF-2 continued moving northeastward where it struck a warehouse in Shelby County killing three, then moved to threatened the Memphis Airport complex where it removed a portion of the hangar roof at Pinnacle Airlines at the Memphis Airport, and then finally striking a glancing blow to the Hickory Ridge Mall.[3] The NWS rated this tornado as an EF-2 (110-137 mph).[3] A map indicating both the EF-2 tornado across southwest Memphis and the EF-4 tornado along Interstate 40 at Jackson, Tennessee, is shown in **Figure 3.1**. The satellite image shown in **Figure 3.2** shows a closer view of the southwest Memphis tornado and those structures investigated.

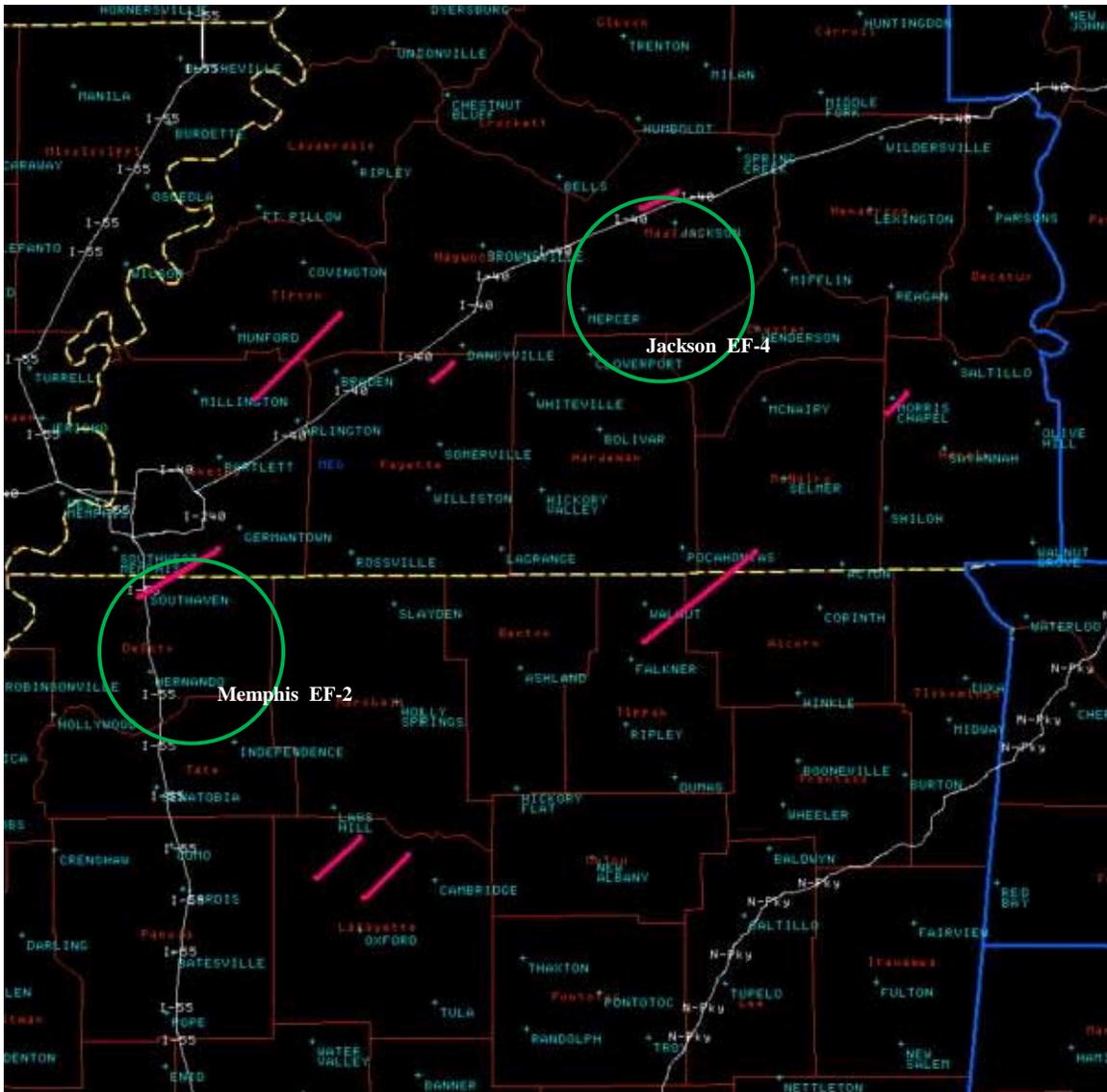


Photo Credit: NWS

Figure 3.1. Mississippi - Tennessee 2008 Tornado Track Map[10]



Map Courtesy of Google

Figure 3.2. EF-2 Tornado Path across northern Mississippi and southwest Memphis

3.1 Airport Industrial Drive Warehouses

The City of Memphis and the Memphis Airport is a distribution hub for FedEx Shipping. Hundreds of product manufacturers and distributors maintain a vast inventory of products in huge warehouses in the general vicinity of the airport to take advantage of favorable FedEx shipping rates. The EF-2 tornado that had formed in Southaven, Mississippi, and shown in **Figure 3.2** first struck a grouping of five tilt-up concrete warehouses located on Airport Industrial Drive, Southaven, Mississippi. Two of the five received extensive structural damage, Bound Tree Medical and Cooper Lighting, see **Figure 3.3**.

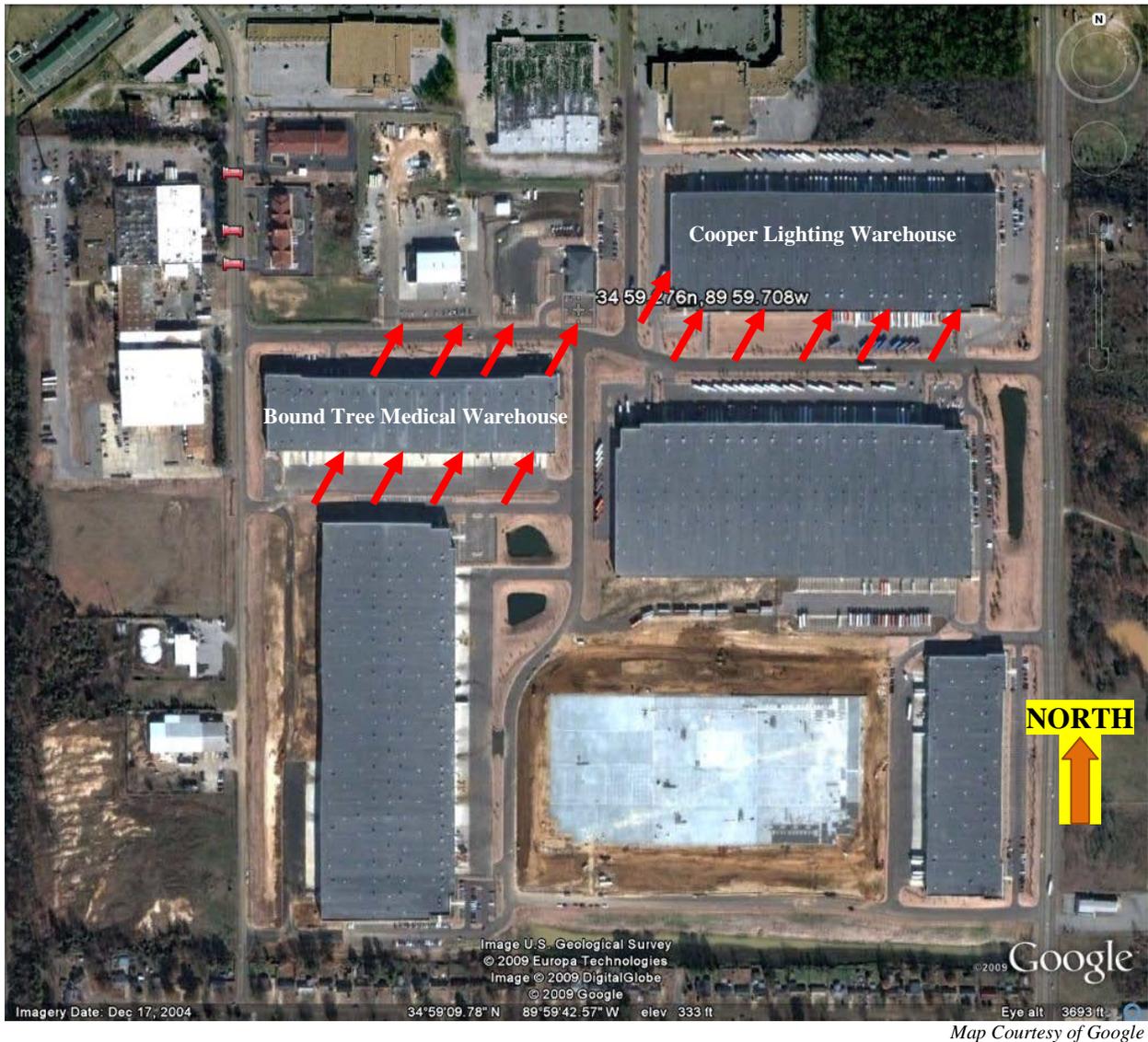


Figure 3.3. Airport Industrial Drive Warehouses (red arrows indicate direction of wind pressures)

3.1.1 Bound Tree Medical Warehouse

The Bound Tree Medical Warehouse is classified on the Scale as a DI 23 Warehouse Building with approximately 230,000 sq ft of floor area. The following description is a classic description of a DI 23 building: The warehouse structure was constructed of 18 ft wide x 40-45 ft. tall and 7 ½ in thick tilt-up concrete walls. The roof structure consisted of 48 in. x 40 ft. long deep joist girders supported by 10 in. x 10 in. tube section (TS) tube columns spaced on 30 ft. centers. The roof was further supported by 28 in. deep steel joists x 30 ft. long and spaced on 5 ft. centers. A steel deck was welded to the joists, and a single-ply mechanically attached rubber or EPDM membrane was mechanically attached through the insulation board into the deck.

The mechanism of failure began with the loss of the coiling overhead doors along the entire length of the south side of the building, **Figure 3.4**, which allowed internal pressurization of the building which, coupled with the exterior uplifting pressures, lead to loss of the roofing, roof deck diaphragm, and finally the joists and most of the joist girders (see **Figure 3.5 thru 3.7**). This near total destruction of this facility was classified by the investigators as DOD 7 which relates to an expected EF-Scale wind speed varying from 150 mph to 160 mph, or a high speed EF-3.

The investigators paid specific attention to the manner in which the panels were laterally supported. The north and south panels were laterally supported at the ends of the joists using a ledger angle welded to embedded plates, and the joist seats were welded to the ledgers (see **Figure 3.8**). The east and west panels were supported by steel angles welded to the joist top chords and ledger angles welded to panel embed plates (see **Figures 3.9 & 3.10**). No interior concrete tilt-up panel shear walls or other types of wind bracing were observed. No panel-to-panel connections were observed since tall panels are subject to extreme shrinkage, thermal expansion, and contraction. However, the *Tilt-up Concrete Construction Guide*, ACI 551.1R-05 requires the designer “to meet structural requirements for wind and seismic loads.”[11]

The Bound Tree Medical Warehouse panel heights were visually broken by horizontal reveal joints, with the first occurring about 3 feet above the ground. According to ACI 551.1R-05, "Chamfers and reveal strips should have a consistent depth and angle. If a deeper reveal is required, its location and subsequent effect on the panel's structural performance should be considered because the reveal, regardless of how shallow, reduces the structural thickness of the panel."[11] A standard reveal detail taken from ACI 551.1R-05 is shown in **Figure 3.11**. The panel designer obviously understood the potential weakness of the reveal and designed short pieces of heavy gage wire to bridge the reveal. **Figure 3.12** shows that the reveal was the weak plane, and the panel failed uniformly along the reveal.

As seen in the above figures, the Bound Tree Medical Warehouse suffered near total destruction by the storm. The investigators determined that the design and construction appeared to be in accordance with normal practice for this type of warehouse. However, the structure lacked the redundancy that could have been provided by a more robust

lateral support system and a panel-to-panel interconnection system that could have allowed for shrinkage and thermal movement, but still have allowed the panels to react to loads collectively, rather than individually. This improved redundancy could have allowed the facility to perhaps resist winds approaching 180 mph.

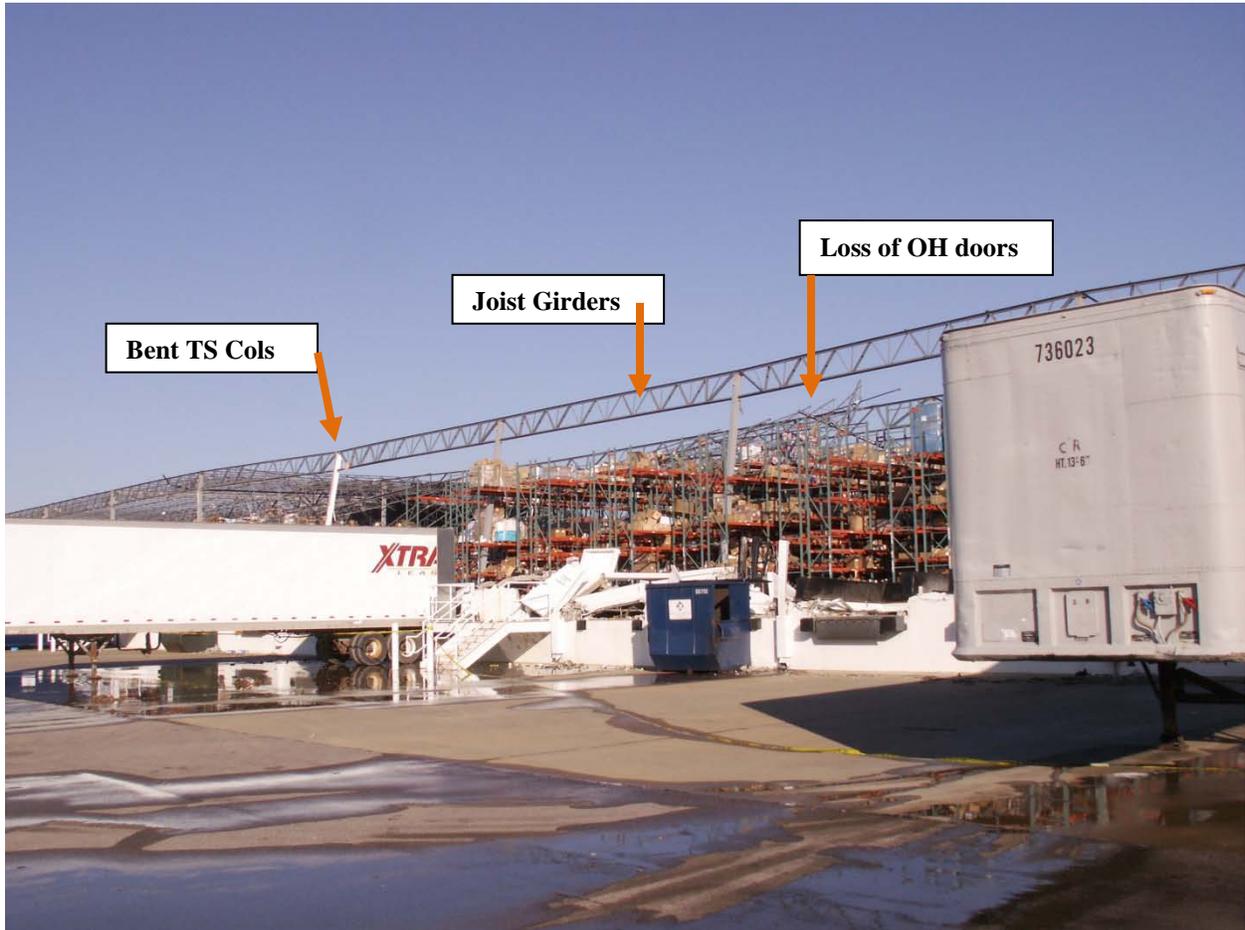


Figure 3.4. Overhead doors, roofing, and roof structure removed by windward, uplift, and internal pressures, DOD 7

