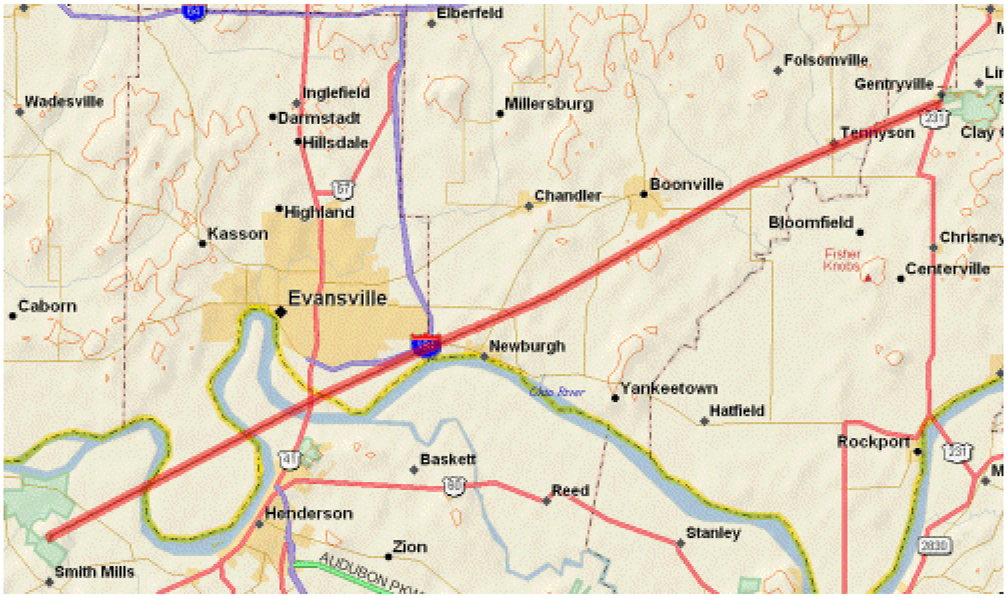
## Tornado Report

# Evansville, Indiana
# November 6, 2005

### With a Focus on

# Eastbrook Mobile Home Park




*Map Courtesy of NWS*

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**&**
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**May 30, 2006**

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## EXECUTIVE SUMMARY

In the early morning hours of Sunday, November 6, 2005, Indiana residents of Vanderburgh County, Warrick County, and Spencer County were awakened by a devastating tornado that destroyed homes, a church, and a race track. The storm killed 22 and injured scores of others. From November 7-9, 2005, the writers of this report documented the storm damage from its beginning to its end. The focus of the investigation was the Eastbrook Mobile Home Park where 110 homes were damaged or destroyed and 18 lives were lost. Since manufactured housing routinely appears to suffer the greatest in extreme wind events, the researchers sought to determine the "Hows?" and "Whys?" by performing a detailed investigation.

This report traces the standards and guidelines for construction and installation of manufactured housing from its infancy to the time of the storm. All units within the park were surveyed for a Degree of Damage utilizing a uniform Damage Scale. A random sample of 1/3 of the units was surveyed specifically for installation performance. This report documents the performance and compares it to the guidelines.

The results of the investigation indicate that manufactured housing can have the ability to resist code design wind speeds, but improvements are needed in the realm of tie-down bracing for racking and shear forces. Metal connectors are necessary for the Zone I (Standard Wind Zone) units in order to maintain a connected and continuous load path, and an improved method of connecting tie-down straps to the units must be developed. The investigation revealed that foundation piers, tie-downs, and anchoring systems were rarely installed properly and were a cause of poor unit performance during the storm. Installation standards now exist in the form of NFPA 225, *Mobile Home Installation Standard 2005 Edition*, which provides in-depth information regarding unit foundations and anchoring procedures. All states, counties, and municipalities, including Indiana, are herein urged to adopt, implement, and inspect to assure a strict compliance to this installation standard. Furthermore, the standards for manufactured construction–Article 3280, *Manufactured Home Construction and Safety Standards, April 2003* and NFPA 501, *Standard on Manufactured Housing, 2005 Edition*—should be revised to include the above listed improvements.

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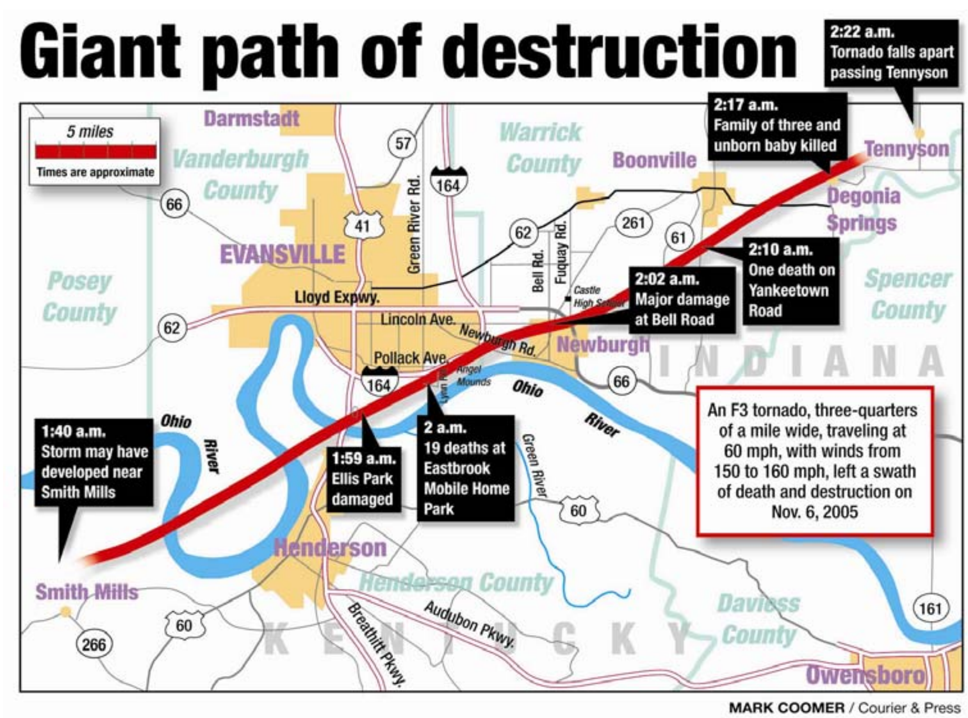
**Evansville, Indiana Tornado**
November 6, 2005

## 1.0 Storm Overview

At 1:50 AM CST, Sunday morning, November 6, 2005, a tornado touched down near Smiths Mills in Henderson County, Kentucky, near the Indiana/Kentucky border and then crossed the Ohio River into Vanderburgh County, Indiana. The tornado struck the Ellis Park Race Track, killing three horses and laying waste to a million square feet of structures. Staying south of I-164, the tornado crossed the corner of the Eastbrook Mobile Home Park in Evansville, Indiana, destroying 110 homes and killing 18. The tornado proceeded into Warrick County, Indiana, causing extensive damage in Newburgh and killing 4 in De Gonia Springs before dissipating in Spencer County (see **Figure 1-1 Storm Path**). The National Weather Service (NWS) classified the tornado as an F-3 on the Fujita Scale with maximum gust speeds in the range of 162-209 mph (according to the NWS's newly adopted Enhanced Fujita Scale, with an implementation date of January 2007, an EF-3 would represent maximum gust speeds of 136-165 mph).[1] The storm lasted approximately 20 minutes, killed 22, injured 150, and damaged several hundred homes. It was the deadliest tornado to strike Indiana since the Super Outbreak of 1974. Though only touching the ground periodically, the total path length was 11.25 miles with a maximum width of 150 yards. **Figures 1- 2** to **1-7** are views of the storm path and illustrate the path width and destruction.




*(Photo Courtesy Courier & Press)*

**Figure 1-1. Indiana Tornado Path, November 6, 2005**
***(actual death toll in Eastbrook Park: 18).***

[1] Enhanced Fujita Scale. http://www.wind.ttu.edu/EFscale.pdf.

*(Photo Courtesy NWS)*

**Figure 1-2. Tornado scars on the earth prior to crossing the Ohio River.**

*(Photo Courtesy NWS)*

**Figure 1-3. Aerial view of tornado damage at Ellis Park Raceway.**

**Figure 1-4. Ellis Park Raceway tornado damage.**


*(Photo Courtesy of NWS)*

**Figure 1-5. Aerial view of Eastbrook Mobile Home Park, Evansville, Indiana.**

*(Photo Courtesy NWS)*

**Figure 1-6. Aerial view of damage to Newburgh neighborhood.**

**Figure 1-7. Residential damage in Newburgh, Warrick County, Indiana.**

## 1.1 Focus of the Investigation and Documentation

The storm investigation was conducted by Larry J. Tanner, P.E., a wind engineer with Texas Tech University Wind Science and Engineering Research Center, and James E. Waller, P.E., a Tennessee structural engineer, President of RemagenSafeRooms, and Past-President of the National Storm Shelter Association. Storm damage was investigated from its beginning at the Ellis Park Raceway to its end near De Gonia Springs; however, the focus of the investigation and detailed documentation was conducted at the Eastbrook Mobile Home Park.

According to the nation's largest publisher of consumer loan information, HSH Associates, one out of 7.5 new single-family housing starts is a manufactured home, and as of 2000, 22 million Americans (about 8 percent of the U.S. population) lived in 10 million manufactured homes.[2] Approximately 1,000-1,200 tornadoes are reported annually in the U.S., and an average of 2 major hurricanes makes landfall on the Atlantic and Gulf Coasts each year. Left in the wake of such devastating storm events are hundreds of dead and seriously injured residents and billions of dollars of destruction to the built environment. Included in this inventory of building damage, and frequently with the greater degree of damage, is manufactured housing, referred to as mobile homes in previous decades.

The Evansville tornado stuck the Eastbrook Mobile Home Park in the early morning of November 6, 2005, inflicting 18 deaths and destroying over 110 homes in the 180 unit complex. The path and narrow width of the path of the vortex of this tornado as it passed through the Eastbrook Mobile Home Park offered a unique opportunity to evaluate the effects of a tornado on mobile home structures ranging from total destruction to little or no damage. The focus of the researchers' investigation was to study the building performance of manufactured housing subjected to such tremendous wind forces in this event and to learn lessons to better mitigate the disastrous effects of such storms on manufactured housing structures and the risks of death and injury to occupants in the future. The following items will be discussed:

- Manufacturing standards for construction and installation of manufactured housing
- Eastbrook Mobile Home Park general damage survey
- Eastbrook Park sample survey documentation
- Analysis and conclusions
- Summary and recommendations

[2] Manufactured Housing Resource Center Manufactured Housing Fast Facts (February, 2006). http://library.hsh.com.

## 2.0 Standards

### 2.1 Manufacturing Standards for Construction and Installation of Manufactured Housing

For over a century, guidelines and standards for "site built" construction have fallen under the realm of the model building codes, i.e., the *Uniform Building Code,* the *Southern Standard Building Code*, and other codes adopted by states, counties, and municipalities. Most of these codes have now given way to the *International Building Code* and the *International Residential Code*. There was no code guidance provided for mobile home design and construction.

In 1964, the first standard for the design of mobile homes was published by the American National Standards Institute (ANSI); however, it was never rigorously enforced. In 1972, the Defense Civil Preparedness Agency in the Department of Defense stated that tie-downs offer the most consistent and effective means for minimizing mobile home damage from high winds and that two types of ties are needed: (1) the "over-the-top" tie and (2) the frame tie. The first type is intended to keep the unit from overturning. The second is intended to prevent it from being blown off the supports.[3] In 1974, the ANSI A119.1, "Standard for Mobile Homes," prescribed different sets of design loads for mobile homes designated to be "hurricane resistant" and ordinary or "standard" homes. It required hurricane units to be designed with a 25 psf wall load on the windward wall and a 15 psf load on the roof and leeward walls. Standard units were to be designed to 15 psf wall and 9 psf loads on the roof and leeward walls with loads being positive on the windward wall and negative on the roof and leeward wall.[4] These prescribed pressures correspond to approximately 88 mph wind speeds for the hurricane units and 71 mph wind speeds for the standard unit. According to ANSI A58.1-1972, *Building Code Requirements for Minimum Design Loads in Buildings and Other Structures,* wind speeds were recorded as the *fastest mile* of wind measured at 33-ft. above the ground in open terrain (Exposure C).[5] These units of wind speed, corrected to today's unit of measurement, *3-second gusts*, would be 108 mph and 86 mph respectively. The 1974 ANSI Standard also called for anchoring devices and required manufacturers to provide instructions for anchoring so that these loads could be transferred from the mobile home to the ground.[6] In 1975 the U.S. Housing and Urban Development Agency (HUD) assumed regulatory responsibility for the industry and published the *Mobile Home Construction and Safety Standards* .[7] This standard was similar to the ANSI standard and applied only to the manufacture and not the installation of mobile homes; however, as early as 1975, an installation standard did exist in the form of NFPA 225-1975, *Mobile*

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[3] Defense Civil Preparedness Agency, Department of Defense, *Protecting Mobile Homes from High Winds*, (Baltimore, 1972), p. 5.