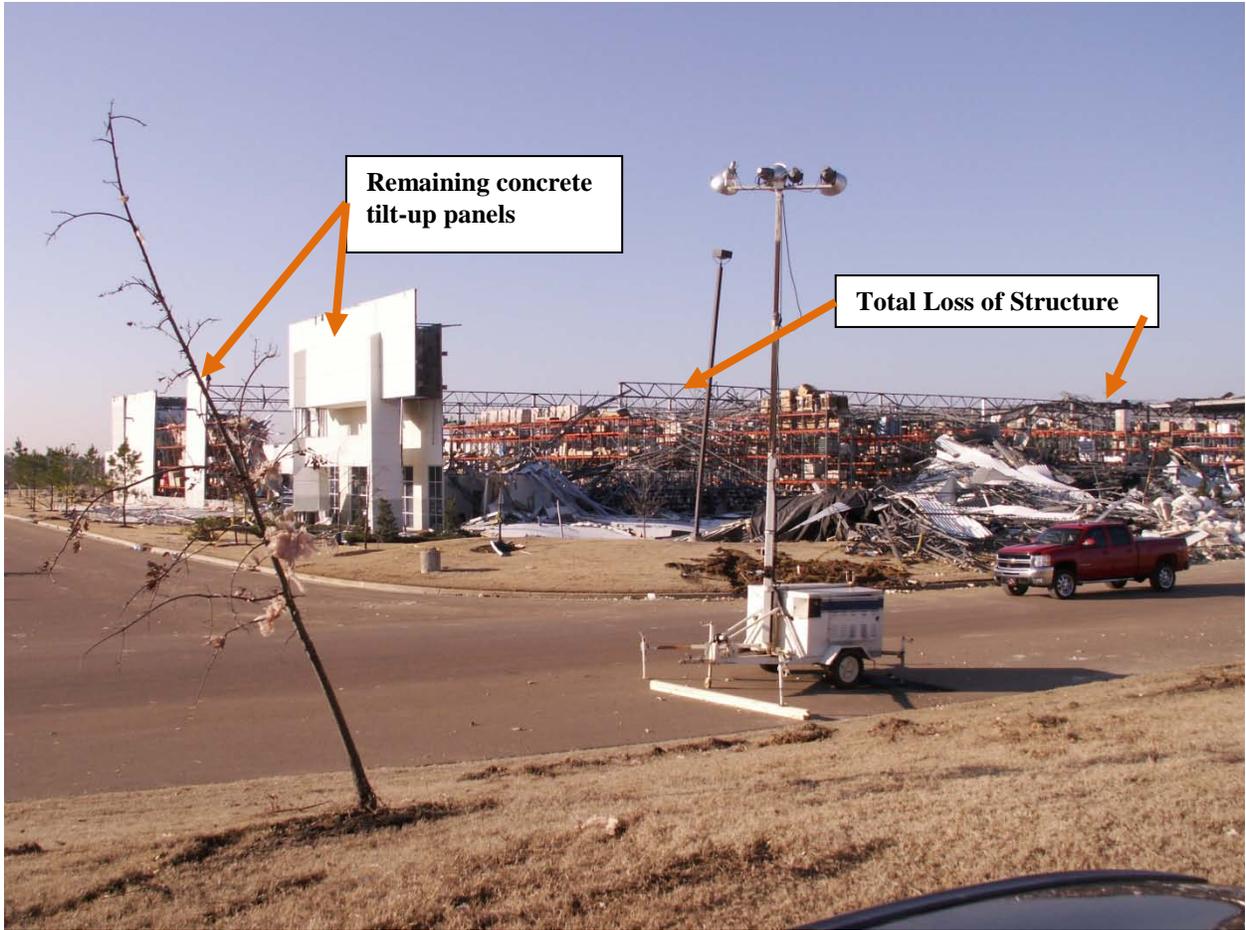


Figure 3.5. Near complete destruction of Bound Tree Medical Warehouse, DOD 7



Figure 3.6. Joists removed by storm and tube column bent, DOD 7

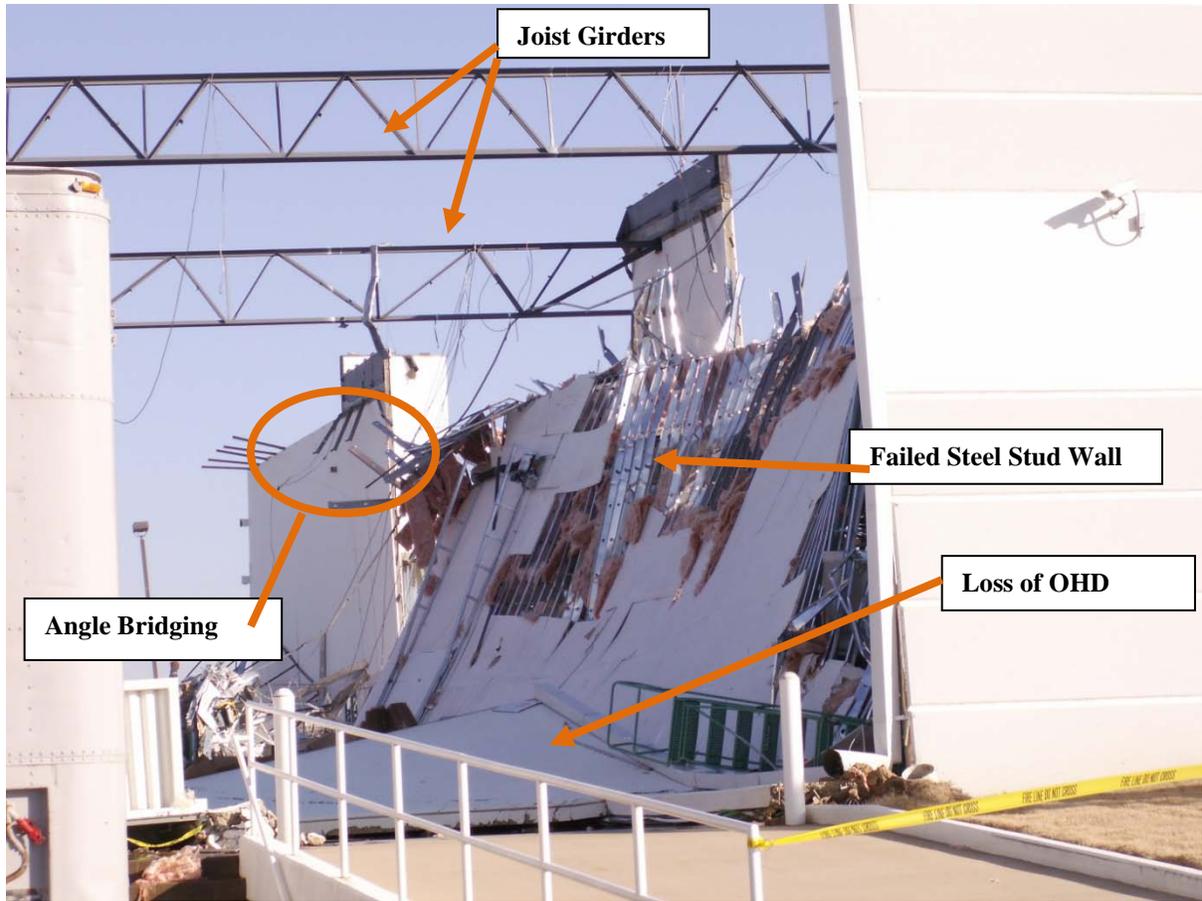


Figure 3.7. Joist girders to two remaining panels, DOD 7



Figure 3.8. Bar joist end bearing on tilt-up panels, DOD 7

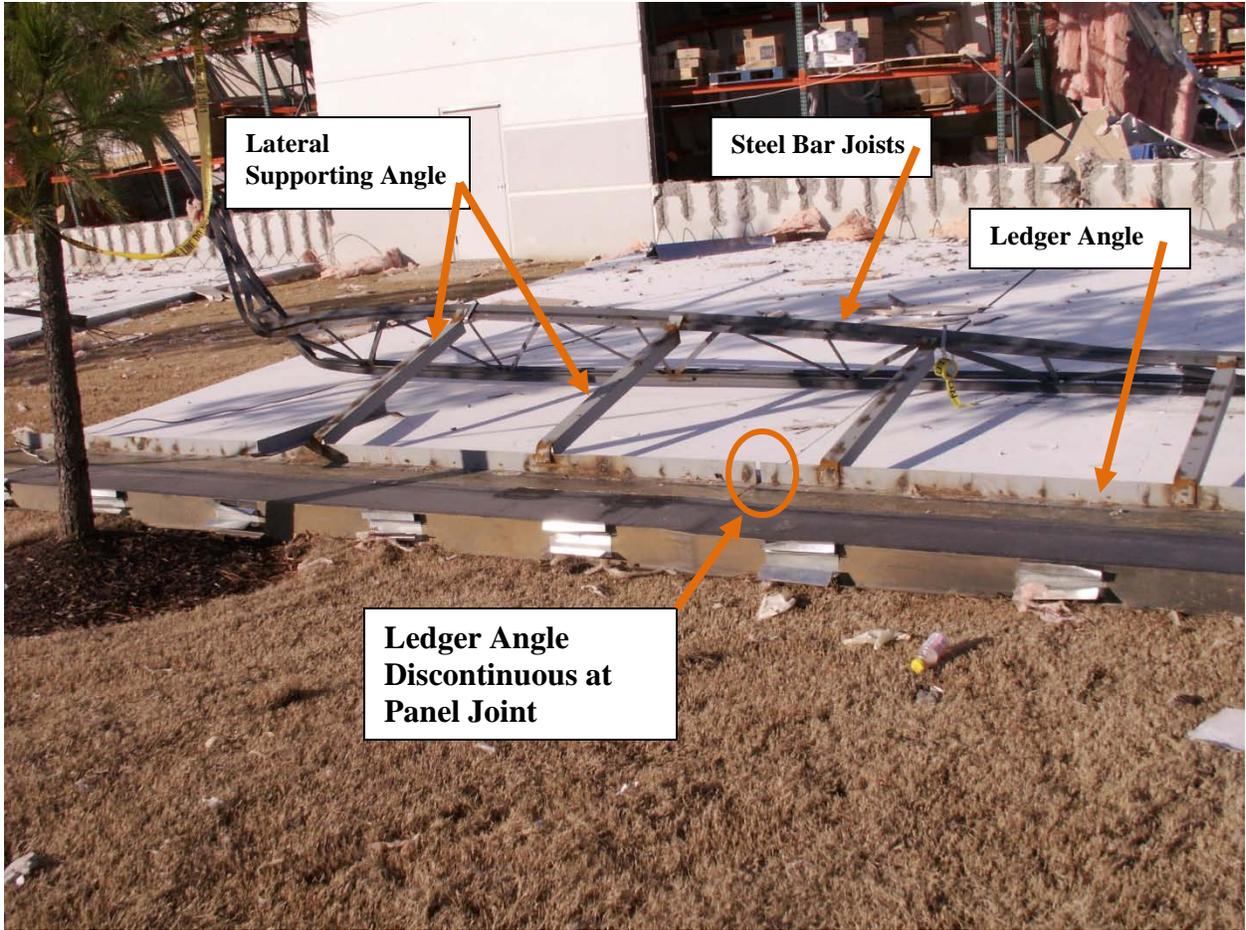


Figure 3.9. Panel lateral support provided by angles tied to joist top chord and ledger angle at panel, DOD 7

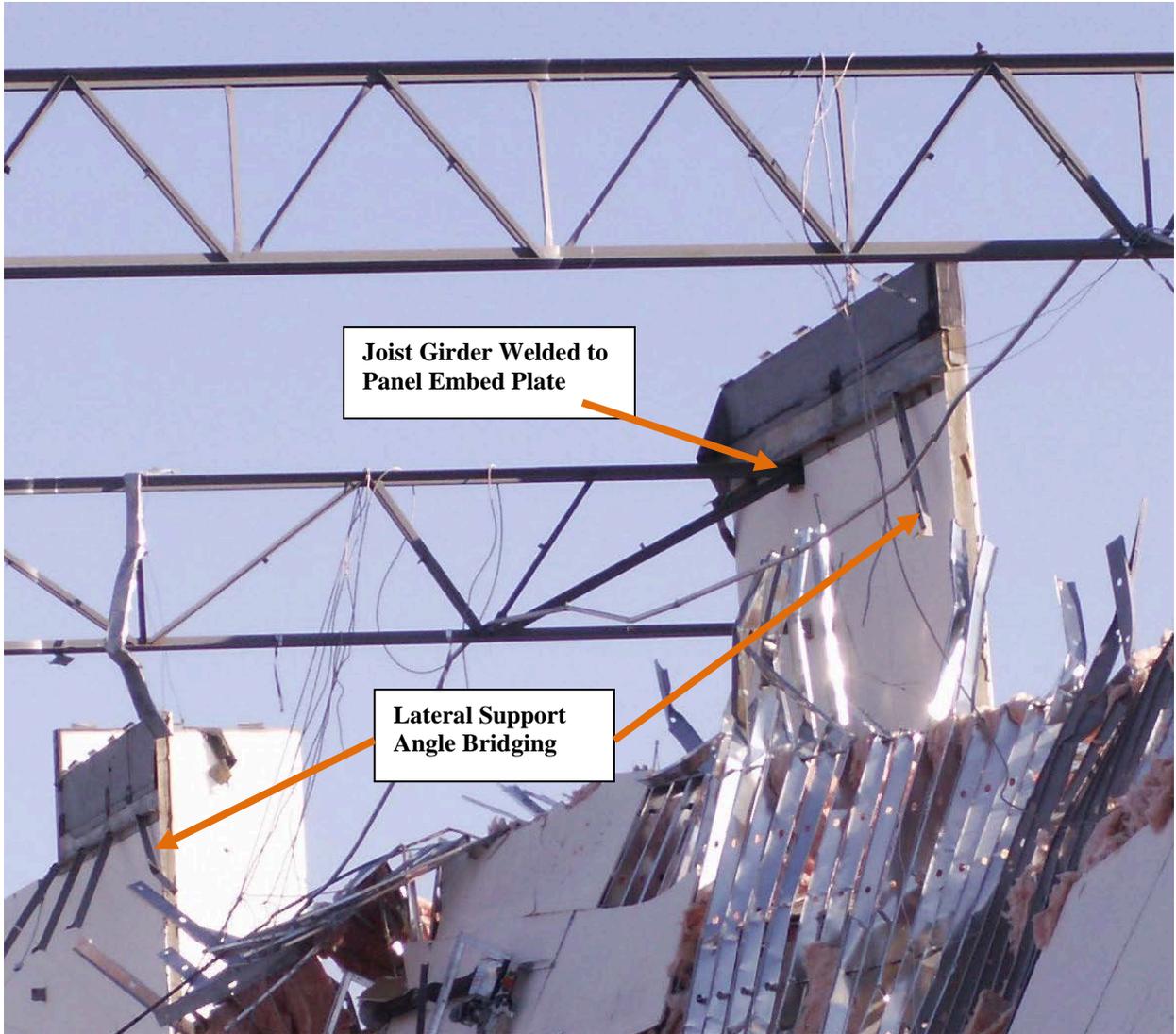


Figure 3.10. Joist girder connected to panel embed plate, DOD 7

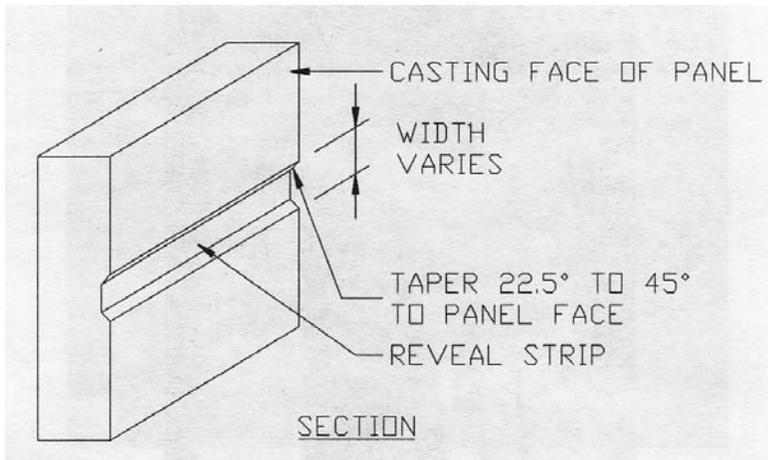


Figure 3.11. ACI recommended reveal strip [11]

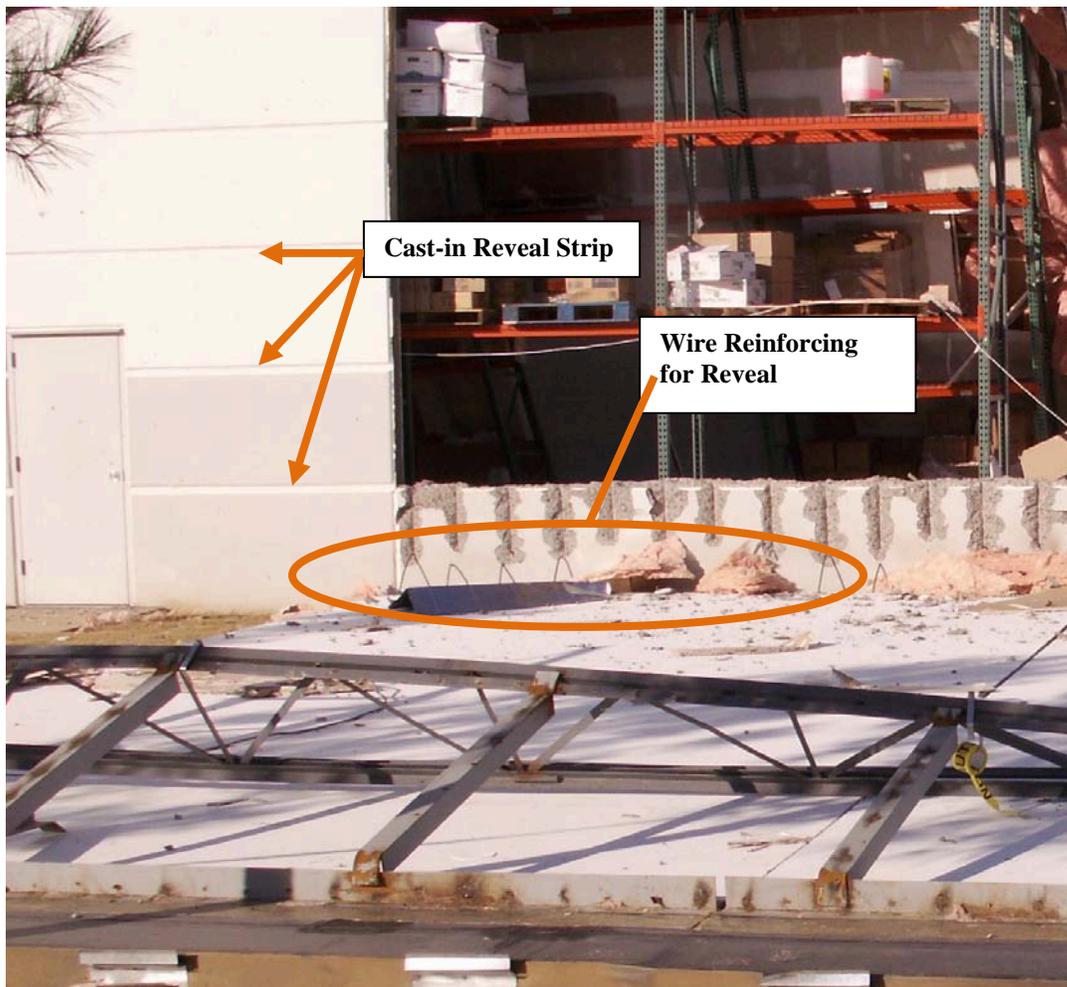


Figure 3.12. Tilt-up panel failure along reveal line, DOD 7

3.1.2 Cooper Lighting Warehouse

The Cooper Lighting Warehouse is located across Airport Industrial Drive, northeast of the Bound Tree Medical Warehouse. Cooper Lighting is classified as a DI 23 and contains approximately 430,000 sq ft of floor area. (Refer to **Figure 3.2** for a satellite image of this building.) Cooper Lighting is constructed similarly as Bound Tree with 18 ft. wide x 40-45 ft. tall and 7 1/2 in. thick tilt-up concrete wall. The roof structure consisted of joist girders supported by tube columns, bar joists, and metal roof decking with a single ply rubber or EPDM roofing.

Unlike Bound Tree, the large service overhead doors were located on the leeward side of the building. The storm's windward pressures on the west side of the building caused six panels to break at the floor line and fall inward, destroying the roof structure. These panels were laterally supported only by the joist girders and joist bridging (see **Figures 3.13 & 3.14**). Excepting the southwest corner of the building which had numerous reentrant walls, virtually all of the wall panels on the south face broke at the floor line and fell inward (see **Figure 3.15**). The roof bar joists were welded to ledger angles connected to these walls, and the horizontal bridging remained reasonably connected. However, the windward pressure loaded the bar joists along the top chords in compression, and, along with the roof uplift, produced catastrophic failure in upward bending about the joist x-x axis (see **Figure 3.16**). This damage was classified by the investigators as DOD 7 which relates to an expected EF-Scale wind speed varying from 150 mph to 160 mph, or a high speed EF-3.

Unlike the Bound Tree Medical Warehouse, no bridging angles were observed installed between the panels and the parallel joists. Similar to Bound Tree, the Cooper Lighting Warehouse suffered near total destruction by the storm. The investigators determined that the design and construction appeared to be in accordance with normal practice for this type of warehouse. However, the structure lacked the redundancy that could have been provided by a more robust lateral support system and a panel-to-panel interconnection system that could have allowed for shrinkage and thermal movement, but still have allowed the panels to react to loads collectively, rather than individually. This improved redundancy could have allowed the facility to perhaps resist winds approaching 180 mph.



Figure 3.13. Cooper Lighting Warehouse west wall, DOD 7

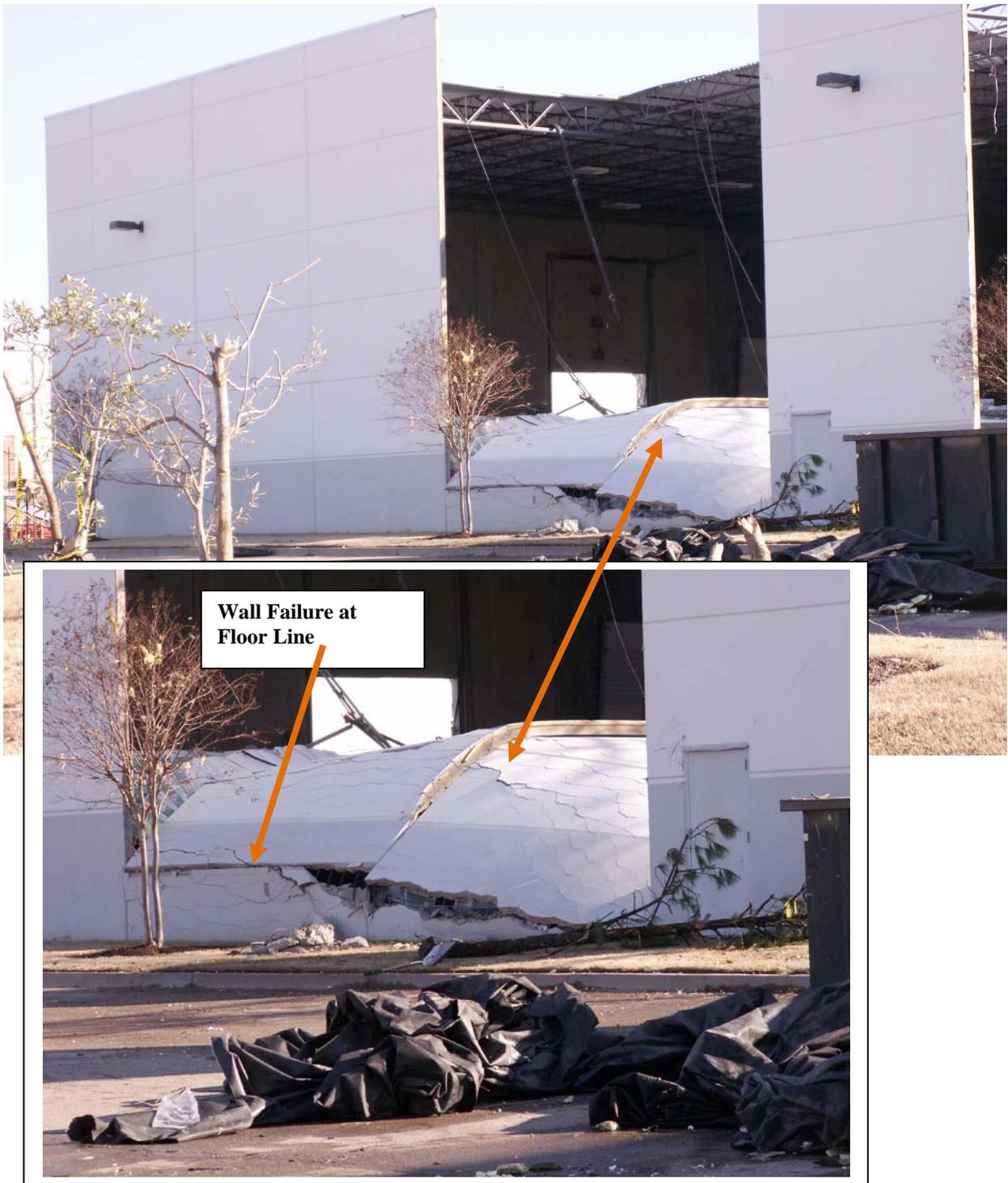


Figure 3.14. West wall failure, Cooper Lighting, DOD 7



Figure 3.15. Cooper Lighting south wall, DOD 7



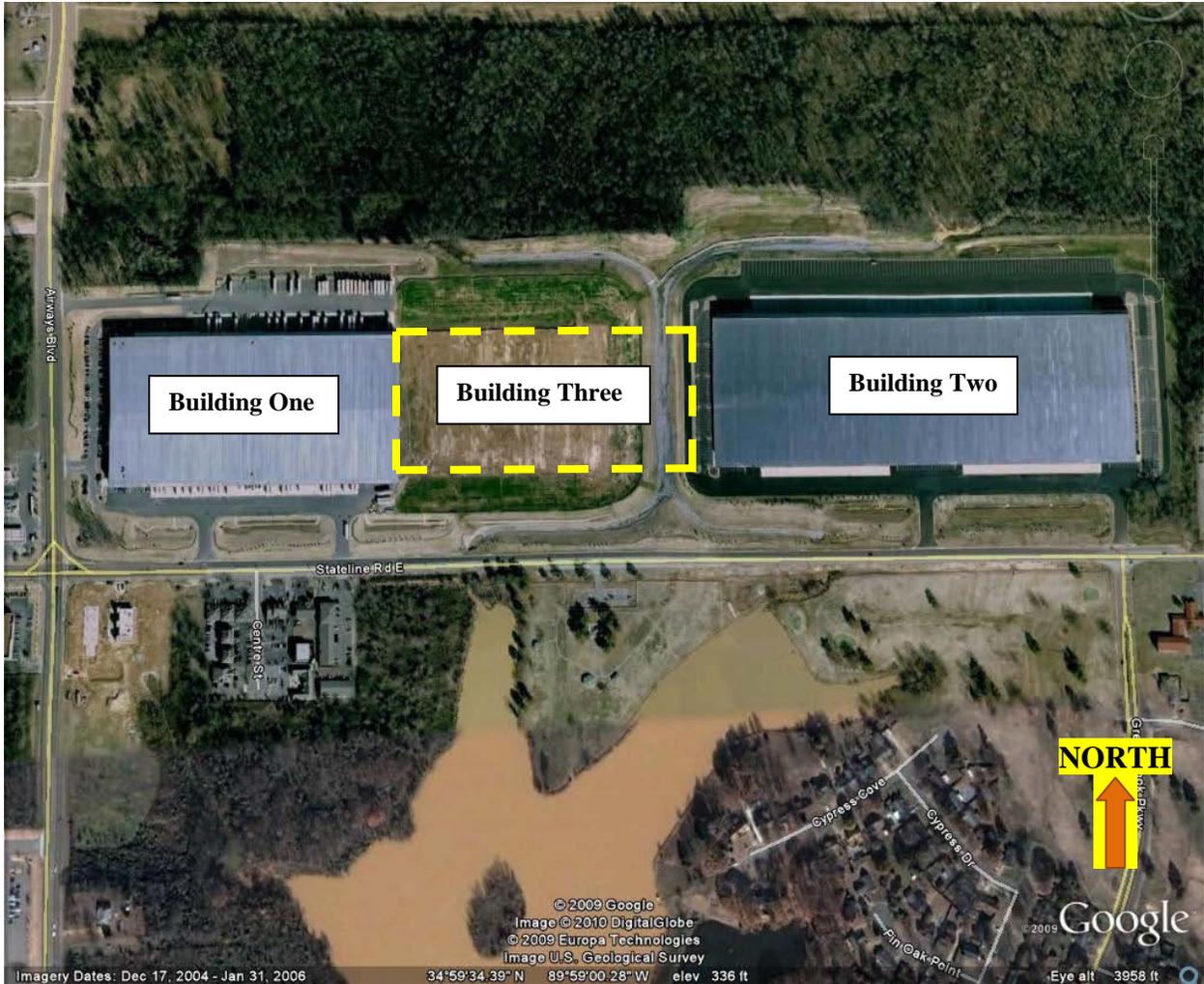
Figure 3.16. Roof structure failure produced by wall collapse, DOD 7

3.2 Southaven Distribution Warehouse

The Southaven Distribution Warehouse consists of three buildings. Building One is located on the corner of Airways Blvd. and Stateline Rd. East and measured 528,000 sq ft, building two on Stateline Road East measured 844,000 sq ft, and Building Three, an infill building between the two, measured 578,000 sq ft. According to the Scale, all three buildings were classified as DI 23. The satellite image shown in **Figure 3.17** was taken prior to the construction of the infill building. The investigators were prevented from a close inspection of the building. However, the original contractor was on the site and stated that the panels were 8 in. thick x 18-20 ft. wide x 38 ft. tall. He stated that the structural elements included 24 in. joists on 5 ft. centers bearing on structural beams and ledger angles at the panels, and 10 in. x 10 in. TS columns that were spaced on 50 ft. centers, with wind bracing on 150 ft. centers. Building three's wind bracing is shown in **Figure 3.18**. The roofing material was a single-ply rubber or EPDM membrane.

The west side of the building suffered minimal damage (**Figure 3.19**), whereas the south face lost approximately 1/3 of the tilt-up panels (**Figure 3.20**) which broke at the finish floor line. The windward pressure on Building One produced failure of the overhead doors and collapse of most of the panels (**Figure 3.21**), removal of the decking, and the collapse of the roof joists (see **Figure 3.22**). The south panels on Building Three were connected to Buildings One & Two with steel embedded plates which failed with the overturning of the panels (see **Figure 3.23**). The failure of Building Three further produced internal pressurization, which along with the roof uplift pressures, produced damage to Building Two (see **Figure 3.24**). This damage was classified by the investigators as DOD 7 which relates to an expected EF-Scale wind speed varying from 150 mph to 160 mph, or a high speed EF-3.

No bridging angles were observed between the panels and the parallel joists, and though robust shear wall frames were installed, the 150' spacing appeared to be inadequate. Similar to the Airport Industrial Drive Warehouses, the Southaven Distribution Warehouse suffered near total destruction by the storm. The investigators determined that the design and construction appeared to be in accordance with normal practice for this type of warehouse. However, the structure lacked the redundancy that could have been provided by a closer spaced lateral support system and a panel-to-panel interconnection system that could have allowed for shrinkage and thermal movement, but still have allowed the panels to react to loads collectively, rather than individually. This improved redundancy could have allowed the facility to perhaps resist winds approaching 180 mph.