[4] ANSI A119.1, *Standard for Mobile Homes,*(American National Standards Institute, New York, 1974).

[5] ANSI A58.1, *Building Code Requirements for Minimum Design Loads in buildings and Other Structures* (American National Standards Institute, New York,1972).

[6] Van PW and. McDonald JR. "An Engineering Analysis: Mobile Homes in Windstorms," Institute for Disaster Research, Texas Tech University (February, 1978), p. 71.

[7] *Mobile Home Construction and Safety Standards,* ( U.S. Housing and Urban Development Agency, 1975).

*Home Installation Standard*. Without enforcement this publication became merely a suggested guideline.[8]

The HUD standards for design and construction of mobile homes remained virtually unchanged until 1994. In 1994, Article 3280 of the Federal Register, *Manufactured Home Construction and Safety Standards,* was revised.[9] A wind zone map that identified three wind zones was included in this standard (see **Figure 2-1**).

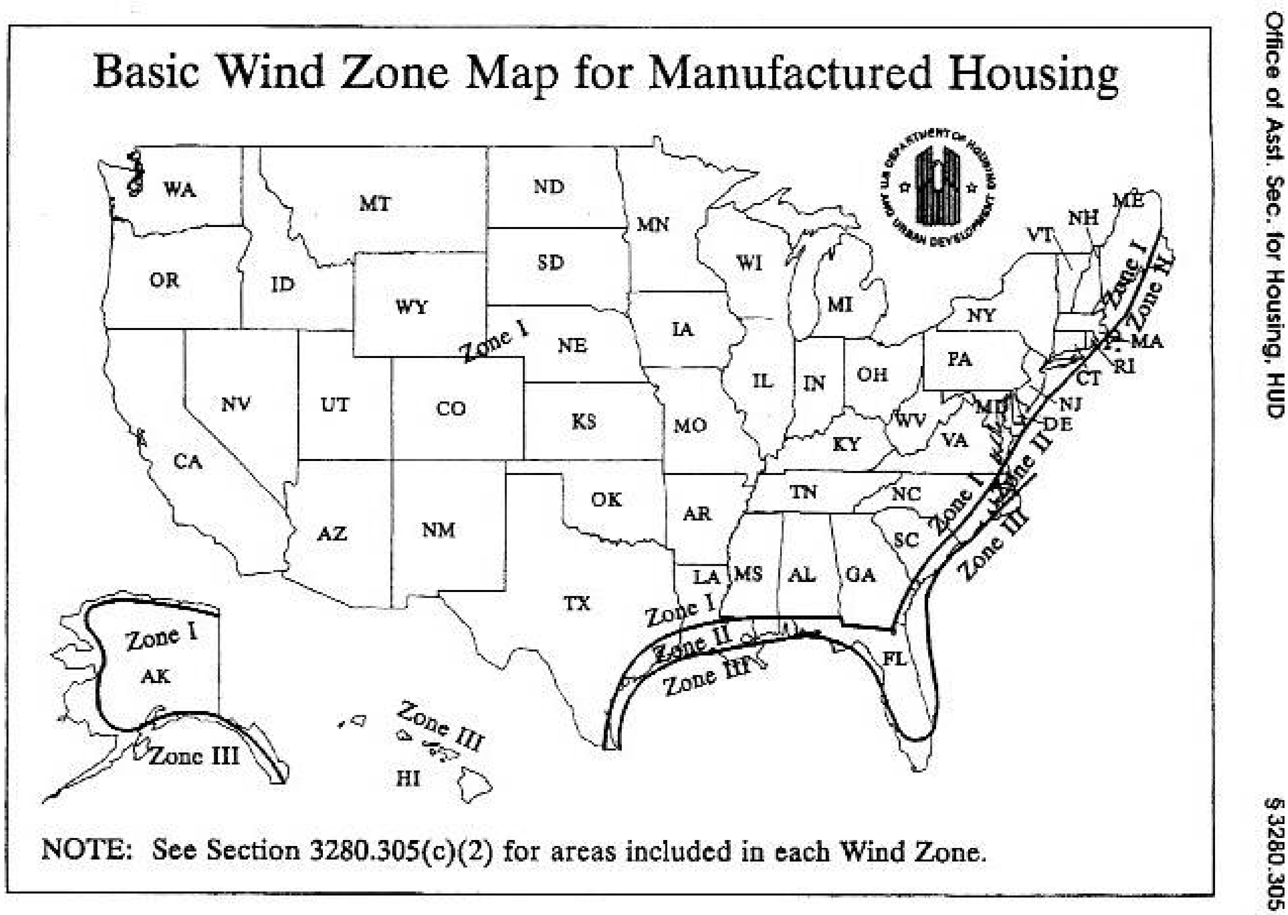


**Figure 2-1. Basic Wind Zone Map, Part 3280,**
**"Manufactured Home Construction and Safety Standards."**

The hurricane high wind zone of the pre-1994 standard was expanded to two zones along the coastal Gulf and Atlantic regions. Wind speeds in this publication continued to be reported in units of *fastest mile* for Exposure C. **Table 2-1** relates zone speeds for both the pre-1994 and the post-1994 standards and includes corrections for *3-second gusts*.

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[8] NFPA 225, *Mobile Home Installation Standard,* (NFPA, Quincy, MA, 1975).
[9] Manufactured Home Construction and Safety Standards, Part 3280, the Code of Federal Regulations, (Department Housing and Urban Development, 1994).

**Table 2-1. Manufactured Housing Zone Wind Speeds**

| Manufacturing Wind Zones | Pre-1994 Standards | | Post-1994 Standards | |
|---|---|---|---|---|
| | *Fastest Mile* | *3-second Gust* | *Fastest Mile* | *3-second Gust* |
| **Zone I** | 71 | 86 | 71 | 86 |
| **Zone II** | 88 | 108 | 100 | 120 |
| **Zone III** | | | 110 | 130 |

In the previous standards, pressures considered for the design of manufactured housing were considered uniform for both the walls and roof. The 1994 Article 3280 recognized the new wind engineering technology that was first contained in the American National Standards (ANSI) Publication A58.1-1982, *Building code requirements for Minimum Loads in Buildings and Other Structures.*[10] This new technology takes into account the velocity pressure acting upon a structure (**Figure 2-2**), but also incorporates the effects of wind gusts and localized pressure coefficients for parts of the building, i.e., building corners, overhangs, etc., where increased wind pressures occur (**Figure 2-3**). Guidance is provided for calculating not only the pressures on the main wind force resisting system (MWFRS), but also those pressures acting on the building components and cladding (C&C). Components and cladding (siding, windows, doors, soffits, etc.), though not a part of the building structure, are essential to maintaining the integrity of a structure during a wind event. The loss of a single component can lead to progressive failures of other components, internal pressurization of the building, and eventual failure of the structure. Unfortunately, the 1994 standard did not address localized building pressures and pressures on components and cladding for Zone I manufactured housing units as seen in **Table 2-2**.

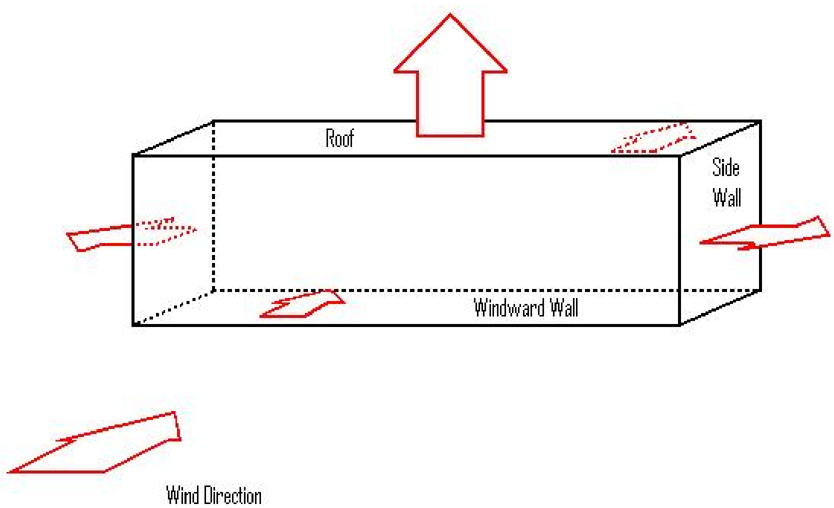


**Figure 2-1. Overall external pressures acting on a mobile home.**

[10] ANSI A58.1-1982, *Building Code Requirements for Minimum Loads in Buildings and Other Structures*, (American National Standards Institute, Inc., 1982).

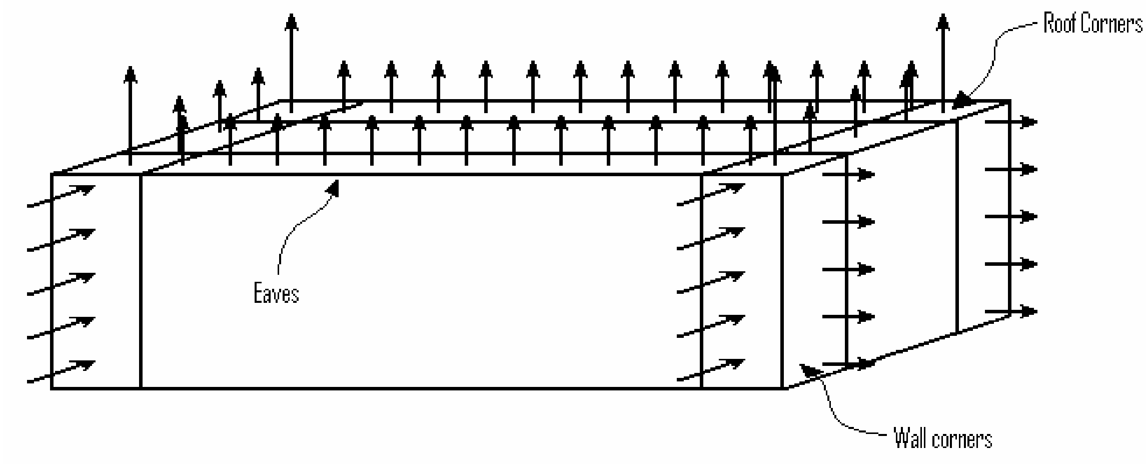


**Figure 2-3. Localized wind pressures on a mobile home.**

**Table 2-2. Comparison of design wind pressures between post-94 and pre-94 code**

| **Element** | | **Wind Zone I 1974 - Present** | **Wind Zone II (pre-94)** | **Wind Zone II (post-94)** | **Wind Zone III (post-94)** |
|---|---|---|---|---|---|
| **MWFRS** | Shear walls, Diaphragms and Anchorage Systems | +/- 15 psf | +/- 25 psf | +/- 39 psf | +/- 47 psf |
| | Ridge beams and other Main Roof Support Systems | - 9 psf | - 15 psf | - 30 psf | - 36 psf |
| **C&C** | Roof Trusses | | - 15 psf | - 39 psf | - 47 psf |
| | Exterior roof coverings, sheathing and fastenings | | - 15 psf | - 39 psf | - 47 psf |
| | Eaves (Overhang at Sidewalls) | | - 15 psf | - 51 psf | - 62 psf |
| | Gables (Overhang at Endwalls) | | - 15 psf | - 73 psf | - 89 psf |

Today, standards for construction and installation of manufactured housing fall under the guidance the federal government agency, Housing and Urban Development (HUD) and the National Fire Protection Association (NFPA). Primary guidance for construction of manufactured housing is contained in HUD, *Manufactured Home Construction and Safety Standards, CFR Part 3280, April, 2003,* and the NFPA 501, *Standard on Manufactured Housing, 2005 Edition.* The HUD 3280 document is virtually unchanged from the original of 1994, and the NFPA 501 document is somewhat repetitive of the HUD standard. Guidelines for construction of manufactured housing are non-prescriptive and general. According to the 2003 Article 3280.305 Structural Design Requirements, "Each manufactured home shall be designed and constructed as a completely integrated structure, capable of sustaining the design load requirements of this standard, and shall be capable of transmitting these loads to stabilizing devices without exceeding the allowable stresses or deflections. Roof framing shall be securely fastened to wall framing, walls to floor structure, and floor structure to chassis to secure and maintain continuity between the floor and chassis, so as to resist wind overturning, uplift, and sliding as imposed by design loads in this part."[11] The design loads include the building dead loads and the applied live loads (wind and snow). The standard requires structural assemblies to be both proof load tested and ultimate load tested. These tests generally regard different structural designs that relate to different unit models, spans, or material types. Proof load tests require that "Every structural assembly tested shall be capable of sustaining its dead load plus superimposed live loads equal to 1.75 times the required lived loads for a period of 12 hours without failure."[12] The standard further states that "ultimate load tests shall be performed on a minimum of three assemblies or components to generally evaluate the structural design. Every structural assembly or component tested shall be capable of sustaining its total dead load plus the design live load increased by a factor of safety of at least 2.5."[13]

In an effort to satisfy these connection requirements 3280.305 requires, "Wind Zone II units must be connected with 26 gage steel strapping or brackets spaced at 24 inches on center and Zone III units with the same type of connectors spaced at 16 inches on center."[14] However, no connecting devices are required for Zone I units. Furthermore, there is no requirement in either Article 3280 or NFPA 501 for any of the zone units to include corner bracing for the resistance of racking shear forces.