Map Courtesy of Google

Figure 3.17. Satellite image of Southaven Distribution Warehouse

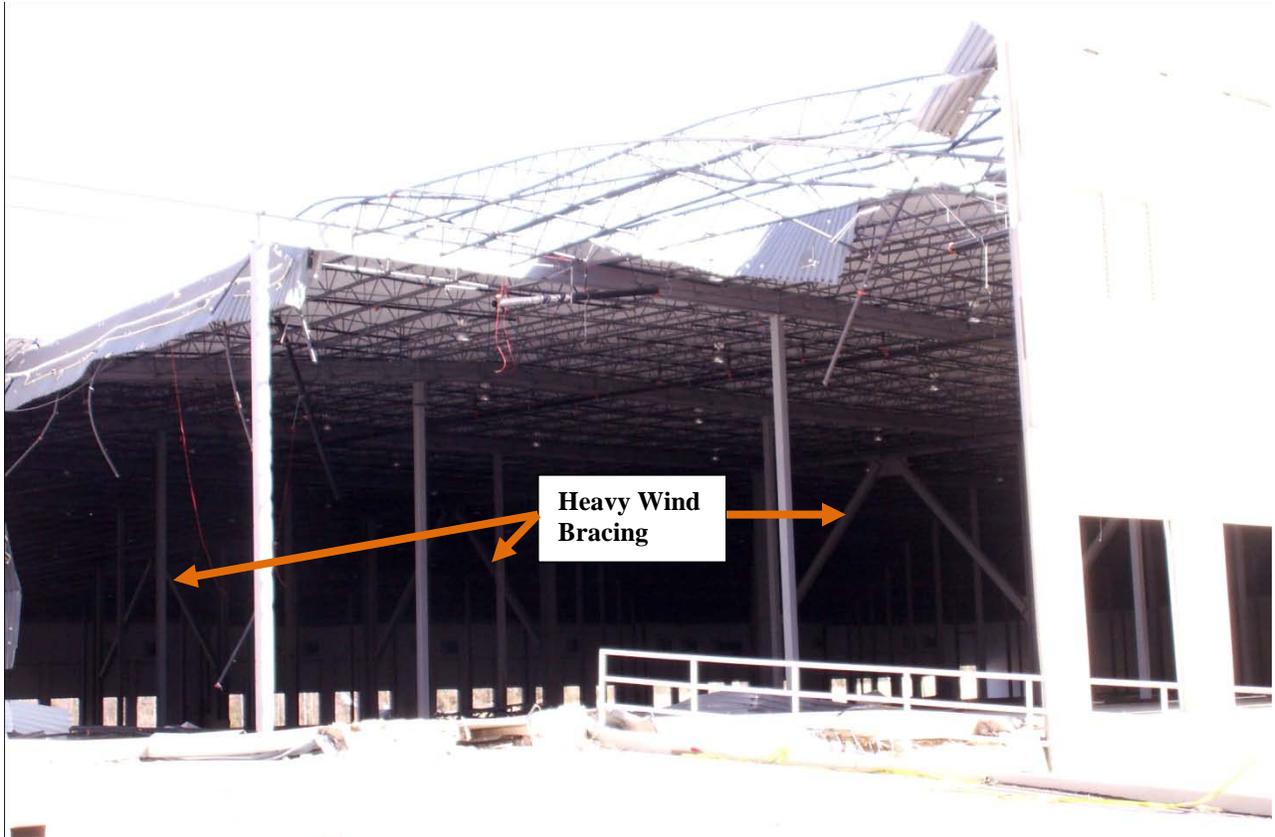


Figure 3.18. Wind bracing on Building Three, Southaven Distribution Warehouse

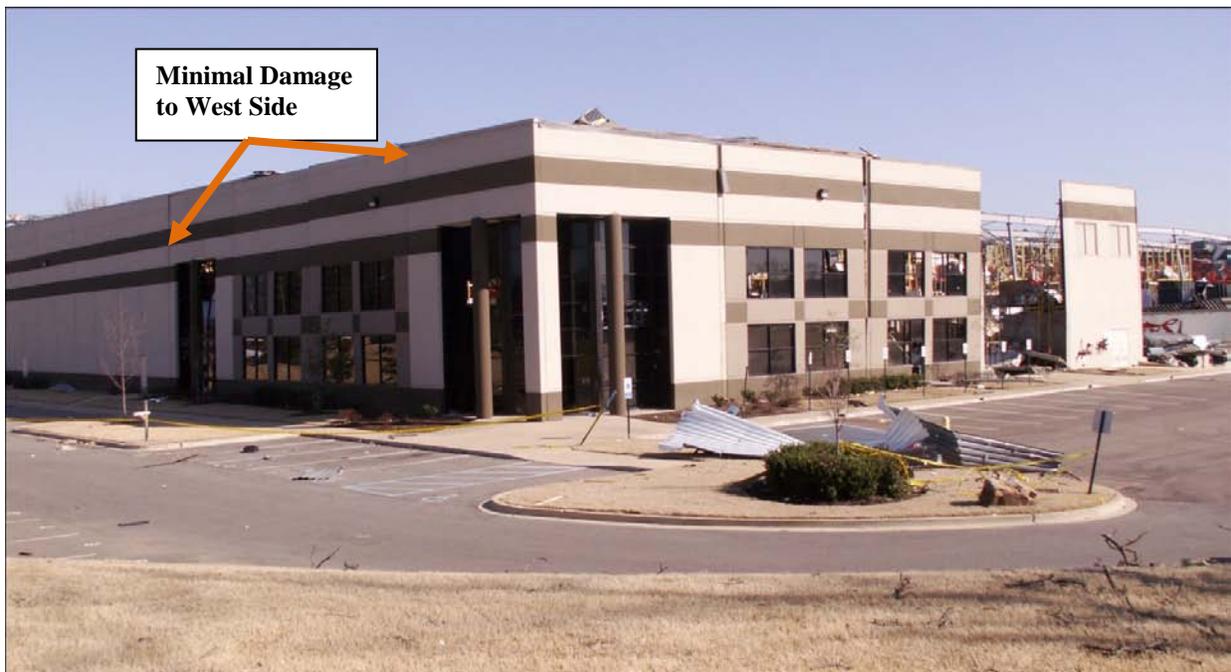


Figure 3.19. Southwest corner of Building One, Southaven Distribution Warehouse, DOD

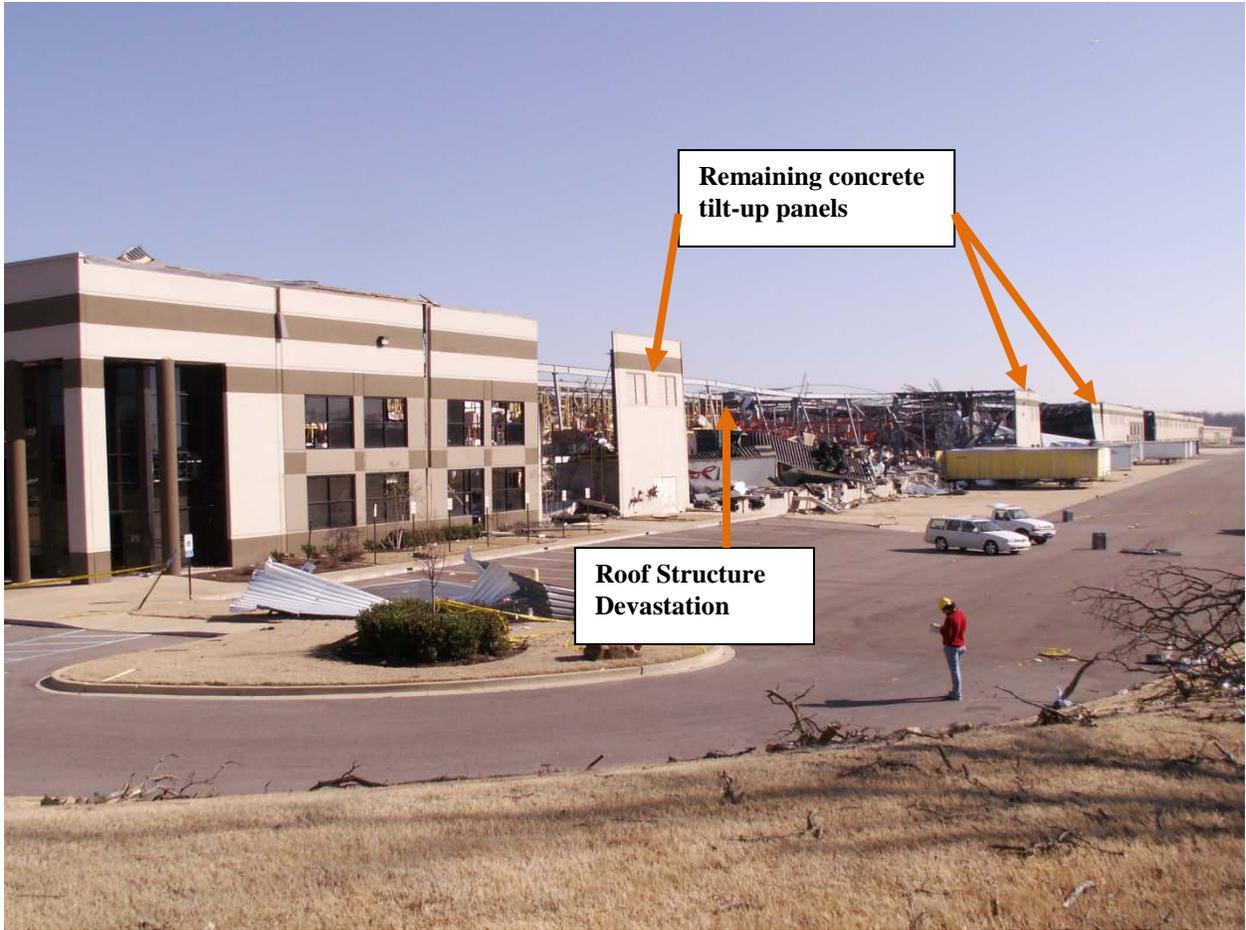


Figure 3.20. South elevation of Building One, Southaven Distribution Warehouses, DOD 7



Figure 3.21. Tilt-up wall panel collapse on Build One, Southaven Distribution Warehouses, DOD 7



Figure 3.22. Roof decking removed by wind pressures and joists destroyed by falling panels, no wind bracing observed, DOD 7

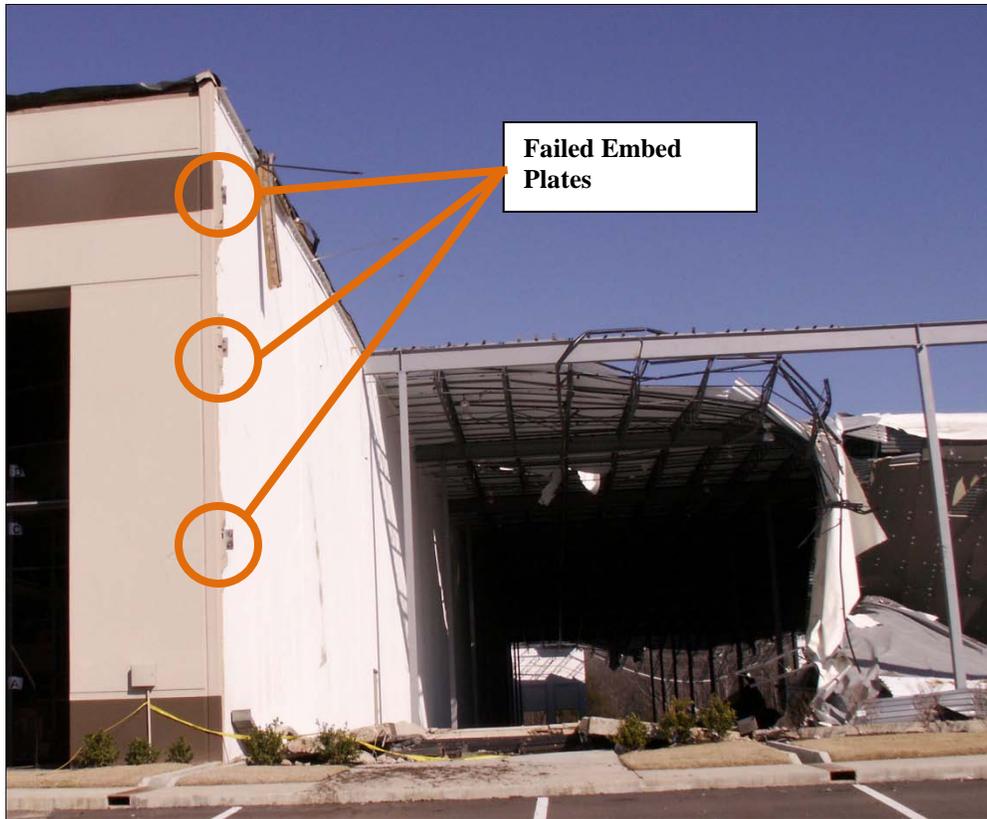


Figure 3.23. Failed embed connector plates between Buildings One & Three

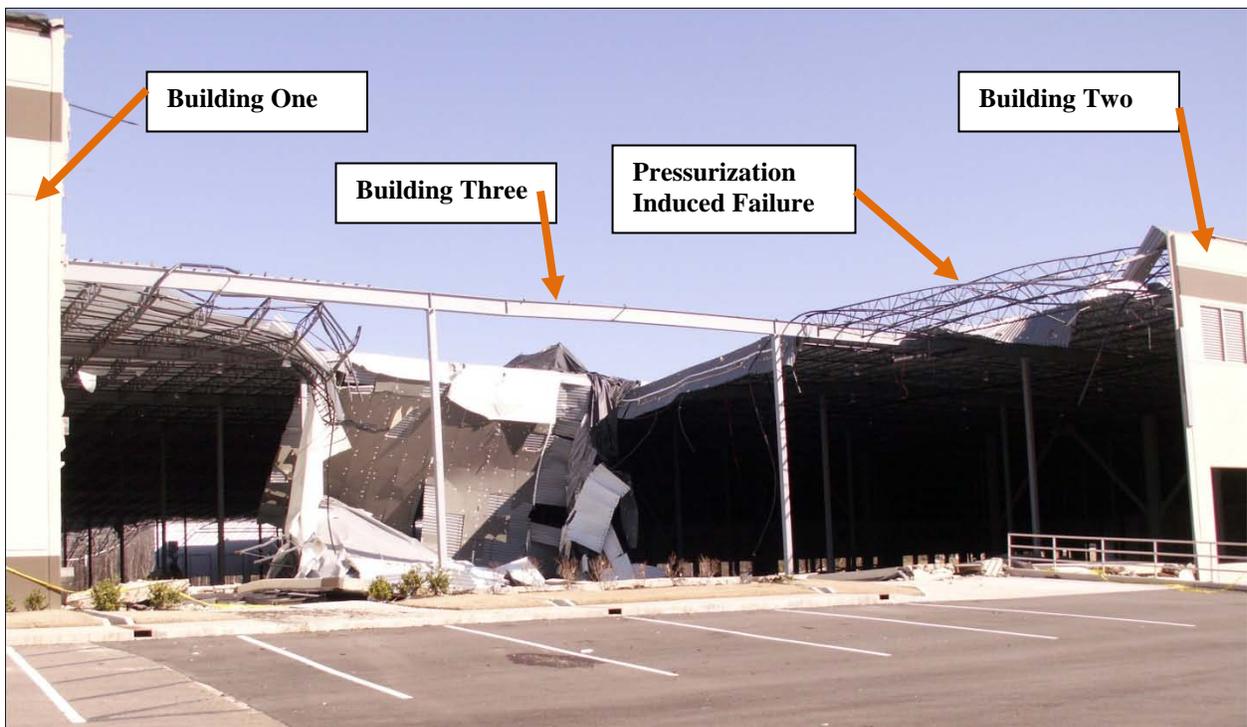


Figure 3.24. Damage to Building Two by Building Three failure, DOD 7

3.3 Pinnacle Airlines

After seriously damaging numerous structures in the Warehouse District, the Memphis EF-2 tornado threatened the Memphis International Airport with the most significant damage inflicted upon the Pinnacle Airlines' hanger facility. There is no specific Damage Indicator assigned to large airplane hangars, and the most appropriate appears to be DI 21, Metal Building Systems (MBS). MBS structures typically have rigid steel frames, and Z or C purlins and girts supporting metal wall panels and standing seam roofs. The Pinnacle hangar structure was composed of some tilt-up concrete panels, and a heavy steel column and beam structure supporting a heavy joist system with significant lateral bracing.

A satellite view of the Pinnacle Airlines' facility is shown in **Figure 3.25**. The hangar facility is approximately 120 ft. x 250 ft., with column bays at 20 ft. on center. The hangar is shown in **Figure 3.26** and exhibits roof edge damage. The hangar doors were not compromised by the windward pressures. Approximately 90 ft. x 120 ft. of the roofing was removed by the tornado (see **Figure 3.27**). Notice should be taken to the heavy wall and roof wind bracing. **Figure 3.28** shows that the clipped roofing panels came unlatched. This damage to a DI 21 structure would indicate a Degree of Damage of DOD 3 resulting from wind speeds of 78 mph to 120 mph. However, given the stiffness of this structure and the lack of wall panel or door failure, it would appear that the wind speeds perhaps were near DOD 5 with wind speeds closer to 115-120 mph and produced by an EF-2 tornado.

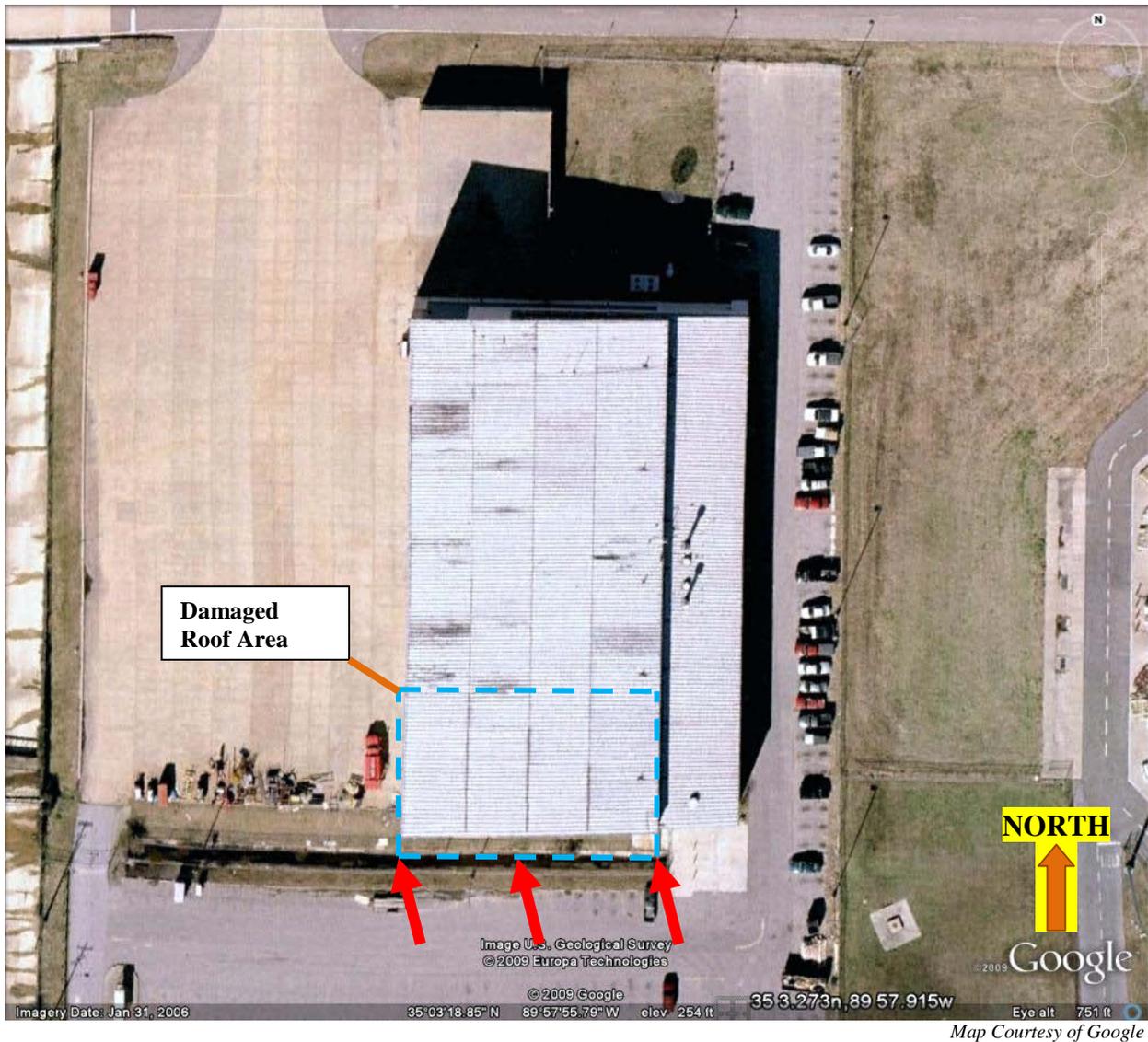


Figure 3.25. Satellite view of Pinnacle Airlines



Figure 3.26. South elevation of Pinnacle Airlines Hangar

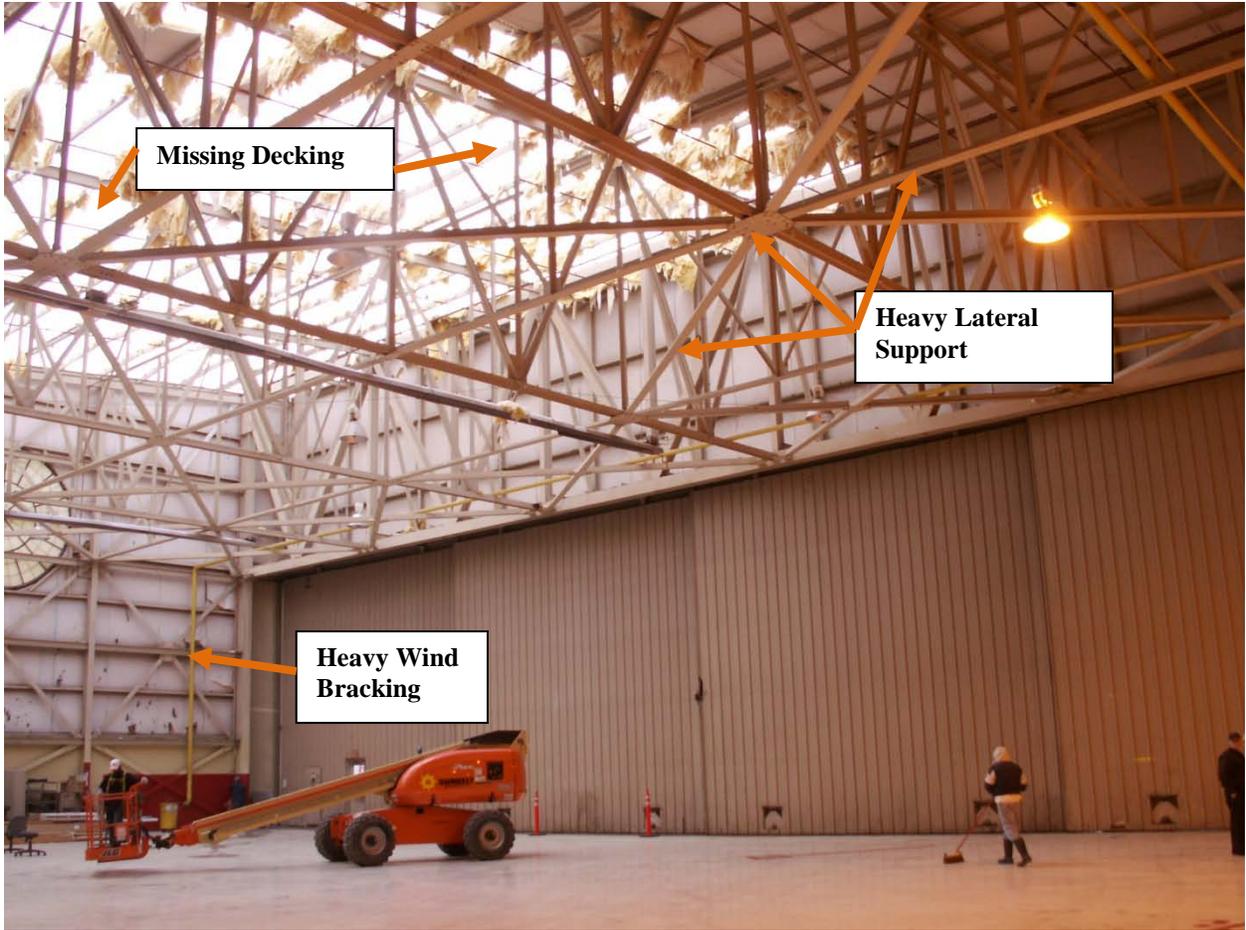


Figure 3.27. Roof Damage to Pinnacle Airlines Hangar, DOD 5

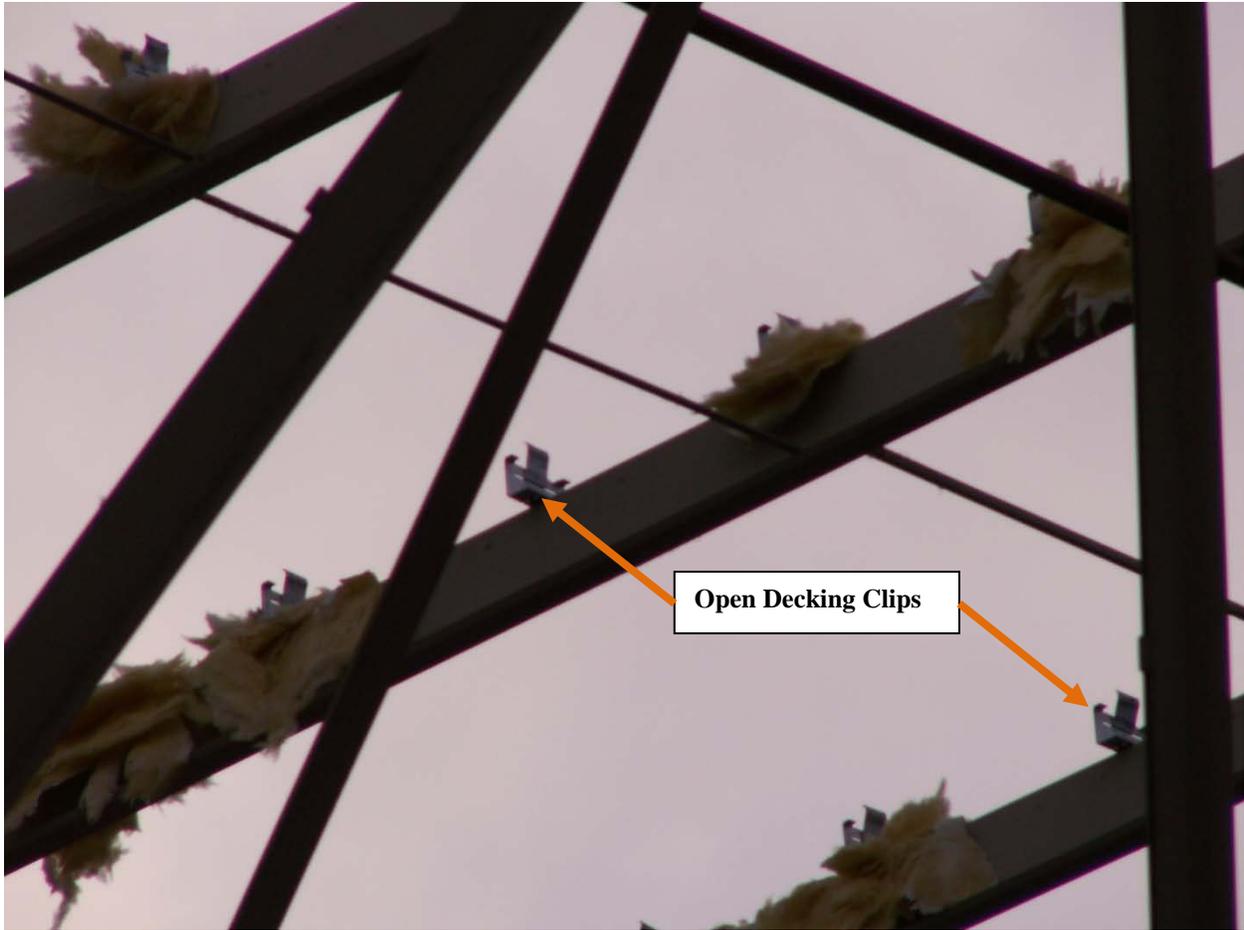


Figure 3.28. Roofing panels released at roofing clips

3.4 Hickory Ridge Mall

The Hickory Ridge Mall is a large regional mall and covers over 800,000 square feet of retail space, with national tenants such as Macy's and Sears (**Figure 3.29**). The Hickory Ridge Mall was the fifth major structure affected by the southwest Memphis EF-2 tornado and was categorized on the EF Scale as a DI 11, Large Shopping Mall. The windward and leeward faces are indicated on the figure, along the various locations of observed damage. It should be noted that, other than roofing damage described below, the full extent of roof damage is unknown, since the investigators were not granted access to the roof.

3.4.1 Hickory Ridge Mall Windward Face

The southwest corner of the Sears Store would have been one of the first portions of the mall to be struck by the tornado. The exterior Sears walls appear to be constructed of steel studs with a brick veneer and are approximately 35 feet tall. The west wall was

laterally supported by the roof joists which were bearing on a perimeter beam that remained standing, whereas the south wall appeared to be only laterally supported by the joist bridging and collapsed (see **Figure 3.30**). According to the Scale, this type of damage could be attributed to a DOD 6 and higher wind speeds, and the damaged light structural elements only at the corner suggests a wind speed of 128+ mph. Exterior Insulation Finish System (EIFS) cladding was removed near the Mall southwest entrance (see **Figure 3.31**). EIFS clad parapet steel stud wall systems were blown over near Macy's (**Figure 3.32**), and metal roof coping along the south wall of Macy's wall was also removed (see **Figure 3.33**). Leeward cladding damage is shown in **Figure 3.34**. The cladding damage and visible roof damage is classic DOD 5 damage, but the EIFS damage was pervasive beyond the corners and could indicate high wind speeds up to 115 mph. However, based on numerous storm damage studies by the senior investigator, EIFS routinely fails at much lower wind speeds, in the range of 100 to 110 mph. Referring back to the satellite image shown in **Figure 3.2**, it appears that the Hickory Ridge Mall was on the storm's periphery and only experienced EF-2 damage on the lower side of the Scale ranging from 110 mph to 115 mph.

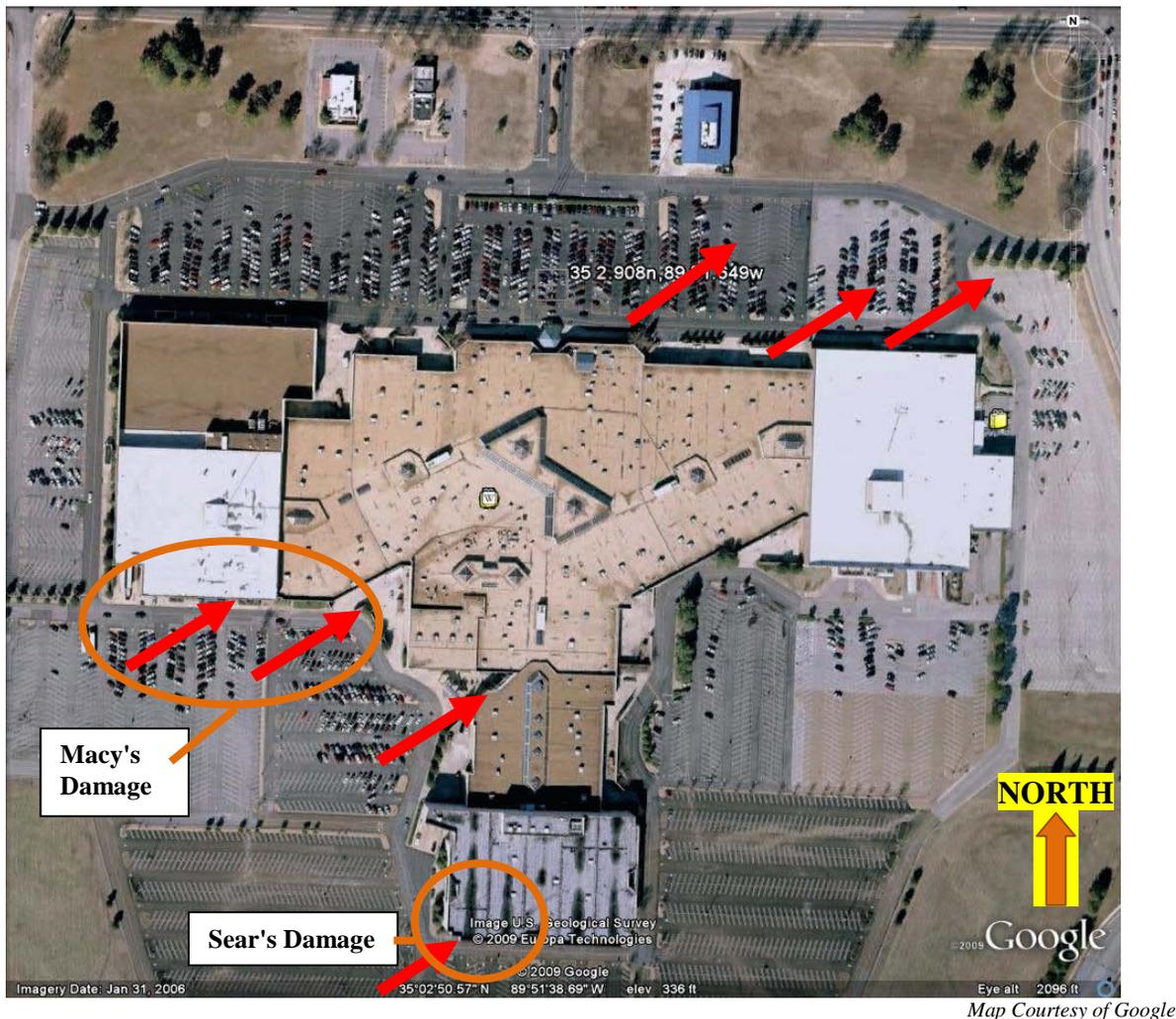
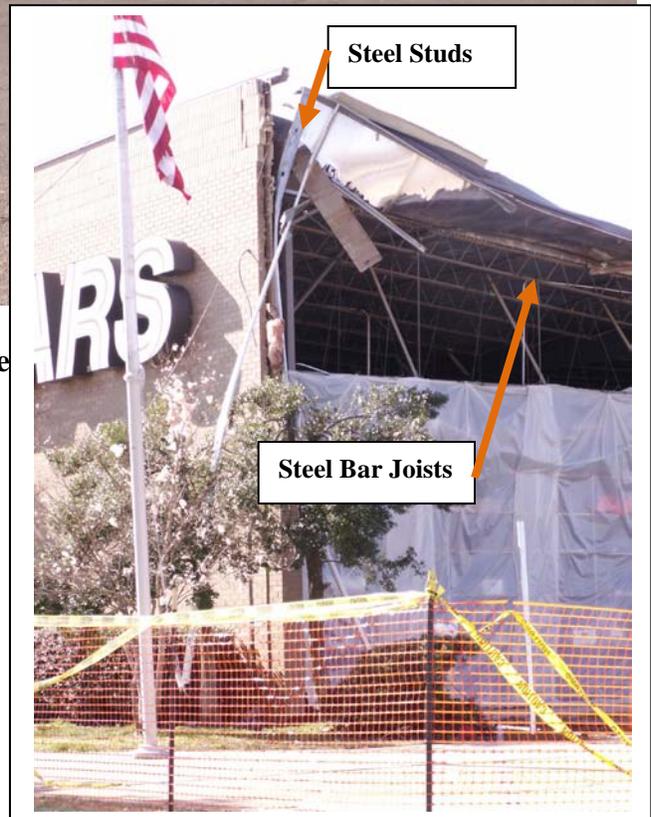


Figure 3.29. Hickory Ridge Mall (red arrows indicate direction of wind pressure)