Article 3280.306 (a), Windstorm Protection, identifies provisions for support and anchoring systems to resist overturning and lateral movement (sliding) of the manufactured home subjected to the design loads. This section states, "For Wind Zone I, the design wind loads to be used for calculating resistance to overturning and lateral movement shall be the simultaneous application of the wind loads indicated in 3280.305, increased by a factor of 1.5."[15] No load increases or factors of safety are required for the design of Wind Zone II & III units. This article also states that anchoring systems should be designed by a registered professional engineer and that the manufacturer should make provisions for these systems but is not required to provide the anchoring equipment, stabilizing, or connecting devices. The manufacturer is required to provide a minimum number of ties—diagonal ties for Wind Zone I and diagonal plus vertical (over-the-top) ties for Zones II & III. Ties are typically Type 1, Finish B, Grade 1 steel strapping, 1 ¼-in. x .035-in. thick. The manufacturer is required to provide instructions that give

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[11] Manufactured Home Construction and Safety Standards, Part 3280, the Code of Federal Regulations, (Department Housing and Urban Development, 2003).
[12] Manufactured Home Construction and Safety Standards, Part 3280.401(a), the Code of Federal Regulations, (Department Housing and Urban Development, 2003).

[13] Manufactured Home Construction and Safety Standards, Part 3280.401(b), the Code of Federal Regulations, (Department Housing and Urban Development, 2003).

[14] Manufactured Home Construction and Safety Standards, Part 3280.305 (e), the Code of Federal Regulations, (Department Housing and Urban Development, 2003).

[15] Manufactured Home Construction and Safety Standards, Part 3280.306 (a), the Code of Federal Regulations, (Department Housing and Urban Development, 2003).

guidance to the homeowner on the installation of tie-downs and ground anchors. The manufacturer is required to provide a minimum number of tie-downs necessary to carry the loads such that each tie-down resisting wind force is stressed to no more than the allowable tensile stress of the steel tie-down device. Steel strapping tie-downs should be capable of resisting an allowable working load equal to or not less than 3,150 tensile pounds plus a 50 percent overload for a total of 4,725 pounds. The manufacturer's instructions must state that diagonal ties are to be evenly spaced, as practicable, with no more that a 2-foot offset from the ends of the mobile home. Vertical ties, where required, are to be positioned at stud locations and with frame diagonal ties placed at each vertical tie locations.

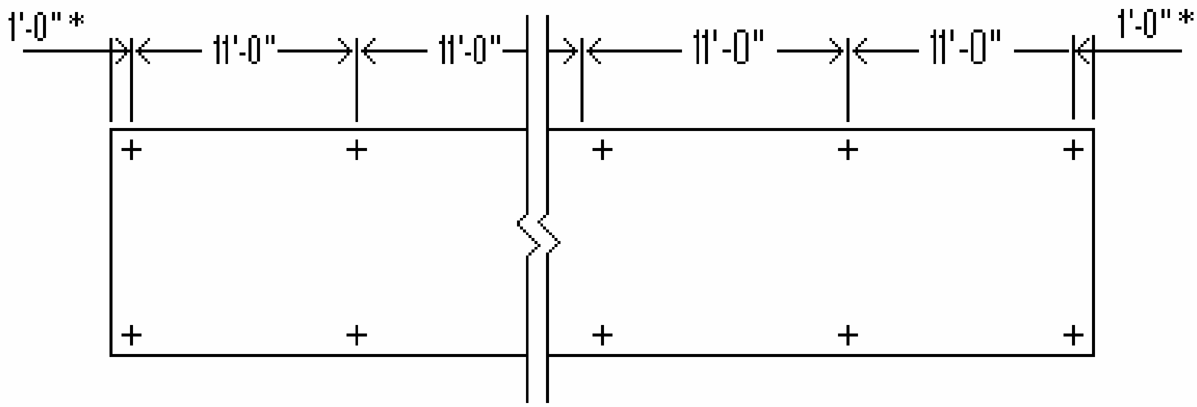
While information regarding the wind resistant design of mobile home tie-downs is discussed in the ANSI and HUD standards, nowhere in the standards are there found specifications governing the installation and the inspection of manufactured housing anchors. Recognizing this loop-hole in the standards, Congress passed the National Manufactured Housing Improvement Act of 2000 requiring each state to develop a manufactured housing installation program in order to provide oversight and enforcement.[16] To assist this endeavor, as well as other installation issues, the NFPA 225, *Model Manufactured Home Installation Standard, 2005 Edition,* was updated. NFPA 225 was modeled on the National Conference of States on Building Codes and Standards (NCSBCS) A 225.1, 1994, which had the original responsibility for managing the ANSI standard. The revised NFPA 225 standard provides specific information on preparing the site, soil bearing capacity determination, design of foundation systems, supporting piers, and anchoring guidelines. For the first time, the maximum anchor spacing was prescribed (see **Table 2-3** and **Figure 2-4**).

[16] *Manufactured Housing Improvement Act of 2000: report of the Committee on Banking, Housing, and Urban Affairs, United States Senate, to accompany S 1452*, (Washington: U.S. G.P.O., 2000).

**Table 2-3. Maximum anchor spacing for manufactured housing**[17]

| Strap Method | Anchor Minimum Ultimate Load Capacity | Maximum Anchor Spacing | | |
|---|---|---|---|---|
| | | Wind Zone I | Wind Zone II | Wind Zone III |
| Single Strap | 4725 lb. | 11-ft. 0-in. | 6-ft. 0-in. | 4-ft. 6-in. |
| Double Strap* | 4725 lb. | 11-ft. 0-in. | 6-ft. 0-in. | 4-ft. 6-in. |

* All homes located in Wind Zones II and III shall have a vertical tie installed at each diagonal tie location.




* Maximum spacing between end of unit and first tie.

**Figure 2-4. Anchor locations and spacings.**

NFPA 225 is very specific in its guidelines for the design of mobile home foundation systems, particularly the design of the piers necessary to provide the transfer of vertical loads from the mobile home to the ground. Piers are permitted to be concrete blocks or pressure-treated wood. Piers less than 36-in. high can be single stacked 8-in. x 8-in. x 16-in. standard weight concrete blocks but must have a solid block at the base and cap on the top of the pier of at least 4-in. x 8-in. x 16-in. Shims between the cap and frame must be a minimum nominal dimension of 2-in. thick x 4-in. wide x 6-in. long (see **Figure 2-5**). Piers greater than 36-in. in height and all corner piers must be double-stacked blocks with blocks interlocked and solid blocks 4-in. x 16-in. x 16-in. at caps and bases, (see **Figure 2-6**). It is important to note that as the pier gets taller, the ability of the tie-down to resist horizontal forces diminishes. As the angle of the tie-down from horizontal increases, tensile force in the tie-down increases for a given horizontal load on the windward side I-beam supporting the mobile home (refer to the force diagrams in **Figures 2-5 & 2-6**).

[17] NFPA 225, *Model Manufactured Home Installation Standard 2005 Edition*, (NFPA, Quincy, MA, 2005). p. 26.

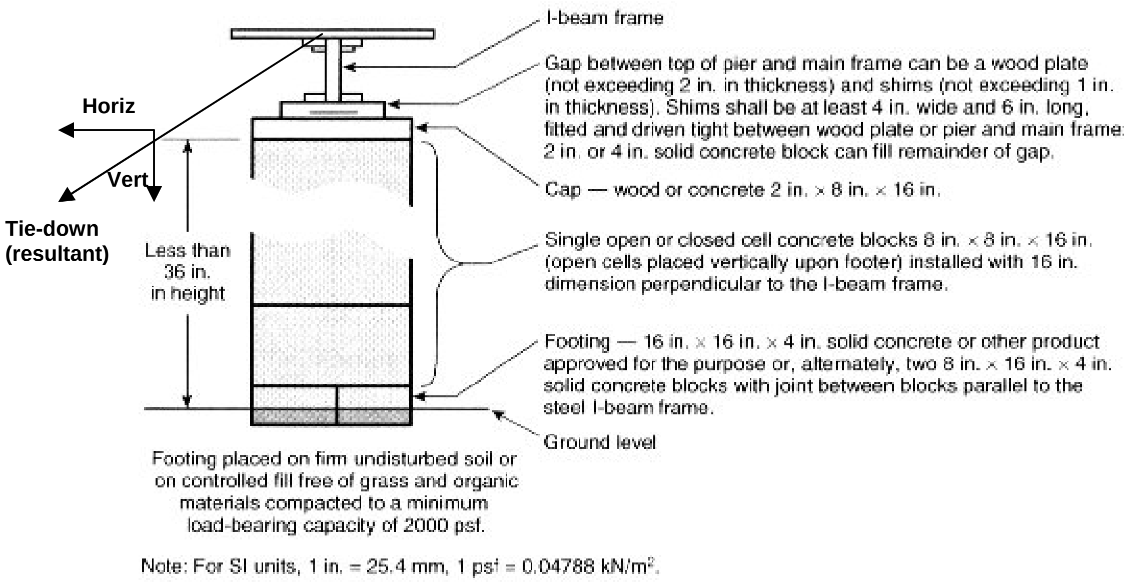



**Figure 2-5. Typical footing and pier installation – less than 36-in. in height.**[18]

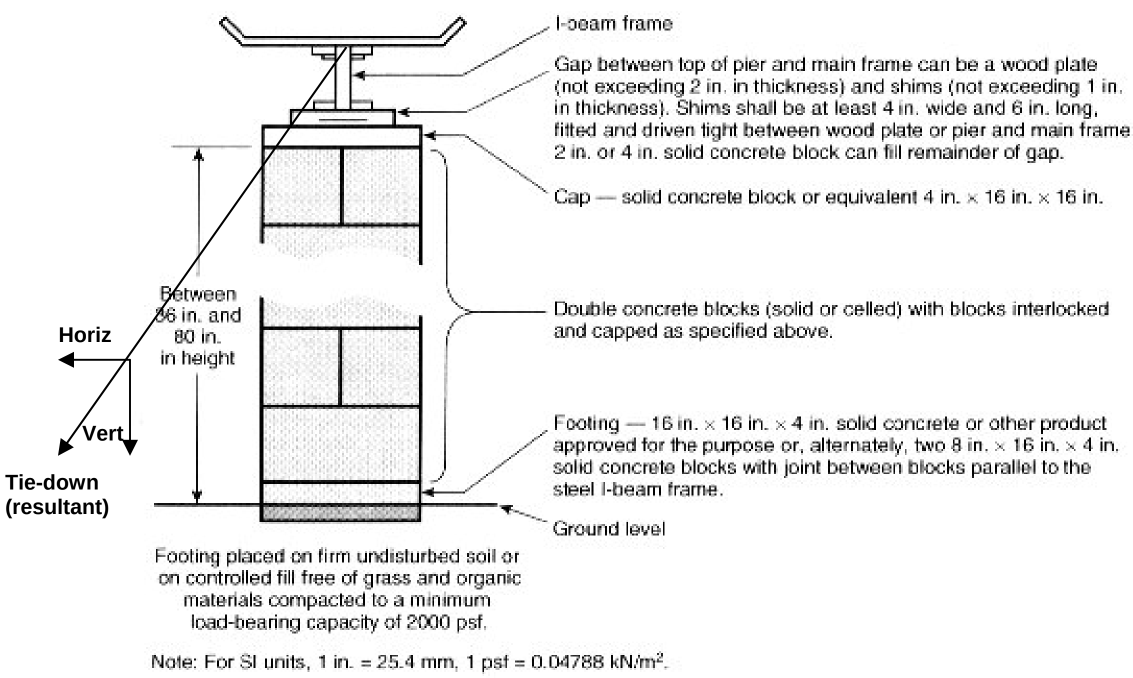



**Figure 2-6. Typical footing and pier installation – Corner locations and heights greater than 36-in.**[19]

[18] NFPA 225, *Model Manufactured Home Installation Standard 2005 Edition*, (NFPA, Quincy, MA, 2005). p. 18.
[19] Ibid.

The load that each pier must carry is dependent upon the unit dimension, roof live load, pier spacing, and the way the piers are used to support the unit.[20] Tables are provided to guide the homeowner and installer as to the location, spacing, and load carrying capacity of the piers. A typical blocking diagram (pier location) is shown in **Figure 2-7**.

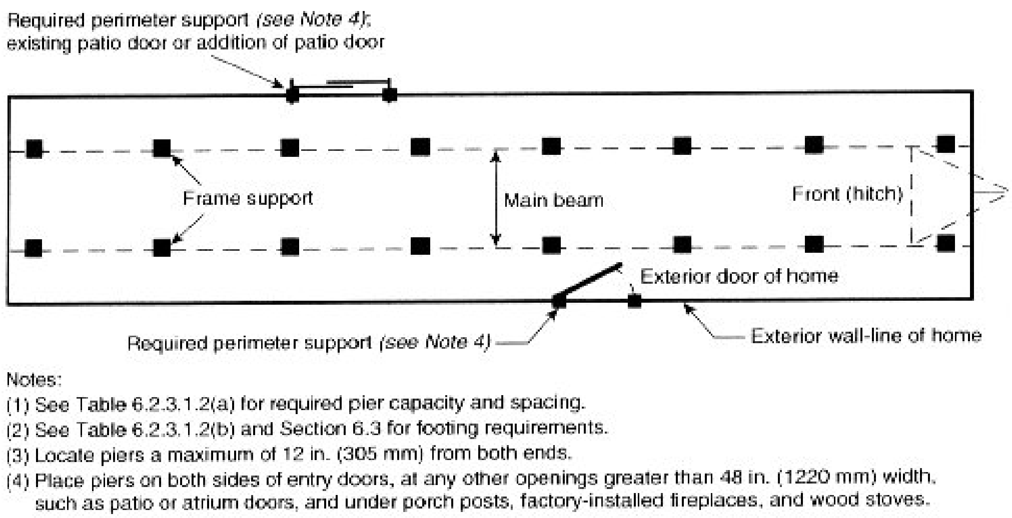



**Figure 2-7. Typical blocking (pier location) diagram for a single-wide home.**[21]

[20] NFPA 225, *Model Manufactured Home Installation Standard 2005 Edition*, (NFPA, Quincy, MA, 2005). p. 21.
[21] Ibid.

## 2.2 Indiana Standards for Manufactured Housing Installation

Prior to the Evansville tornado of November 6, 2005, responsibility of oversight for installation of manufactured housing fell under the auspices of the Indiana Department of Health empowered by the IC 16-41-27 Mobile Home Parks Law. Unit installation was governed by Article 6 Permanent Foundation and Article 7 Temporary Supports. The law generally states that the installation must transfer the loads on the home to the ground.[22] After the November 6 tornado, both articles were repealed by P.L. 87-2005, Section 40, and installation oversight was shifted to the counties and municipalities.

Prior to November 6, the Building Inspection and Code Enforcement Department of Evansville had no authority or inspection responsibilities regarding the installation of manufactured housing. With the repeal of Articles 6 & 7 of the Mobile Home Parks Law and the resulting shift of authority, Evansville/Vanderburgh County drafted Policy Statement 2006-01, covering standards for licensing, permits, and installation of mobile/manufactured housing in parks/communities. The policy requires installers and remodelers to be licensed by the state of Indiana and that all such work is required to be permitted and inspected by the County Building Commission. The following Standards for Installation are contained within the new policy:

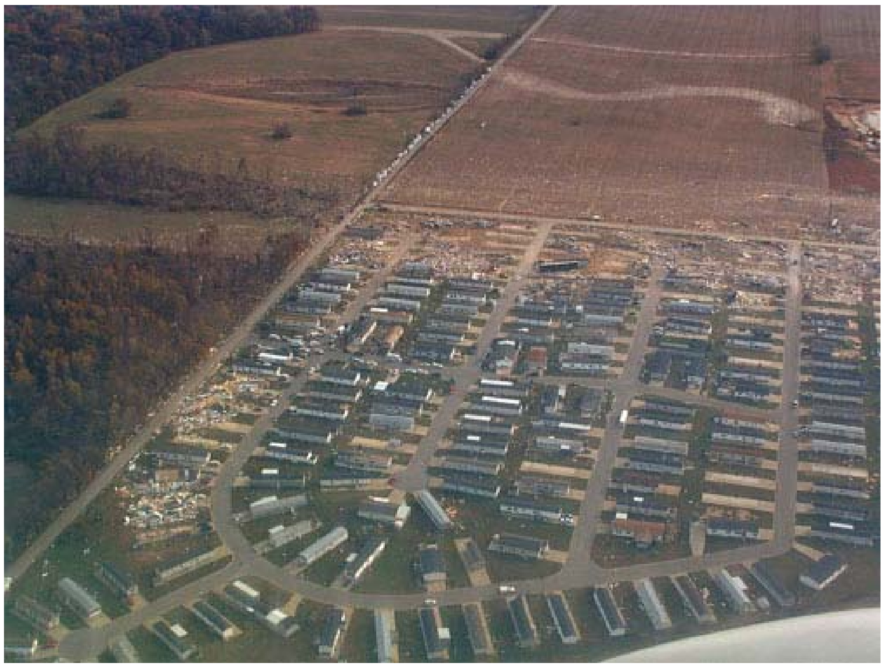
1) New or newer home installations: Manufacturer's specification (inside and outside of parks, including "over the top" straps, if provided).
2) Older home new installations in parks: Transverse anchor straps within 2 ft. of each end and a maximum of 12 ft. on center. Longitudinal straps – 2 on each end (single wide) (including "over the top" straps, if provided).
3) Existing homes on existing lots in parks: current standards – Transverse anchors straps within 6 ft. of each end and a maximum of 24 ft. on center (including "over the top" straps, if provided).
4) Inspection by Building Commission before skirting installed.[23]

[22] IC 16-41-27 *Mobile Home Parks Law*, State of Indiana, 2005.
[23] Policy Statement 2006-1, *Standards for Licensing, Permits, and Installation of Mobile/Manufactured Housing in Parks/Communities in Evansville Vanderburgh County*, (February 27, 2006).

## 3.0 Eastbrook Mobile Home Park Survey

### 3.1 Curbside Park Survey and Damage Assignment

A complete survey of all homes at the Eastbrook MH Park was conducted by investigators Tanner and Waller. **Figure 15**, a partial aerial view looking south, shows the extent of damage across the park. **Figures 16 & 17** are site plans of the park that indicate unit locations and the Degree of Observed Damage (DOD) based upon a Damage Scale of 0-4 (see **Table 3, Damage Scale Portrayal**).

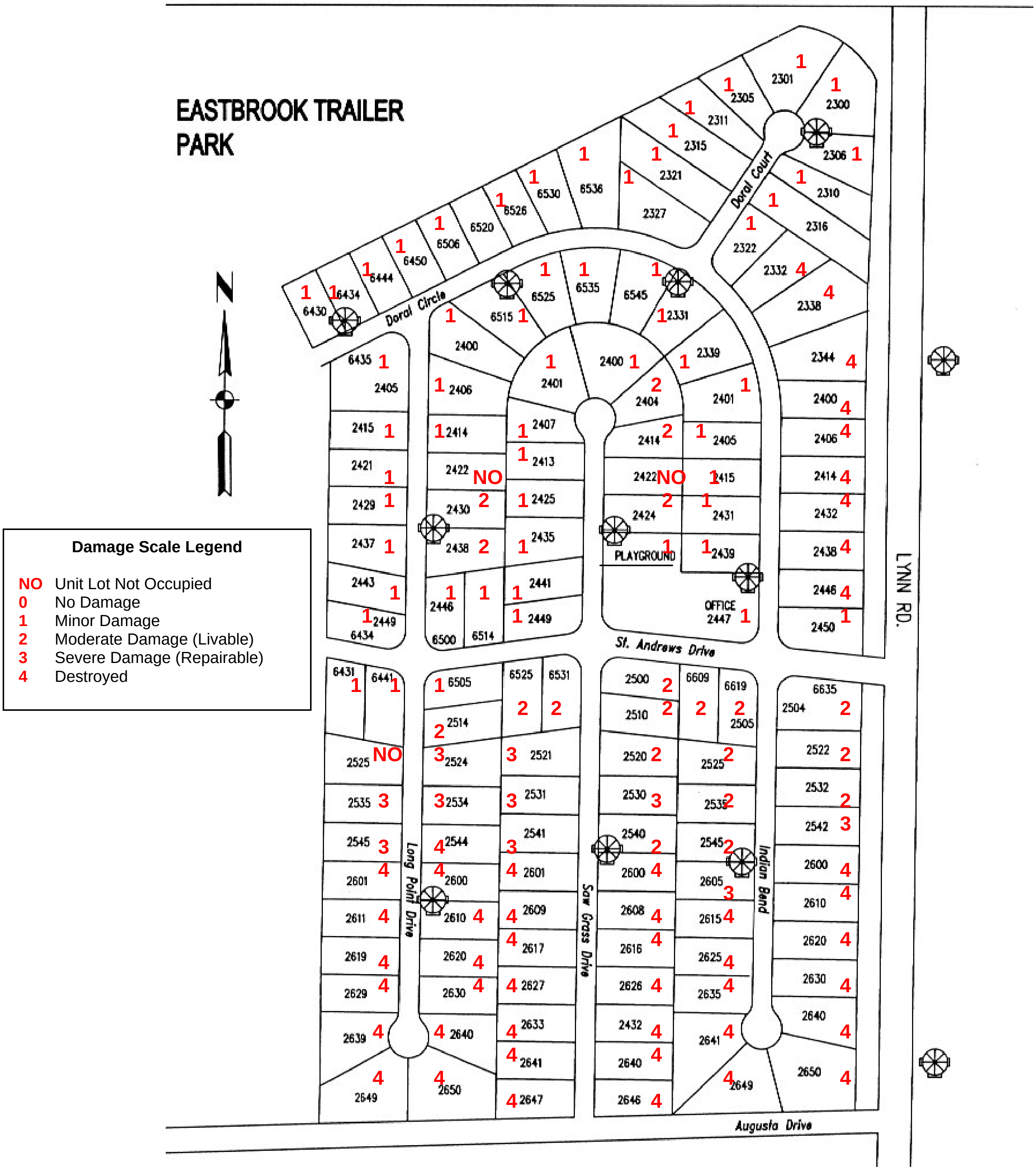


*(Photo Courtesy of NWS)*

**Figure 3-1. Aerial view of east half of Eastbrook Mobile Home Park.**

**Table 3-1. Damage Scale Portrayal**

| | |
|---|---|
| **0 – No Damage**<br><br>No externally visible damage. |  |
| **1 – Minor Damage**<br><br>Cladding and skirting damage, minor shifting off blocking. |  |
| **2 – Moderate Damage**<br><br>Significant cladding and/or roof damage; skirting damage and moderate shifting off blocking; unit still livable. |  |
| **3 – Severe Damage**<br><br>Loss of cladding and/or roofing; doors, windows and walls open to outside; usually complete loss of anchors and blocking; unit repairable, but not livable. |  |
| **4 – Destroyed**<br><br>Unit shifted off of foundation with loss of structure integrity; unit rolled or vaulted; unit walls and roof swept from floor platform; and/or unit impacted and crushed by missiles. |  |




(Maps Courtesy of Eastbrook Mobile Home Park)

**Figure 3-2. Eastbrook Trailer Park-Phase I unit damage per curbside survey.**


*(Maps Courtesy of Eastbrook Mobile Home Park)*

**Figure 3-3. Eastbrook Mobile Home Park-Phases II & III unit damage per curbside survey.**

### 3.2 Failure Mechanisms of Units in the Eastbrook Mobile Home Park

Distribution of wind pressures exerted on individual structures, such as mobile homes, is essentially the same regardless of the type of windstorm. The three basic types of windstorms include: (1) tornado, (2) hurricane, and (3) straight line winds. Tornado winds rotate about a central core or vortex, and though hurricane winds rotate about an eye, their winds appear more straight line due to the width of the storm. Straight line winds incorporate all other types of winds associated with high and low pressure systems, frontal passages, squall lines, thunderstorms, and orthographic winds on the lee sides of mountain ranges. On November 6, 2005, the Eastbrook Mobile Home Park was struck by cyclonic winds from an F3 tornado.

There are three possible mechanisms of failure by which a windstorm can damage a mobile home or other structure: (1) high aerodynamic pressures resulting from air flowing (velocity pressures) over and around a structure; (2) impacts from flying debris or missiles (sheet metal, wood siding and framing, furniture, appliances, vehicles, etc.) dislodged or disgorged from upwind locations; and (3) atmospheric pressure change, sometimes referred as the "explosive effect," which is unique to tornados.[24]

[24] Van PW and McDonald JR., "An Engineering Analysis: Mobile Homes in Windstorms," (Institute for Disaster Research, Texas Tech University, February, 1978), p. 9.