**Figure 3.30. Sears windward corner damage
DOD 6**



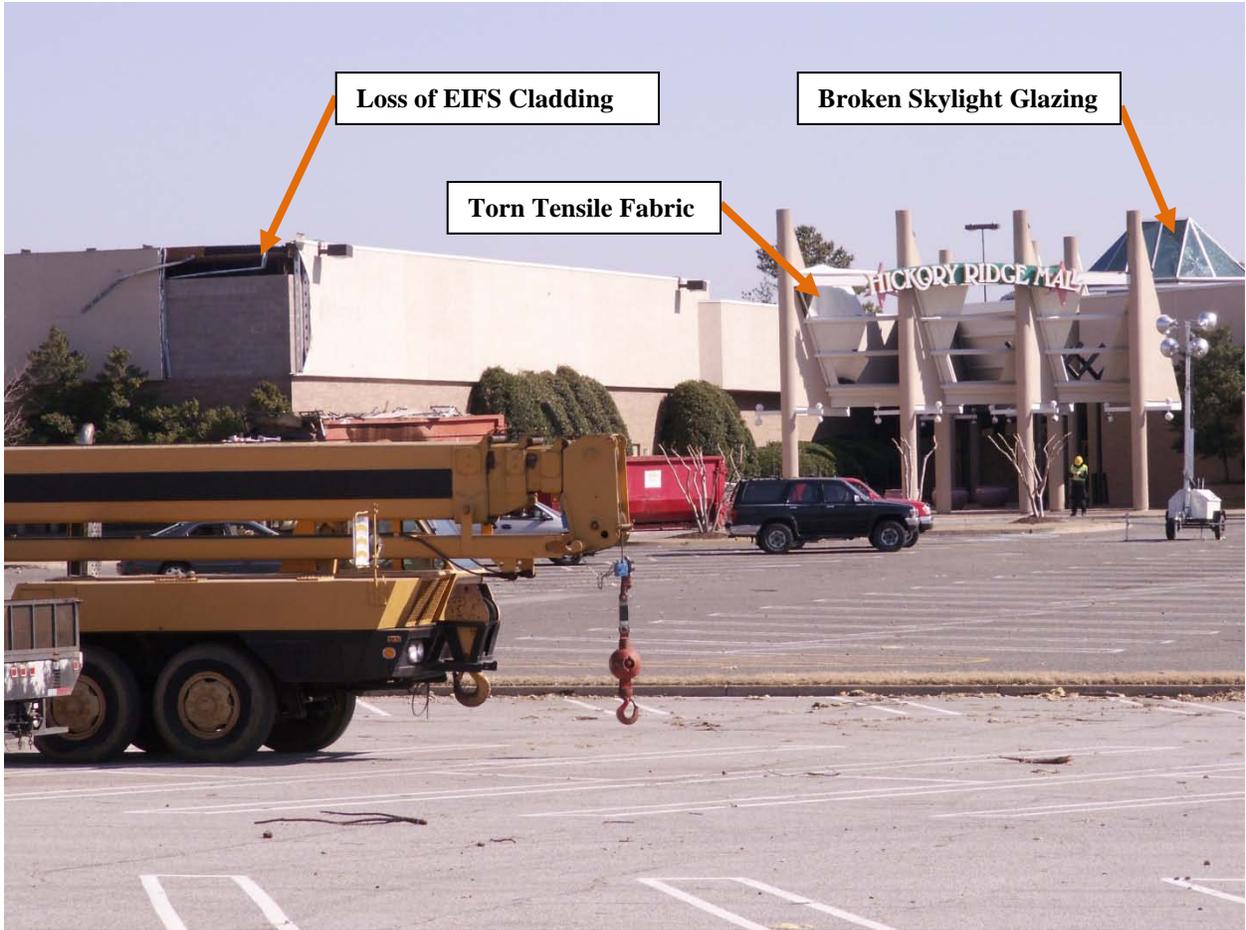


Figure 3.31. EIFS Damage on windward corner near entrance to mall, DOD 5



Figure 3.32. Steel stud parapet collapse, DOD 5



Figure 3.33. Parapet coping damage at Macy's windward face, DOD 2 only visible

3.4.2 Leeward Damage at Hickory Ridge Mall

Storm damage inflicted by suction pressures on the leeward and mall sides appeared to be confined to EIFS cladding, parapets, and glazing (as seen in **Figure 3.33**). This type of damage is best categorized as a DOD 2 with wind speeds of 65-83 mph.



Figure 3.34. Mall parapet, cladding, and canopy damage, DOD 2

4.0 TORNADO - CITY OF JACKSON, TENNESSEE

According to Mr. David McBriden the Director of Facilities at Union University, Union University was formerly located in downtown Jackson and moved to its current location in southwest Jackson in the early 1970's. He stated that all campus buildings were professionally designed by architects and engineers, and that the building code utilized by the designers prior to the year 2000 was the Standard Building Code (SBC)[12] and since 2000 was the 2000 International Building Code (2000 IBC).[13]

4.1 Union University

According to the NWS, the same supercell that had produced the southwest Memphis EF-2 tornado spawned the Jackson tornado.[14] At exactly 7:03 pm on February 5, 2008, an EF-4 tornado formed crossed Interstate 40 highway and struck the campus of Union University in Jackson, Tennessee (see **Figures 4.1 & 4.20**). A satellite map of the campus shows the basic path of the storm (see **Figure 4.3**). A University map of the campus is shown in **Figure 4.4**.



Figure 4.1. Tornado Damaged Miller Tower on Union University Campus

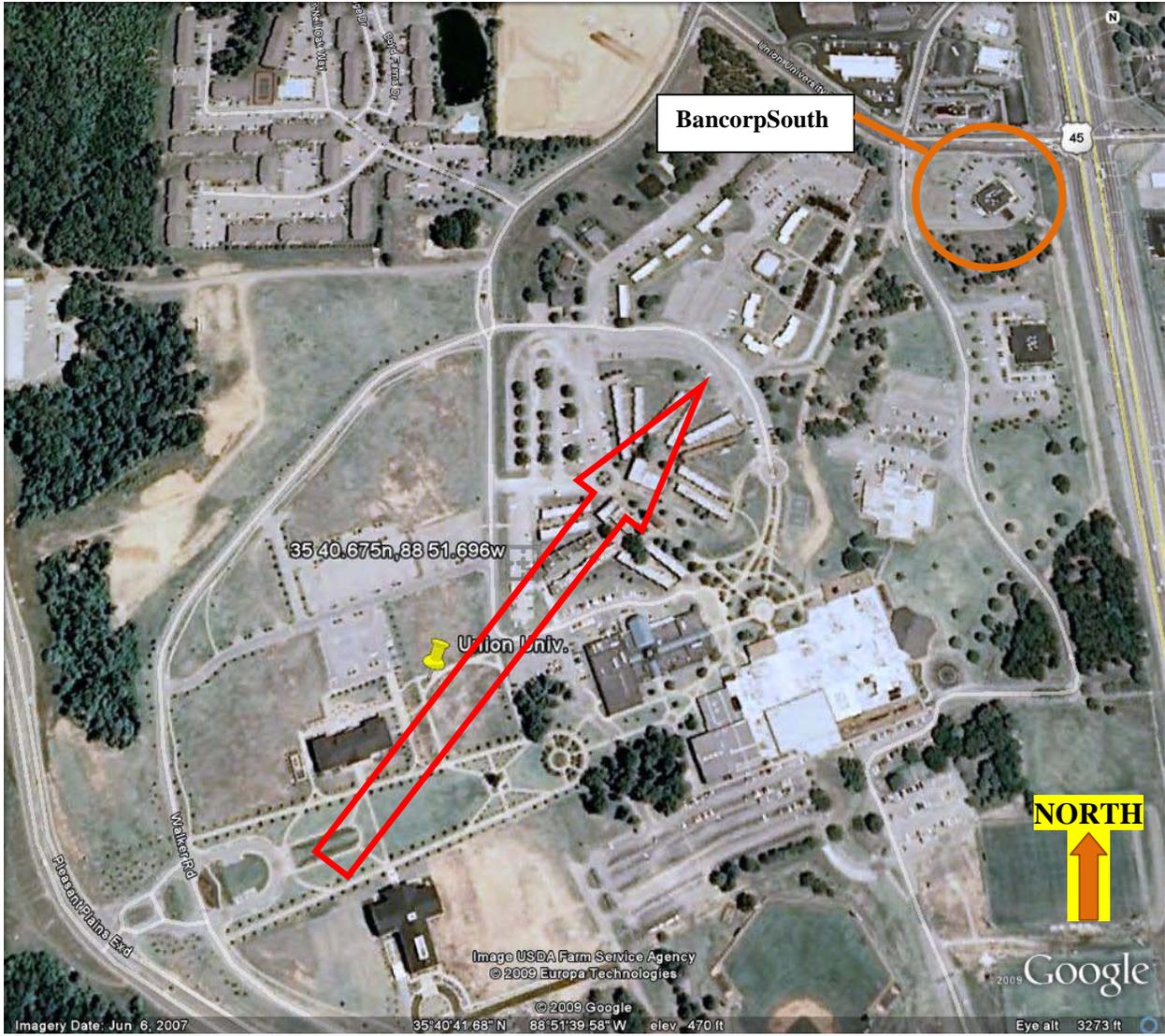


Figure 4.3. Union University Aerial Photograph

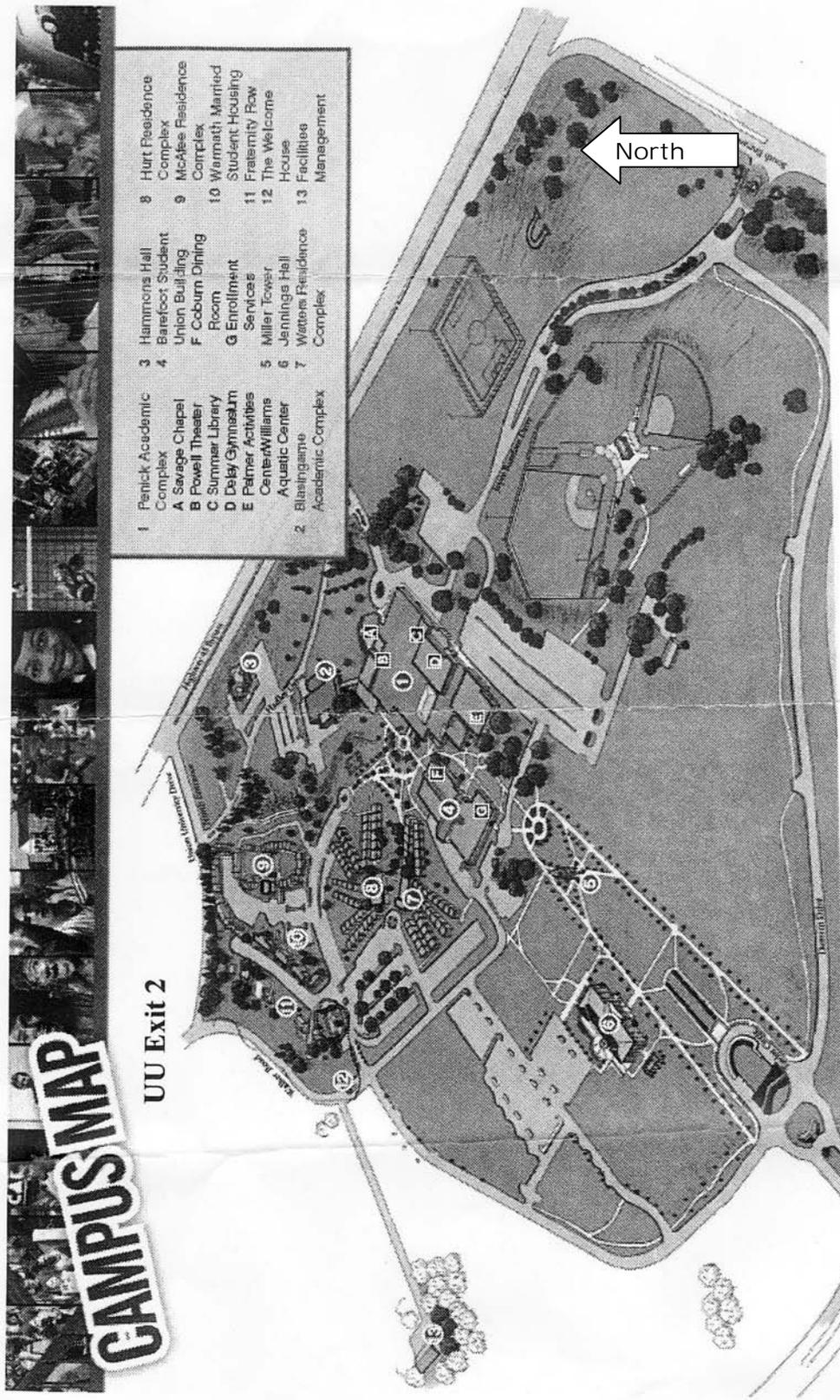


Figure 4.4. Union University Campus Map

4.1.1 Union University Academic Buildings

Based upon the observed damage, it appears that the tornado began dropping to the ground on the southwest side of the campus where the bulk of the campus academic buildings are located. Damage to Jennings Hall (**Figure 4.5**), White Hall (**Figure 4.6**), and Miller Tower (**Figure 4.1**) were basically relegated to loss of roof shingles, damage to glazing, and failure of an equipment roof parapet wall. Blasingame Academic Complex received numerous debris impacts (see **Figure 4.7**). On the EF Scale, each of these buildings would be classified as a DI 20, Institutional Building. At the time of the storm, Jennings Hall was 2 years old, and White Hall was about ½ year old. According to the Director of Facilities at the University, these buildings were professionally designed in accordance to the 2000 IBC.[13] The IBC further references Section 6 of the *Minimum Design Loads for Buildings and Other Structures*, ASCE 7-98 [15] with regard to wind design. These standards require that these building types in this geographical region be designed to resist code winds of 90 mph, 3-second gust at 33 feet above the ground in Exposure C (open terrain). The Degree of Damage for these structures was assessed by the investigators to be DOD 4. This type of damage relates to “high” damage produced either by a weak storm or a stronger storm that has not touched ground. Given these assumptions that are based on these observations and those later observed down wind, and the NWS rating of a EF-4 for this storm, it is believed that storm produced EF-1 damage with approximately 95 mph winds (EF-1) prior to touch down near the residential complex.