### 3.2.1 Wind Pressures

Failures produced by high wind pressures were predominant in the Evansville tornado. Minor failures are normally characterized by damage to light components and cladding elements (skirting and shutters), damage to weak attachments (awnings and patio covers), damage from debris impacts, roof damage (shingles and roof fascias), and minor sliding on supporting piers (see **Figure 3-4**). Minor damaged units often remain livable during repairs.


**Figure 3-4. Minor, repairable and livable - roof, cladding and skirting damage**.

Repairable moderate to severe damage was observed with units located nearer to the storm vortex. This type of damage usually began with failure of anchoring ties, resulting in sliding and isolated structural failures. **Figure 3-5** shows a Zone II/III unit front and back that suffered cladding damage and slid off its stabilizing blocks, collapsing some foundation piers and producing warping of the floor frame. The sliding was initiated with the failure of ties (see **Figure 3-6**). Also shown in this figure is an overhead (Zone II/III) tie that was not attached.


**Figure 3-5. Unit tie downs were inadequate to hold the wind pressures and broke, thereby allowing the unit to slide. Unit suffered repairable roof and wall cladding damage.**

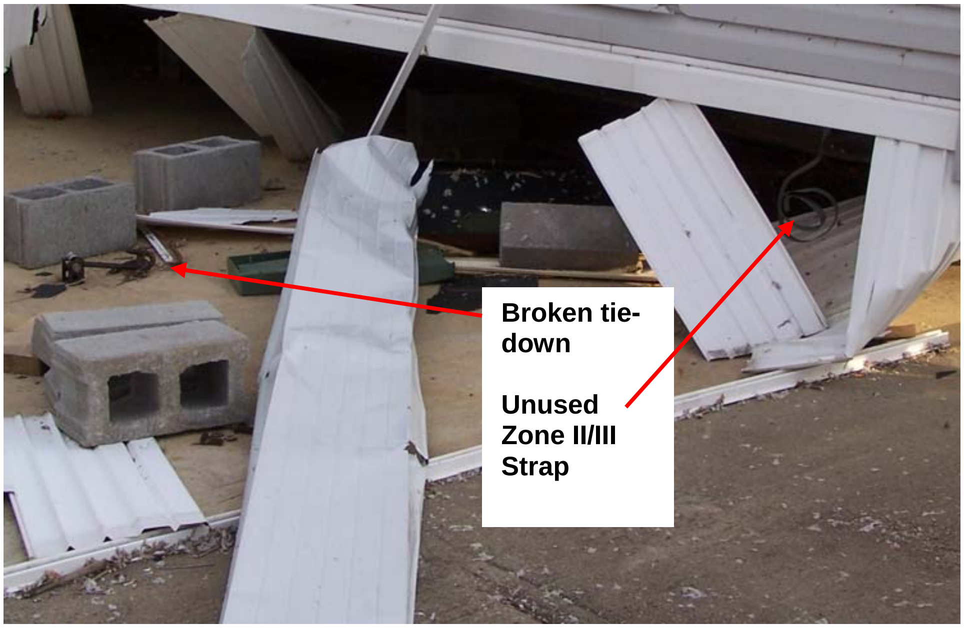



**Figure 3-6. Unit sliding initiated by broken tie-downs.**

All of the roof cladding and fascia material was blown from the unit shown in **Figure 3-6.** Although the unit is structurally repairable, significant damage to the interior walls, finishes, and contents resulted from storm rainwater. Wind pressure produced forces on tie-downs that broke the tie-downs restraining the unit in **Figure 3-7**, slid the unit off its piers, and peeled off a portion of the roof and siding.


**Figure 3-7. Unit severely damaged by the removal of the roof and fascia cladding.**


**Figure 3-8. Major damage - hole in unit roof, cladding and fascia damage, and missile impacts.**

Total unit destruction was extensive, as seen in the aerial photo (**Figure 3-9**). It is estimated that approximately 110 of the 180 units were destroyed, Degree of Damage (DOD) 4. In most cases, failure was initiated by loss of the unit anchors. It should be noted that this investigation was conducted the first three days after the storm. The accumulation of debris was extensive in the areas of the greatest devastation and in-depth investigation in these areas was therefore limited. Typical modes of failure leading to unit destruction were overturning; structural racking from sliding; house separation from the under-frame (undercarriage); walls separated from the floor decking; and vaulting or tossing of the unit from its original location (see **Figures 3-10** to **3-14**). At least four units were found to have been installed without any tie-downs (**Figure 3-15**).


*Photo Courtesy Courier & Press*

**Figure 3-9. Southeast corner of Eastbrook Mobile Home Park.**

**Figure 3-10. Mobile home from Poppy Hills Drive that slid from its anchorage and was structurally racked.**

**Figure 3-11. Unit lost anchorage and rolled into an adjacent home.**


**Figure 3-12. Unit rolled onto adjacent mobile home.**


**Figure 3-13. Mobile home tossed and rolled – walls, roof, and floor separated from undercarriage.**

**Figure 3-14. Units tumbled and tossed by the wind forces.**


**Figure 3-15. Previous location of double-wide unit without any tie-downs; unit was tossed and tumbled to destruction.**

### 3.2.2 Storm Debris

Debris and windborne missiles were abundant. **Figure 3-16** portrays the debris collected just east of the Park and includes a 20-ft. 2"x 6" piece of lumber. Small missiles such as asphalt shingles damaged and penetrated the vinyl cladding of units (**Figure 3-17**), and larger missiles completely perforated walls (see **Figure 3-18**). The largest missile observed was a truck that cut a mobile home in half (see **Figure 3-19**).


**Figure 3-16. Field east of the Eastbrook Park littered with debris, including a 20-ft. long 2"x 6" piece of lumber.**

**Figure 3-17. Shingle embedded in mobile home wall.**


**Figure 3-18. Unit perforated with a 2”x 8” wooden missile.**

**Figure 3-19. Mobile home impacted and cut in half by a large van.**

### 3.2.3 Atmospheric Pressure Change

Atmospheric pressure change is the third mechanism of failure and is unique to tornadoes. A tornado is an extremely low pressure weather event. The drop in pressure from the outside to the inside of the core of an intense tornado may be as great as 285 psf and is related to the tangential wind speed of the tornado. If a tornado core (vortex) passes directly over a structure and the structure is not vented so that the air inside can escape to the outside, a net outward pressure equal to the pressure drop is induced on all of the structure's inside surfaces producing a "virtual explosion" of the damaged structure. In reality, most structures have doors and windows that are not air tight and become "naturally" vented by missile impacts. The phenomena is normally an aerodynamic result when the interior of the structure becomes internally pressurized by the wind pushing in a windward surface or debris impacts create an opening in the building envelope through which the wind may enter. The end result is an "explosive effect," with the exception of an inwardly failed portion of a windward wall.[25] No specific evidence was found to reveal any failures as the result of atmospheric pressure change in the Evansville tornado; however, the total disintegration of so many mobile home units, as seen in **Figure 3-19**, strongly suggests that internal pressurization may have contributed to the fragmentation of many units.

[25] Van PW and McDonald JR, *An Engineering Analysis: Mobile Homes in Windstorms*, (Institute for Disaster Research, Texas Tech University, February, 1978), p. 15.

### 3.3 Sample Damage Survey

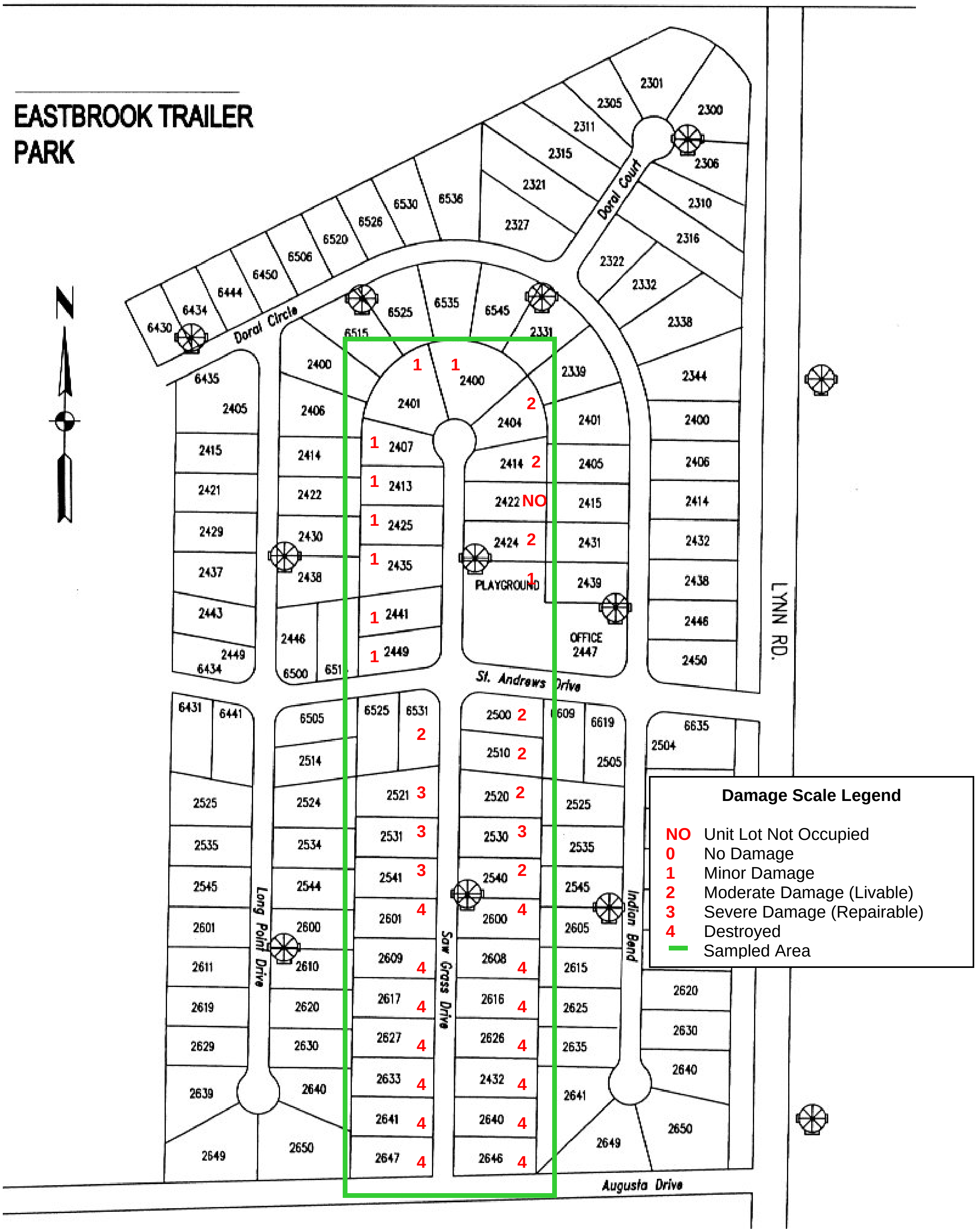
The performance of mobile homes subjected to extreme winds is directly related to unit construction and anchorage of the unit to the ground. The strength of the unit, as previously detailed, is prescribed by the HUD *Manufactured Home Construction and Safety Standards, Article 3280*. The design wind speed for a Zone I unit, typical for Indiana and non-coastal regions, is 86 mph, 3-second gust. Mobile homes at or near the vortex of the tornado that struck on November 6 experienced winds far in excess of that velocity. The unit shown in **Figure 3-20** was located very near the vortex and was structurally unable to resist the wind forces even though it had numerous, closely spaced tie-downs. Its tie-downs failed, thereby allowing the unit to be displaced from its original location and the home superstructure behaved like a "wind sail" and was separated from the structural steel frame.