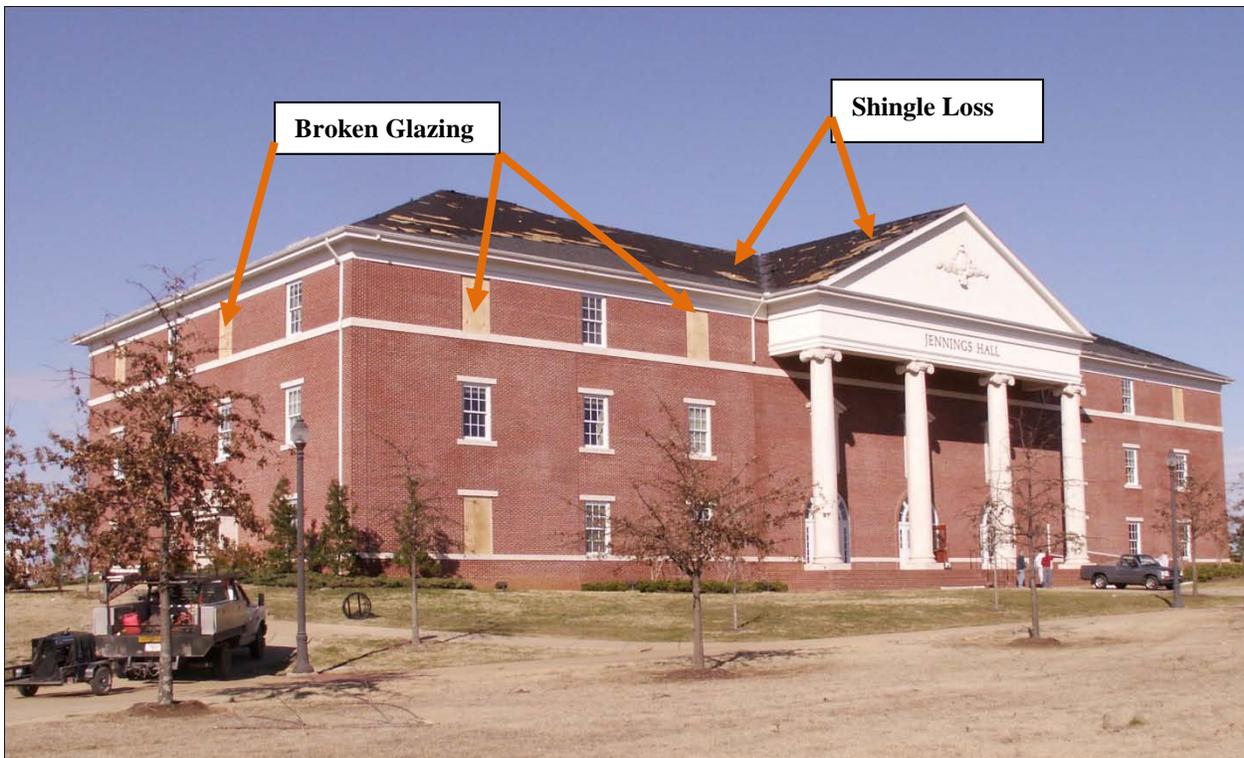


Figure 4.5. Jennings Hall, Union University, DOD 4

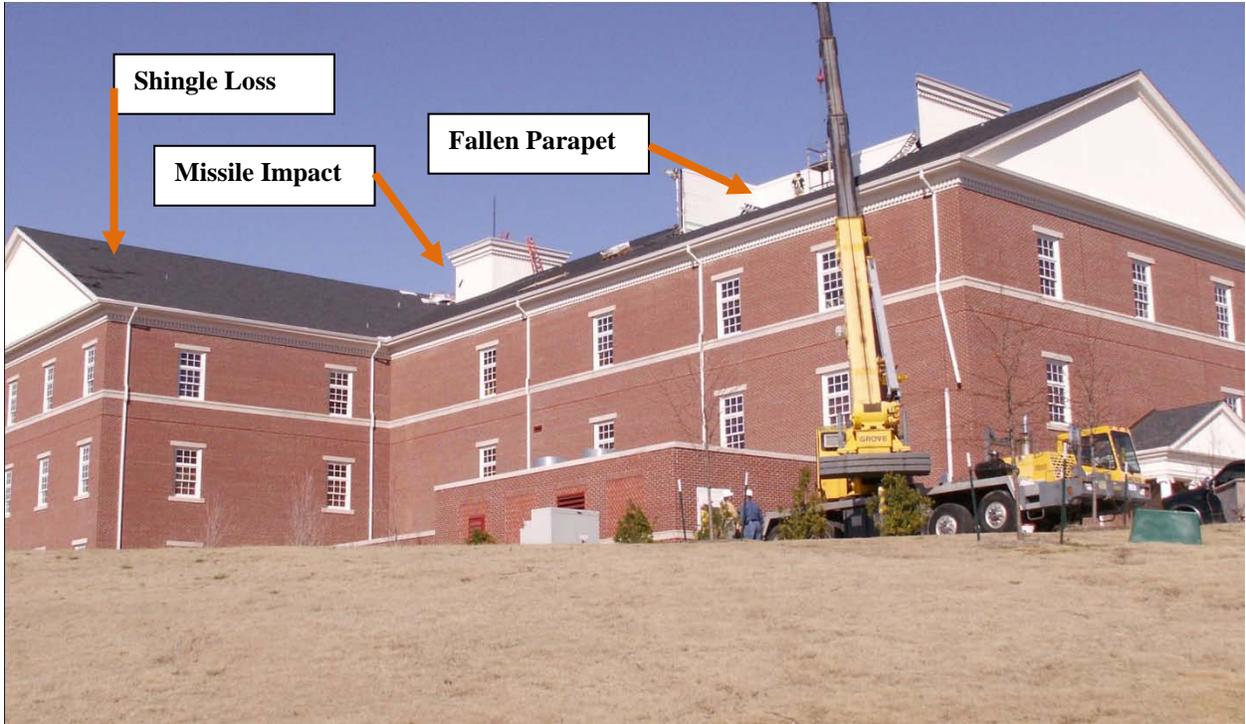


Figure 4.6. Roof damage at White Hall, Union University, DOD 4



Figure 4.7. Debris Impacts on Blasingame Academic Complex, Union University

4.1.2 Residence Halls, Union University

The residence hall complexes were professionally designed and constructed in various years between the early 70's and the 90's. Though their structural system changed from one project to the next, the general design concept remained unchanged. Two-story modules that housed 8-10 students per floor were combined, and sometimes offset, to make a string of modules separated by a load bearing unreinforced (URM) concrete masonry unit (CMU) fire wall. The roof structure, either steel bar joist, wood trusses, or hollow core concrete deck, bore on the CMU demising walls. The second floor structure was either wood trusses, hollow core deck bearing on the CMU walls, or dimensional lumber bearing on interior walls and the CMU walls.

All of the designs would have been guided by the Standard Building Code. Wind design would have also have been governed by the SBC with reference to ANSI A58.1, *Minimum Design Loads for Buildings and Other Structures*[16], which was the predecessor to the ASCE 7 document. Both the SBC and ANSI standards require buildings in this geographical region to be designed to withstand 70 mph, fastest-mile

speed at 33 feet above the ground for Exposure C. This fastest-mile speed converts to 85 mph, 3-second gust (the standard of today) at 33 feet above the ground for Exposure C.

Upon review of the Damage Indicators for the EF Scale, it was determined that DI 5 for Apartments, Condos, Townhouses (3 stories or less) was most suitable for the Union University housing complexes. After passing over the Academic Complexes, the tornado appeared to touch ground in the parking lot west of Waters Residence Complex tumbling cars and trucks (**Figure 4.8**), DOD 6 (expected wind speed of 180 mph), then traveled through the heart of the residence hall structures, with Waters and Hurt Residence Complexes being virtually destroyed (**Figure 4.90**, DOD 6 (expected wind speed of 180 mph). Frequently, the CMU end walls failed as the result of windward pressure (**Figure 4.8**), and sometimes the leeward CMU wall collapsed as the result of suction + internal pressurization, (**Figure 4.10**), DOD 4 (expected wind speed 135 mph). The other complexes exhibited peeled cladding (**Figures 4.11**), DOD 4 (expected wind speed of 135 mph) and loss of exterior wall structure produced by internal pressurization (**Figure 4.12**), DOD 4 (expected wind speed of 135 mph). The more remote housing units lost roofing, rooftop equipment, glazing, and suffered extreme interior damage (**Figure 4.13**), DOD 3 (expected wind speed of 125 mph).



Figure 4.8. Windward CMU wall collapsed and tumbled cars and trucks in Waters Residence Hall parking lot, DOD 6



Figure 4.9. Total destruction of Waters Residence Hall parking lot, DOD 6



Figure 4.10. Leeward collapse of CMU wall, DOD 4



Figure 4.11. Peeled cladding and roofing from housing unit, DOD 4



Figure 4.12. Loss of exterior wall veneer due to internal pressurization, DOD 4

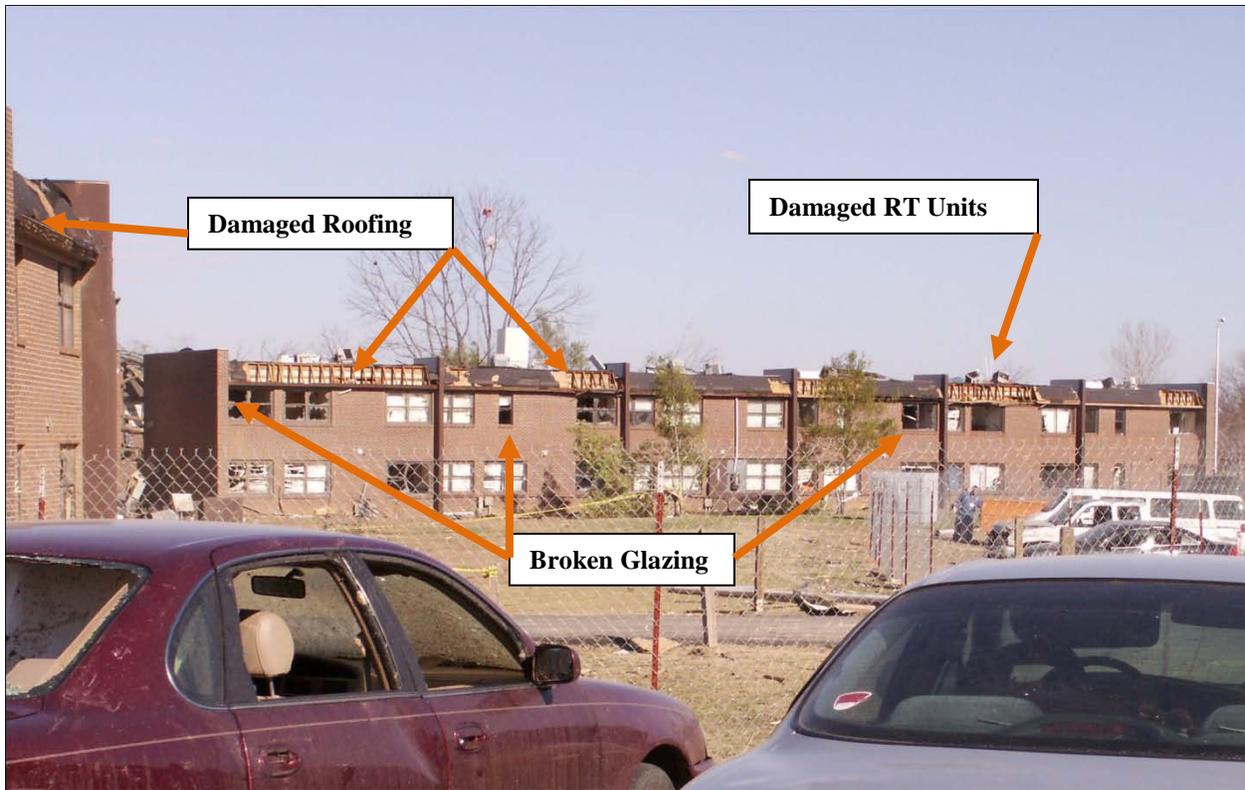


Figure 4.13. Glazing, roofing, and rooftop equipment damage to remote housing units, DOD 3

At the time of the storm, the residence units were heavily occupied. In accordance to previous drills, the occupants were notified by intercoms in their units that all residents were to seek shelter in the first floor bathrooms in each module. Though these bathrooms were not interior spaces and were not hardened shelters, they were windowless with fiberglass tub/shower enclosures located against the exterior wall (see **Figures 4.14 & 4.15**).

No safe rooms were provided in the housing units; however, the designation of the windowless shower enclosure on the first floor did provide reasonable protection for the occupants. The notification of the students by the intercoms had been practiced and was effective. However, the shower stalls on the ends of the units proved to be vulnerable (see **Figures 4.14 & 4.15**). The ends of the units were clad in URM and frequently crumbled under the wind load (see **Figure 4.16**). Though the roof structure might still have been removed by the storm, concrete and steel reinforcement in these walls would have provided stiffness to the adjacent wood stud and brick veneer perpendicular walls and would have provided protection to the end unit designated safe shower stall.

It is believed by the investigators that the storm touched down the parking lot west of the housing complex as an EF-4 storm with wind speeds approaching 180 mph and then began to lift on the east side of the complex, but still producing damage in the realm of an EF-2 storm with approximate wind speeds of 125 mph. It appears that the storm proceeded northeast at this same approximate altitude and speed and struck the BancorpSouth Bank.



Figure 4.14. Place of Refuge



Figure 4.15. Place of Refuge



Figure 4-16 Failed End Unit URM Wall

4.2 BancorpSouth Building

The BancorpSouth Bank building is located at the northeast entrance to Union University on the corner of Union University Drive and Highway 45. A satellite image of the building is shown in **Figure 4.17**. According to an employee of the bank, the building opened in early 1996. The investigators further learned from the Jackson Building Inspection Department that the building was professionally designed under the 1994 SBC Building Code.[17] According to S.K. Ghosh, PhD, in his paper, *The Evolution of Wind Provisions in Standards and Codes in the United States*, the 1994 SBC adopted ASCE 7-88 by reference and that the ASCE 7-88 was an updated version of ANSI A58.1-1982, but with the same wind speed map.[18] Accordingly, the BancorpSouth building would have been designed to 85 mph 3-second gust (converted from 70 mph fastest mile) at 33 ft. in Exposure C.

The BancorpSouth building is two-story and contains over 10,000 square feet of floor space. A DI 17 for a Low Rise Building, 1-4 Stories was selected as the Scale classification. The exterior walls are brick veneered; however, the backup wall construction is unknown. A faux hip roof encircles the roof plane forming an equipment enclosure around rooftop equipment on a flat roof. The hip roof consists of a truss structure with plywood decking and asphalt shingles. Over half of the shingles were removed by the storm (**Figure 4.18**), DOD 3. Although the number of broken windows could not be determined, the bank employee stated that the interior damage was so significant that the interior was gutted and refinished (see **Figure 4.19**), DOD 3-4. Several of the hip roof trusses and the drive-thru teller canopy were destroyed (**Figure 4.20**), DOD 5.

The most significant structural damage to the BancorpSouth building was the removal of the teller canopy and the damage to the mansard roof trusses which were located on the windward face of the building. The remaining roofing and glazing damage occurred on the leeward face. It was assessed that collectively the damage to the BancorpSouth building could have been produced by an EF-2 storm with winds varying from 125 mph to 133 mph.



Map Courtesy of Google

Figure 4.17. Satellite Image of BancorpSouth Building (red arrows indicate positive and negative pressures)

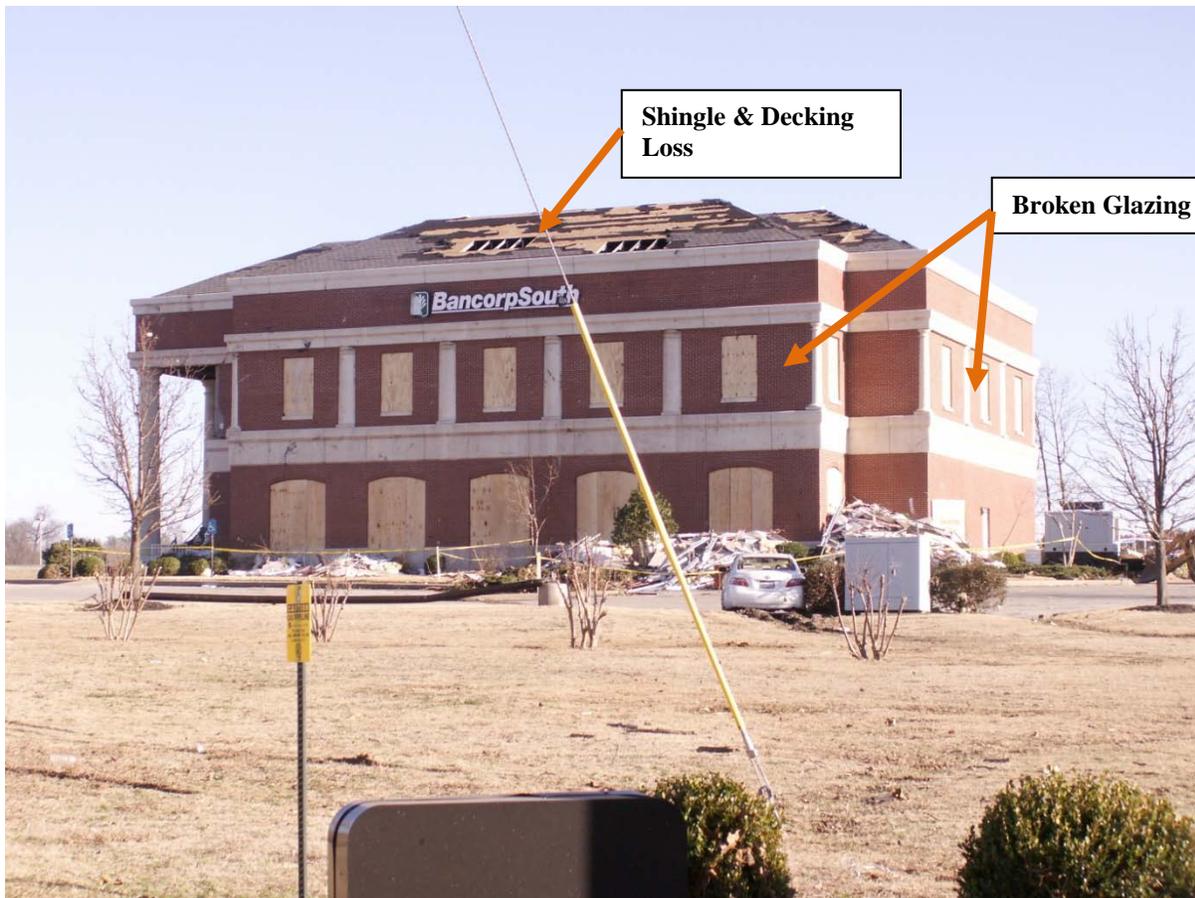


Figure 4.18. Damage to BancorpSouth roofing and glazing, DOD 3



Figure 4.19. Glazing failures led to destruction of interior finishes, DOD 3-4



Figure 4.20. Destruction of Drive-In Canopy and Roof Trusses, DOD 5

4.3 Brookdale Senior Living

From the Union University area, the storm continued on a northeasterly path striking Brookdale Senior Living Center (see **Figure 4.2**). A closer satellite image of the Brookdale complex is shown in **Figure 4.21**. Previously known as Jackson Oaks Retirement Home, Brookdale Senior Living is a complex of different buildings of varying ages, many of which appear to be 25 years old or older. In an interview with an onsite manager, the investigators were told that all residents were moved to building interiors for refuge from the storm. He stated that this was a monthly drill and that no one was injured in the storm.