**Figure 3-20. Under-frame of unit from a destroyed mobile home.**

Unit installation and anchorage is prescribed by the NFPA 225, *Model Manufactured Home Installation Standard,* and at the time of the storm's occurrence in the state of Indiana, it was enforced by the Indiana Department of Health under IC 16-41-27 Mobile Home Parks Law. The researchers sampled two of the park's streets selected at random (see **Figures 3-21** & **3-22**). Information collected included the types of tie-downs and anchors, if any; whether the unit was moved by the storm or by debris impact; and the condition of the unit under-skirting (see **Tables 3-1** & **3-2**). Data was uncollectible from 17 units due to debris. The collected data from this sample follows:

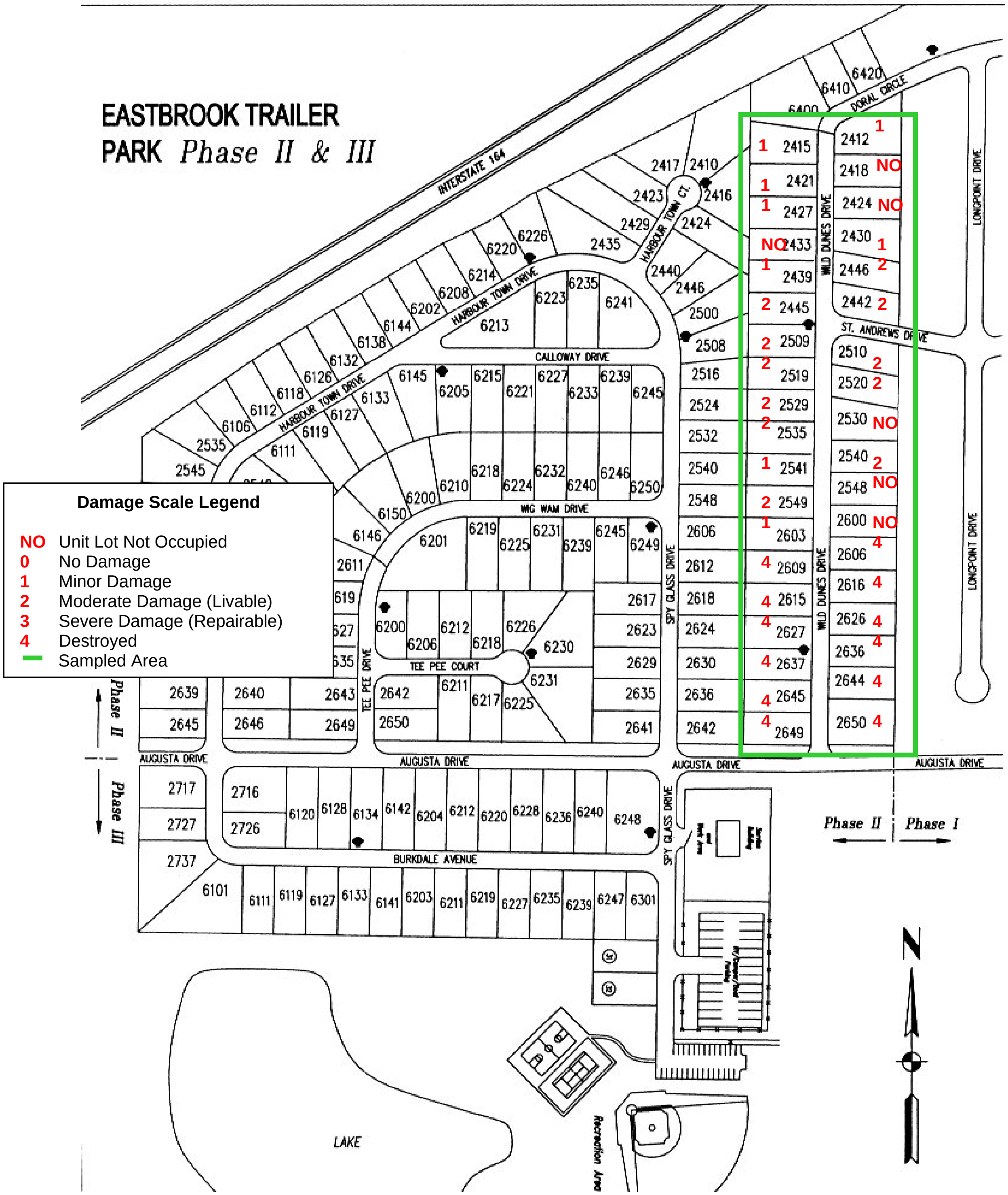
- 30 of the 66 units (45%) were severely damaged or destroyed
- 72% of the units had some form of tie-downs, 54% of those tight
- 53% of the units had shifted off foundation piers
- 80% of the units utilized the park supplied cast-in-place anchors
- 3 units were double-wide mobile homes
- 10 units were Zone II/III mobile homes, but only 4 units had their over-the-top ties connected

Data was collected regarding the performance of the unit skirting. Many believe that skirting prevents the wind from getting under the unit, thereby preventing the unit from being lifted. Research is inconclusive regarding the benefit of skirting. Some research has shown that the presence of skirting prevents the development of suction pressures on the underside of the home that could assist in uplift and overturning resistance. It is a given that the presence of skirting does increase the wall area receiving wind pressures. Where tie-downs had broken, skirting was almost always blown away. Skirting was also missing from many units where tie-downs were still intact. Regardless, skirting seldom survives a high wind event. In the case of the homes sampled, the skirting was a lightweight vinyl material that was easily damaged and removed by high winds and debris impacts.




*(Maps Courtesy of Eastbrook Mobile Home Park*

**Figure 3-21. Sampled units, Sawgrass Drive.**




(Maps Courtesy of Eastbrook Mobile Home Park

**Figure 3-22. Sampled units, Wild Dunes Drive.**

## Table 3-1. Installation Description of Sampled Units on Sawgrass Drive

| Mobile Home Address | Unit Has Tie-Downs | Tie-Downs are Tight | Unit Shifted on Pad | Expansion Anchors | Earth Anchors | Cast-in Hook Anchors | Unit Moved by Debris Impact | Skirt Damaged or Missing | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 2401 Sawgrass | No | | No | No | No | No | No | Yes | Zone II/III Unit, no straps attached |
| 2407 Sawgrass | Yes | No | No | Yes | Yes | Yes | No | Yes | Zone II/III Unit, overtop straps not attached, no attachment on south side |
| 2414 Sawgrass | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2425 Sawgrass | Yes | Yes | No | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps connected, except east end |
| 2435 Sawgrass | Yes | No | No | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps connected |
| 2441 Sawgrass | Yes | Yes | No | Yes | No | Yes | No | Yes | Zone II/III Unit, overtop straps connected |
| 2449 Sawgrass | Yes | Yes | No | No | Yes | No | No | Yes | |
| 2400 Sawgrass | Yes | Yes | No | Yes | No | No | No | Yes | Double Wide Unit, Frame straps broke |
| 2404 Sawgrass | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2414 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps not connected |
| 2424 Sawgrass | Yes | Yes | No | Yes | No | No | No | Yes | |
| 2426 Sawgrass | Yes | No | No | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps connected |
| 6531 St. Andrews Drive | Yes | Yes | No | No | Yes | Yes | No | Yes | Double Wide Unit |
| 2500 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | |
| 2510 Sawgrass | Yes | No | No | No | No | Yes | No | Yes | |
| 2520 Sawgrass | Yes | No | No | No | No | Yes | No | Yes | Zone II/II Unit, overtop straps not connected |
| 2521 Sawgrass | Yes | Yes | Yes | No | No | Yes | No | Yes | Minor shifting of unit off blocks |
| 2530 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps not connected |
| 2531 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | |
| 2540 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | Zone II/III Unit, overtop straps not connected |
| 2541 Sawgrass | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2600 Sawgrass | Yes | No | Yes | Yes | No | No | No | Yes | Unit Destroyed |
| 2601 Sawgrass | No | | Yes | | | | No | Yes | Unit Destroyed |
| 2608 Sawgrass | Yes | | | | | | | | Unit Destroyed |
| 2609 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | Unit Destroyed |
| 2615 Sawgrass | Yes | No | Yes | No | No | Yes | No | Yes | Unit Destroyed |
| 2617 Sawgrass | Yes | No | Yes | Yes | No | No | No | Yes | Unit Destroyed |
| 2626 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2627 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2432 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2633 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2640 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2641 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2646 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |
| 2647 Sawgrass | Unknown * | | | | | | | | Unit Destroyed |

Site covered in debris

## Table 3-2. Installation Description of Sampled Units on Wild Dunes Drive

| Mobile Home Address | Unit Has Tie-Downs | Tie-Downs are Tight | Unit Shifted on Pad | Expansion Anchors | Earth Anchors | Cast-in Hook Anchors | Unit Moved by Debris Impact | Skirt Damaged or Missing | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 2412 Wild Dunes Drive | Yes | No | No | No | No | Yes | No | Yes | |
| 2415 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | Yes | Yes | |
| 2421 Wild Dunes Drive | Yes | No | No | No | Yes | No | No | Yes | |
| 2427 Wild Dunes Drive | Yes | No | No | No | No | Yes | No | Yes | |
| 2430 Wild Dunes Drive | Yes | No | Yes | Yes | No | No | No | Yes | |
| 2439 Wild Dunes Drive | Yes | No | No | Yes | No | Yes | No | Yes | |
| 2446 Wild Dunes Drive | Yes | Yes | No | Yes | No | Yes | No | Yes | |
| 2442 Wild Dunes Drive | Yes | Yes | No | Yes | No | Yes | No | Yes | |
| 2445 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2509 Wild Dunes Drive | Yes | No | No | No | No | Yes | No | Yes | |
| 2510 St. Andrews Drive | Yes | No | No | No | No | Yes | No | Yes | |
| 2519 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2520 Wild Dunes Drive | Yes | No | No | No | No | Yes | No | Yes | |
| 2529 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2535 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2540 Wild Dunes Drive | Yes | Yes | No | No | No | Yes | No | Yes | |
| 2541 Wild Dunes Drive | Yes | No | No | No | No | Yes | No | Yes | Double Wide Unit |
| 2549 Wild Dunes Drive | Yes | No | Yes | No | No | Yes | Yes | Yes | |
| 2603 Wild Dunes Drive | Yes | No | Yes | Yes | No | No | Yes | Yes | |
| 2609 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2606 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2615 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2616 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2626 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2627 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2636 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2637 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2644 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2645 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2649 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |
| 2650 Wild Dunes Drive | Unknown * | | | | | | | | Unit Destroyed |

* Site covered in debris

### 3.3.1 Mobile Home Pier Supports and Tie-Downs

As previously discussed in the Modes of Failures section of this report and as indicated in the Unit Sample Survey, the performance of unit tie-downs was a major factor affecting the general performance of the mobile homes subjected to this severe wind event. Numerous types of ties, tie spacing, methods of anchoring, and pier installations were observed. The corner pier in **Figure 3-23** is a single wide concrete block unit that is an improper installation per NFPA 225. The double wide block pier as shown in **Figure 3-24** is correctly installed. The corner pier shown in **Figure 3-25**, though properly sized, is shimmed with ¾-in. lumber that easily loosened in the buffeting winds. Note also, the steep angle of the tie-down. There is little horizontal resistance capacity in this tie to the sliding wind forces, the result of which is shown in **Figure 3-31** with its leaning pier.

Over 20 of the 180 units were Zone II/III units with over-the-top straps; however, only 4 of these units were observed with these straps connected to ground anchors. NFPA 225 clearly states that, "If sidewall or over-the-top roof straps are installed on the home, they shall be connected to an anchoring device…"[26] It further states that "Manufactured homes shall have anchors to resist longitudinal forces."[27] Longitudinal straps, as seen in **Figure 3-23,** were seldom observed at the Eastbrook Park. The unit end-strapping typically found installed at the Eastbrook Park is shown in **Figure 3-24**.

Two types of diagonal tie-down systems were observed, with the most common being the 1 ¼-in. x .035-in. steel strap prescribed Article 3280.306 and NFPA 501 (see **Figure 3-25**). These straps were normally connected to the under-frame by virtue of a hook or a buckle on the end of the strap. The steel type strap was utilized on the Zone II/III units, though few were installed, also shown in **Figure 3-25**. The other type of tie-down system was a strut-tie-anchor system shown in **Figure 3-26**.

[26] NFPA 225, *Model Manufactured Home Installation Standard 2005 Edition*, (NFPA, Quincy, MA, 2005), p. 26.
[27] Ibid.

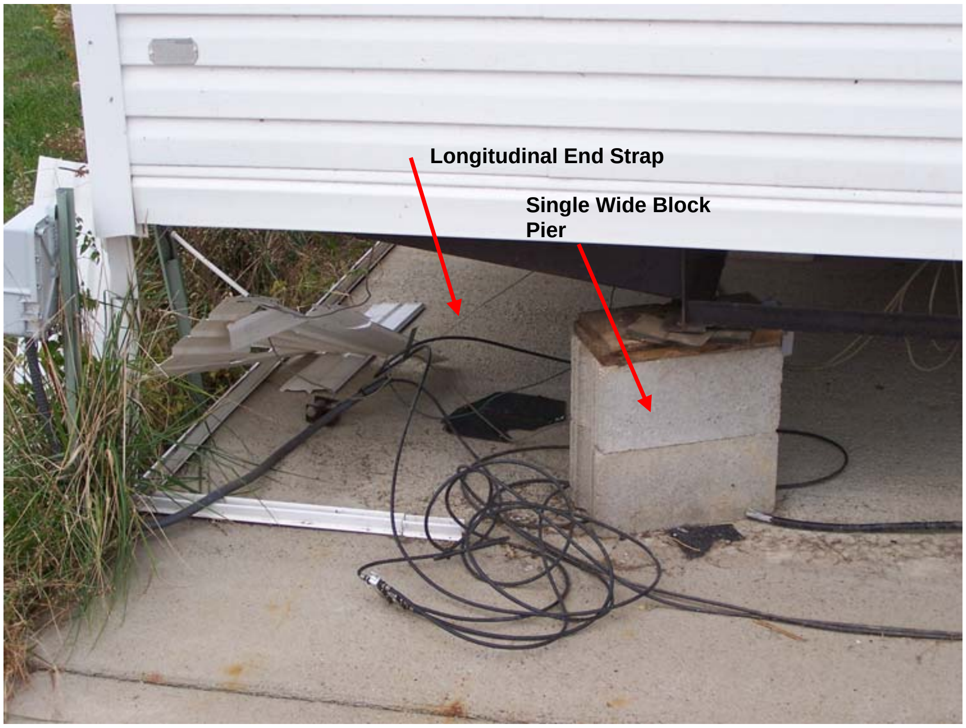



**Figure 3-23. Properly installed longitudinal unit end strap.**

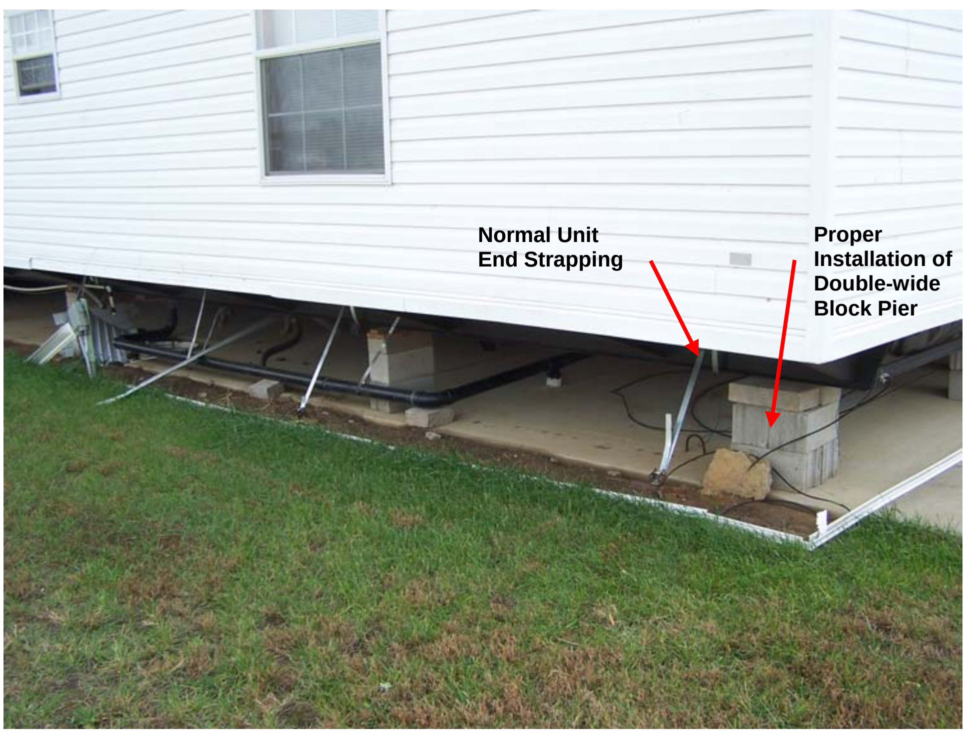



**Figure 3-24. Normally observed unit end strapping.**

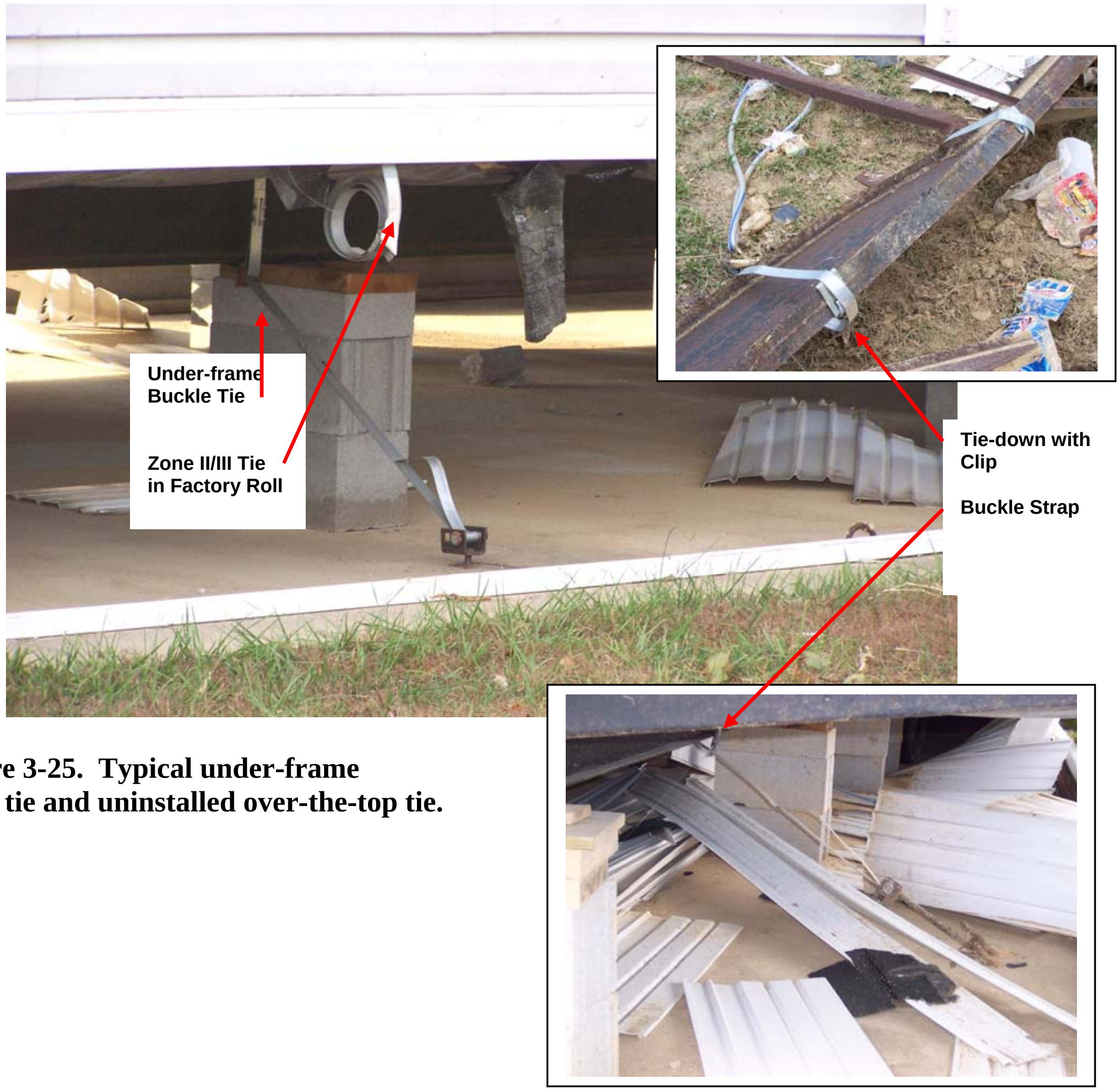



**Figure 3-25. Typical under-frame strap tie and uninstalled over-the-top tie.**

**Figure 3-26. Strut-type under-frame tie.**

Numerous methods were used to connect and anchor the ties to the ground. The Eastbrook Park provided concrete pads on which to locate the units. Typically, but not always, anchoring loops made of #4 (1/2-in.) reinforcing steel were embedded in the concrete on approximately 12-ft. to 24-ft. centers. A steel hook with a ratcheting cam bolt was used to connect and tighten the strap (**Figure 3-27**). Two other types of anchors were observed: earth helical anchor (**Figure 3-28**); and a cam-bolt connector screwed into a threaded expansion anchor mechanically embedded in the concrete (**Figure 3-29**). It was also common to find mobile homes anchored with a combination of all three types of anchor systems.

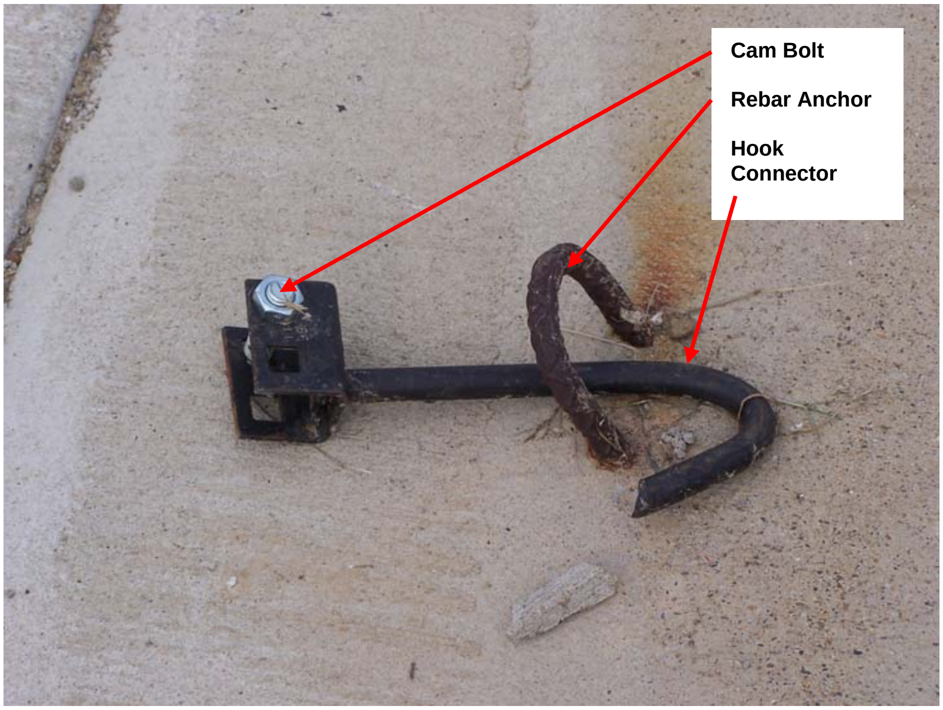



**Figure 3-27. Rebar loop anchor with hook and cam connector.**

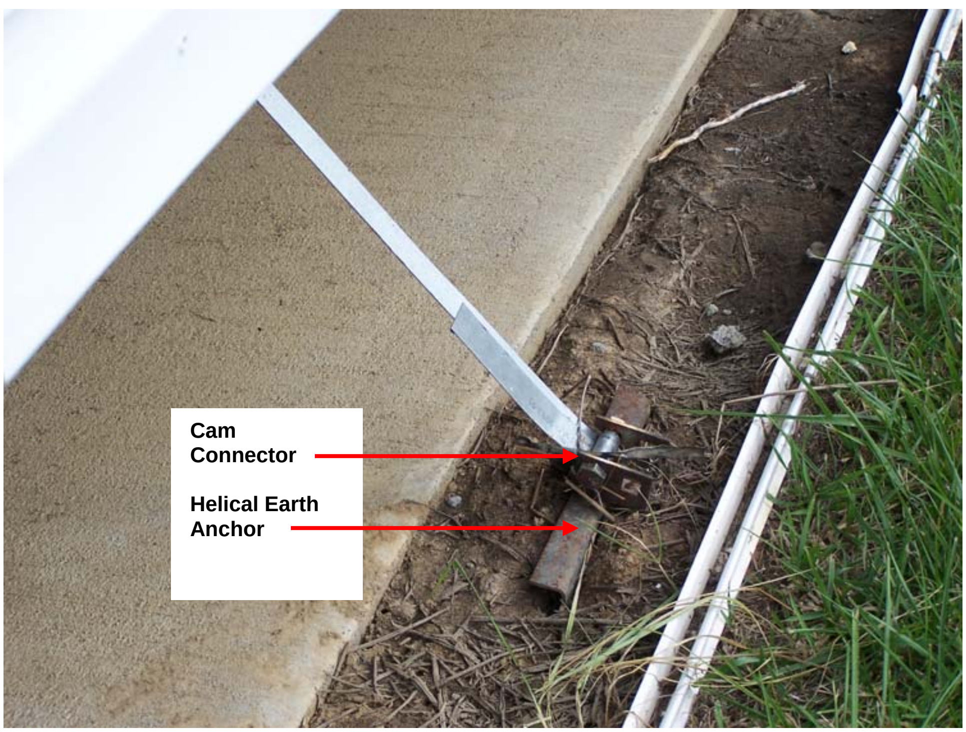



**Figure 3-28. Helical earth anchor with cam connector.**


**Figure 3-29. Expansion bolt anchoring system.**

Regardless of the type of anchoring system utilized, the mechanism of failure was generally the same; the strap broke, as shown in **Figure 3-30**. The failure sequence would begin with the wind forces pushing, lifting, and sliding the unit off its piers (see **Figure 3-31**), a process facilitated by loose ties, and ultimate failure of the strap at a bend on the frame flange, (see **Figure 3-30**).The standard method of connecting the strap to the frame was to loop the strap around the frame, much like a belt and buckle or to hook the strap on one flange of the frame and then wrap the strap around the frame (**Figure 3-32**). The writers conclude from the evidence observed that the tie-down strap failure was most commonly the combined results of excessive tensile stresses from the wind forces, combined tensile and flexural stresses resulting in steel straps by shifting of the under-frame (see **Figure 4-17**), and brittle fatigue or shearing of the straps hooked around the sharp flange edges which was produced by the rocking motion of the unit (see **Figure 3-33**).