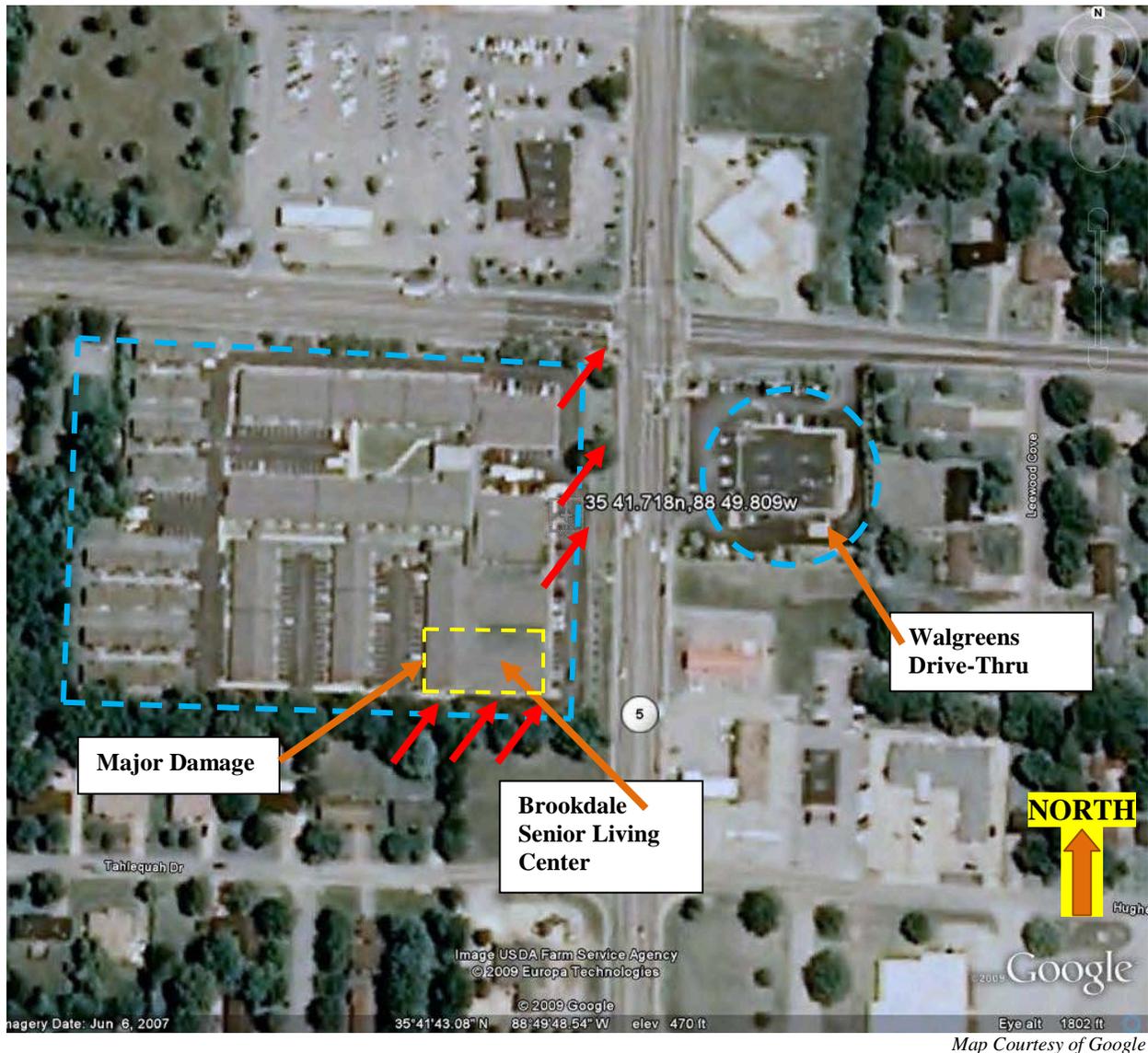


Figure 4.21. Satellite Image of Brookdale Senior Living Center (red arrows indicate positive and negative wind pressures)

Based upon previous code discussions in this report, the design wind speed for these structures would have been a converted 85 mph, 3-second gust, measured at 33 ft. above the ground in Exposure C. There is no specific DI for Assisted Living/Senior Living facilities among the 28 Damage Indicators for the EF Scale. Brookdale is a single-story, light wood-framed structure, with asphalt shingles and varying types of wall veneer, including brick. This type of construction is best represented by DI 5 for Apartments, Condos, Townhouses, 3 stories or less. Over 50% of the roof shingles were damaged or blown off the units (**Figure 4.22**). Windward pressures collapsed the south wall of a unit (**Figure 4.23**), producing roof structure failure (**Figure 4.24**) and internal pressurization of the east wall causing near collapse of the wall, **Figure 4.25**. Other areas of the complex experienced loss of siding and broken glazing (**Figure 4.26**). The canopy on the Walgreen Drug Store drive-thru (**Figure 4.21**) was bombarded by debris, most probably from Brookdale (see **Figure 4.27**).

All of the observed damage appeared to be classic DOD 3 & 4 representing wind speeds from 125-135 mph. However, the age of the structures and the quality of construction led the investigators to assess the damaging wind speeds to be more likely in the range of 100 mph to 105 mph or a high speed EF-1 tornado.



Figure 4.22. Significant loss of roof covering on leeward side, DOD 3



Figure 4.23. Collapse of windward wall and roof structure, DOD 4



Figure 4.24. Damage of windward roof structure and loss of leeward roof structure, DOD 4



Figure 4.25. Damage to side wall (leeward face) due to loss of lateral support and internal pressures, DOD 4

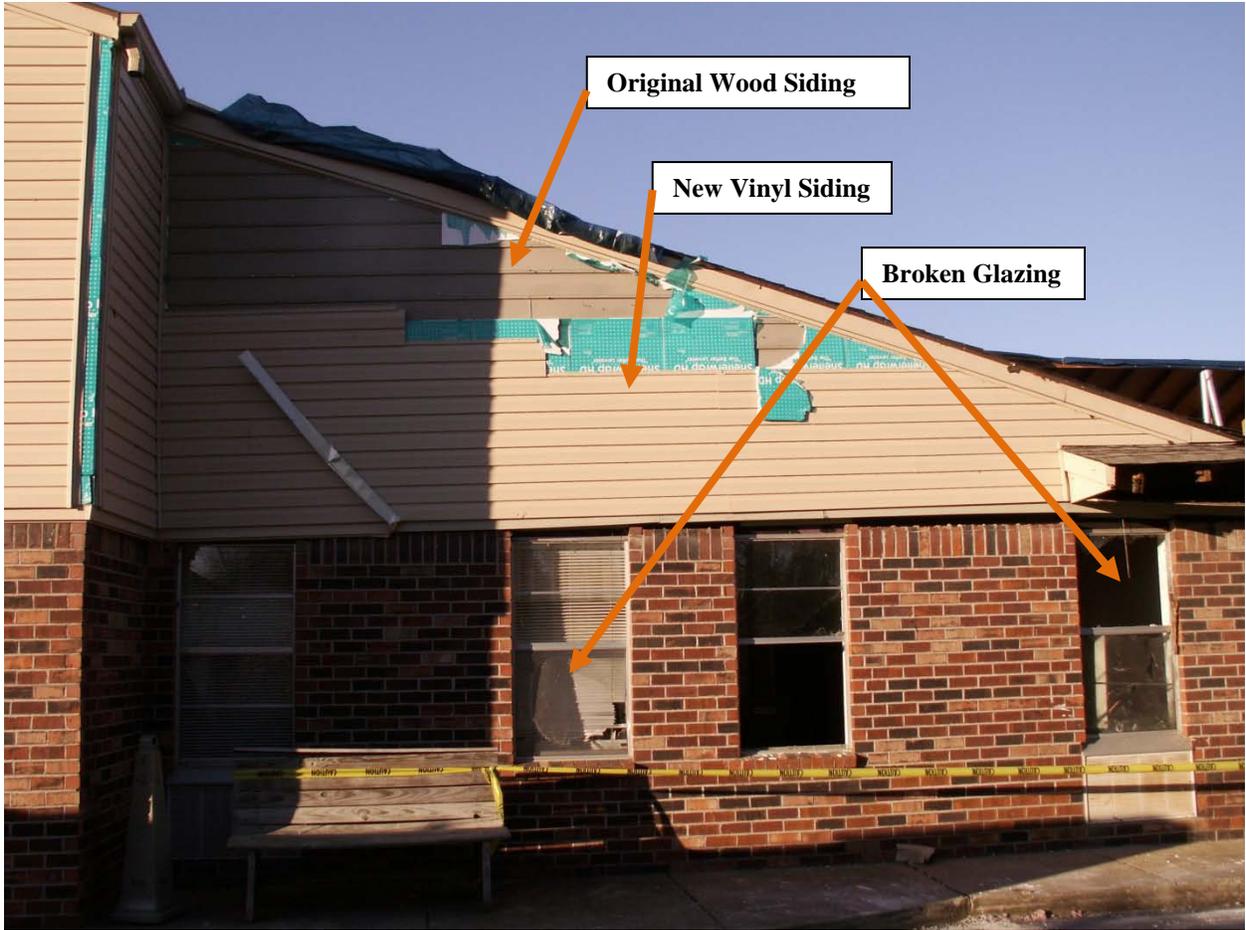


Figure 4.26. Classic loss of siding and glazing materials, DOD 2



Figure 4.27. Debris impacts of EIFS clad canopy at the Walgreens across from Brookdale

5.0 SUMMARY AND CONCLUSIONS

On February 5, 2008, when voters in 24 U.S. states were voting in the Super Tuesday Presidential Primary Elections, a massive storm system containing numerous supercells and 87 reported tornadoes raked across nine states producing 57 fatalities in the states of Arkansas, Alabama, Tennessee, and Kentucky. It was the deadliest outbreak in both Tennessee and Kentucky since the 1974 Super Outbreak.[2] According to the NWS in their *Service Assessment Report* [3]:

- All states covered by Watches and Warnings had an average lead time of 17 minutes.
- Fifty-four of the deaths were residential related, with 36 of these occurring in manufactured housing.
- Three deaths occurred in a single commercial building.
- No deaths occurred in “Safer Places” or hardened shelters. Eight deaths did occur when hardened shelters were within 100 yards to ½ mile.
- Most fatalities occurred at night.
- Most of the areas affected by the deadly tornadoes were heavily forested.
- Over 50 percent of the people interviewed indicated it was too early in the year for tornadoes and, as a result, minimized the threat.

The research effort of the WISE investigators was directed at two specific tornadoes, the EF-2 that struck northeast Mississippi and southwest Tennessee, and the EF-4 tornado that struck Jackson, Tennessee. Both of these tornadoes produced significant damage to professionally designed commercial structures that have design safety factors, as compared to residential structures that traditionally are not professionally designed. The focus of the research was to determine the mechanisms of failure and compare the failure to Degrees of Damage for the specific Damage Indicator contained within the *Enhanced Fujita Scale* [1] and thereby determine the boundaries of wind speed that could have produced such damage.

The EF-2 storm initially struck in northeast Mississippi destroying two warehouses on Airport Industrial Drive. Classified as a DI 23 on the EF Scale, the damage corresponded to DOD 7 with winds estimated between 150 mph to 160 mph for a EF-3 storm. Failure of the first warehouse was the result of internal pressurization from overhead door failure and external outward pressures. The second warehouse failure was attributed to windward pressures. In both cases, the tornado wind loads exceeded the building design wind load; however, damage could have been lessened with a more robust system of lateral support of the roof structure and the tilt-up wall panels. The Southaven Distribution Warehouses were next to be catastrophically damaged by the EF-2 tornado. These warehouses succumbed to internal pressurization due to overhead door loss and windward positive wall and negative roof pressures. Unlike the Airport Industrial Drive warehouses, the Southaven Distribution Warehouses had strong wind-braced framing which prevented total loss of the windward panels; however, the spacing of the wind bracing was too wide to prevent significant damage. All three of these buildings relied heavily for lateral support to be provided by the roof decking and the horizontal bridging. The loss of the decking due to the pressures allowed tipping of the joists about their y-y axis and the eventual failure of

the joists, along with the tilt-up panels being laterally supported. In the case of axial loading by wall failure, the joists, along with their extended bottom chords, were unable to carry the compressive axial loads. Estimated wind speeds of 150-160 appear reasonable for such damages and depict winds from a EF-3 tornado. It is believed that, with a more robust lateral support system, the wind resistance of these buildings could have been increased, and the observed DOD 7 destruction might not have occurred until wind speeds reached 170-175 mph.

The EF-2 tornado damage extended to Pinnacle Airlines located at the Memphis Airport. Though located in an open exposure in the airport landscape, the Pinnacle building only suffered loss of roof decking and minor door and wall damage. Classified as a Metal Building System, DI 21, the Pinnacle building had a heavy structural system. The minimal damage is attributed to the robust structural system and lateral support system of the joists and wall system. The damage classification of DOD 5 is indicative of an EF-2 storm. Given the strong structural system, the damage was probably associated with wind speeds of 115-120 mph.

The Hickory Ridge Mall (DI 11) was the last major commercial structure damaged in Memphis by the EF-2 tornado. Most damage was related to roofing and wall cladding. The Sears store suffered failure of a steel stud and brick veneer wall. The DOD 5 damage suggests that the Mall was located on the periphery of the tornado and experienced wind speeds of 110-115 mph.

Based upon the study of these five damaged commercial structures, the investigators believe that the storm began as an EF-3 (150-160 mph) in northeast Mississippi and then reduced in strength to a EF-2 (115-120 mph) when it hit Pinnacle Airlines.

The Jackson, Tennessee, tornado was classified by the NWS as an EF-4. An EF-4 tornado includes a range of wind speeds 168 mph to 199 mph. By studying the types of buildings damaged (Damage Indicators-DI) and the associated degrees of damage (DOD) of those buildings, the investigator can “fit” an assumed wind speed using the EF Scale. The path of the tornado through Union University appears to have traveled above the ground between the new academic buildings, Jennings and White Halls, producing damage from wind speeds of approximately 95 mph (EF-1) then touched down with cyclonic speeds approaching 180 mph (EF-4) near the cluster of residence halls (see **Figure 4.3**). These academic buildings were designed to the 2000 IBC [13] and suffered nominal roofing and glazing damage, which seems to support the premise that the tornado was not on the ground. However, the cluster of residence halls were severely damaged, losing second floor roof and wall structures, and is clear evidence of the storm traveling along the ground. The tumbled vehicles (**Figure 4.8**) in the parking lot west of the housing units appear to be the initial point of touch-down. These residential structures were professionally designed using the 1985 SBC [12] and a design wind speed of 85 mph 3-second gust (converted from fastest-mile) both are taken at 33 ft. above the ground in Exposure C. These buildings should be capable of withstanding wind speeds higher than the basic design wind speed, implying an overall safety margin with respect to loading of at most of 1 1/2 to 2.[19] It then follows from the proportionality of the wind loads to the square of the wind speeds, that these buildings would be expected to collapse under wind speeds in excess of $85 \text{ mph} \times \sqrt{2} = 120 \text{ mph}$. The residual strength of the housing complex structures was rapidly overcome by the approximated 180 mph wind speed. It is further believed that the storm began to lift on the northeastern side of the complex, still producing damage, but at lesser speeds,

approximately 125 mph (EF-2). The storm continued on this path and general elevation striking the BancorpSouth Bank building with the 125 mph winds of this EF-2 tornado. It is believed that the storm may have further elevated, since little evidence of damage was observed between the Bank and Brookdale Senior Living Center. Given the age and lesser quality of construction, the Brookdale damage was, at best, produced by speeds near $85 \text{ mph} \times \sqrt{1.5} = 104 \text{ mph}$. [19] Damage estimated by the investigators was best associated with an EF-1 storm and 105 mph. Therefore, it is concluded that the strongest damage caused by the Jackson tornado can be explained by wind speeds corresponding to a high speed EF-2 or low speed EF-3 (130 mph to 147 mph).

Performing detailed storm investigations can be challenging; however, the data is important for the development of information which can be used to better mitigate the loss of lives and property. Dr. Fujita's Scale provided a methodology to quantify the damage and the destructive forces of the wind. The Enhanced Fujita Scale further provides tools to identify different types and qualities of construction using the Damage Indicators and associated wind speeds based on Degrees of Damage unique to the construction types.

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7.0 APPENDIX – Abbreviations and Acronyms

ACI	American Concrete Institute
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
CMU	Concrete Masonry Unit
dBZ	radar echo intensity/reflectivity
DI	Damage Indicator
DOD	Degree of Damage
EF-Scale	Enhanced Fujita Scale
EIFS	Exterior Insulation Finish System
EPDM	Synthetic Rubber used as single ply roofing
F Scale	Fujita Scale
FedEx	Federal Express Shipping
FEMA	Federal Emergency Management Agency
ft.	feet
IBC	International Building Code
in.	inch
knot	unit speed (1.151 mph)
mb	millibar (unit of pressure)
mph	miles per hour
NIST	National Institute of Standards & Technology
NOAA	National Oceanic & Atmospheric Administration
NWS	National Weather Service
SBC	Standard Building Code
SPC	NWS Storm Prediction Center
sq ft	square feet
TS	Structural Steel Tube Section
URM	Unreinforced Masonry
UTC	Coordinated Universal Time (CST- 6 hours)
WISE	Wind Science & Engineering Research Center