Anchorage failures were not limited to the breaking of tie-down straps. Numerous expansion bolted anchors and several of the rebar loop anchors were sheared at the slab line (see **Figures 3-34** & **3-35**). A large number of anchors were installed improperly, some of which would have led to failures if the units had been closer to the tornado's vortex. In **Figure 3-36** the earth anchor is fully embedded into the ground. The extended stem is easily subject to bending, loosening of the strap, and eventual withdrawal of the anchor from the soil. Similarly, the bolt in the expansion anchor in **Figure 3-37** is not snug to the slab and therefore is subject to bending.

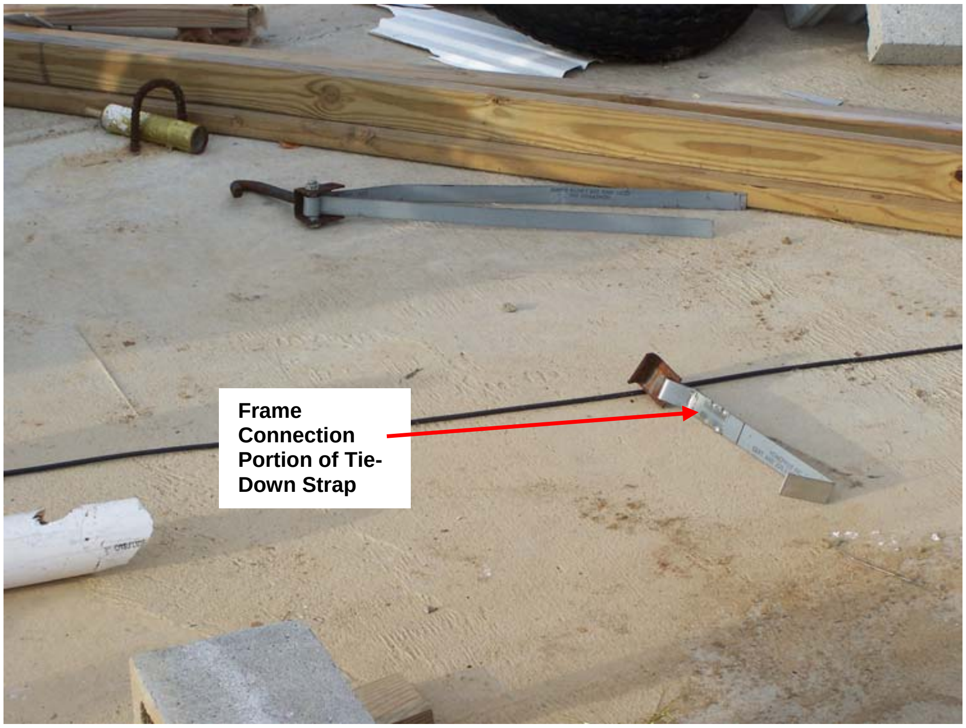



**Figure 3-30.  Typical broken tie-down strap.**


**Figure 3-31.  Support piers shifted by mobile home sliding.**


**Figure 3-32. Typical installation–tie-down strap hooked and wrapped over frame.**


**Figure 3-33. Fatigued tie-down strap.**

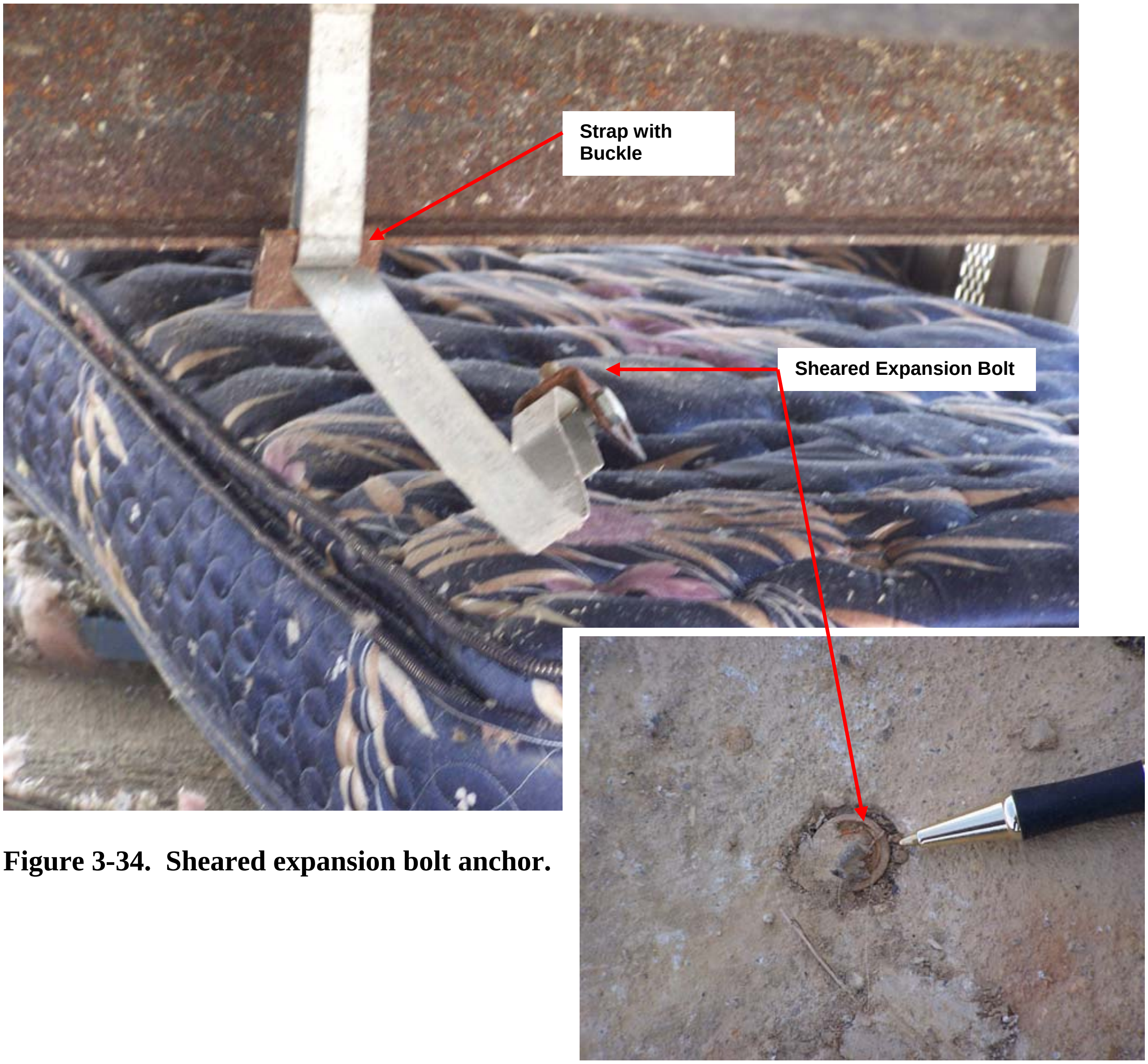



**Figure 3-34. Sheared expansion bolt anchor.**

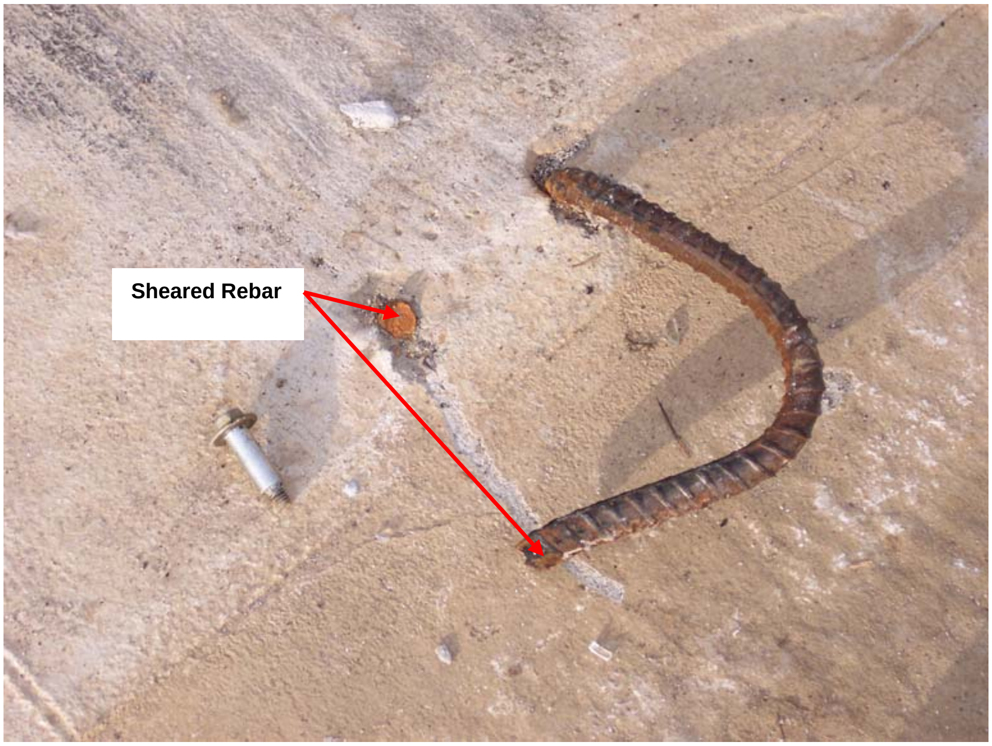



**Figure 3-35. Sheared rebar loop anchor.**

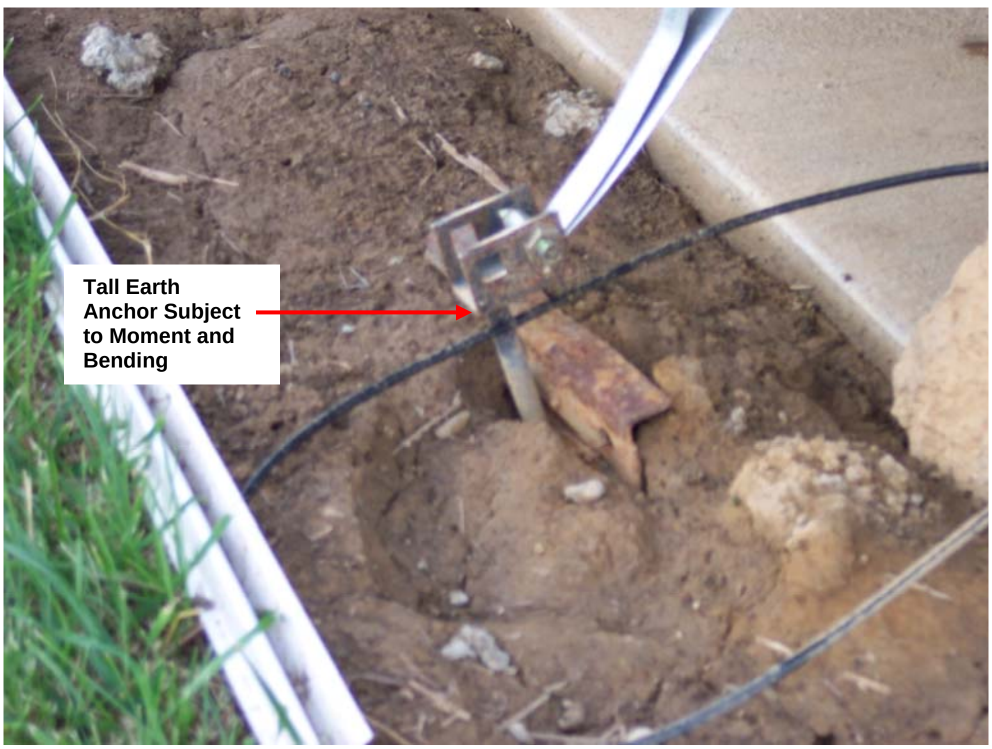



**Figure 3-36. Tie-down connected to earth anchor.**

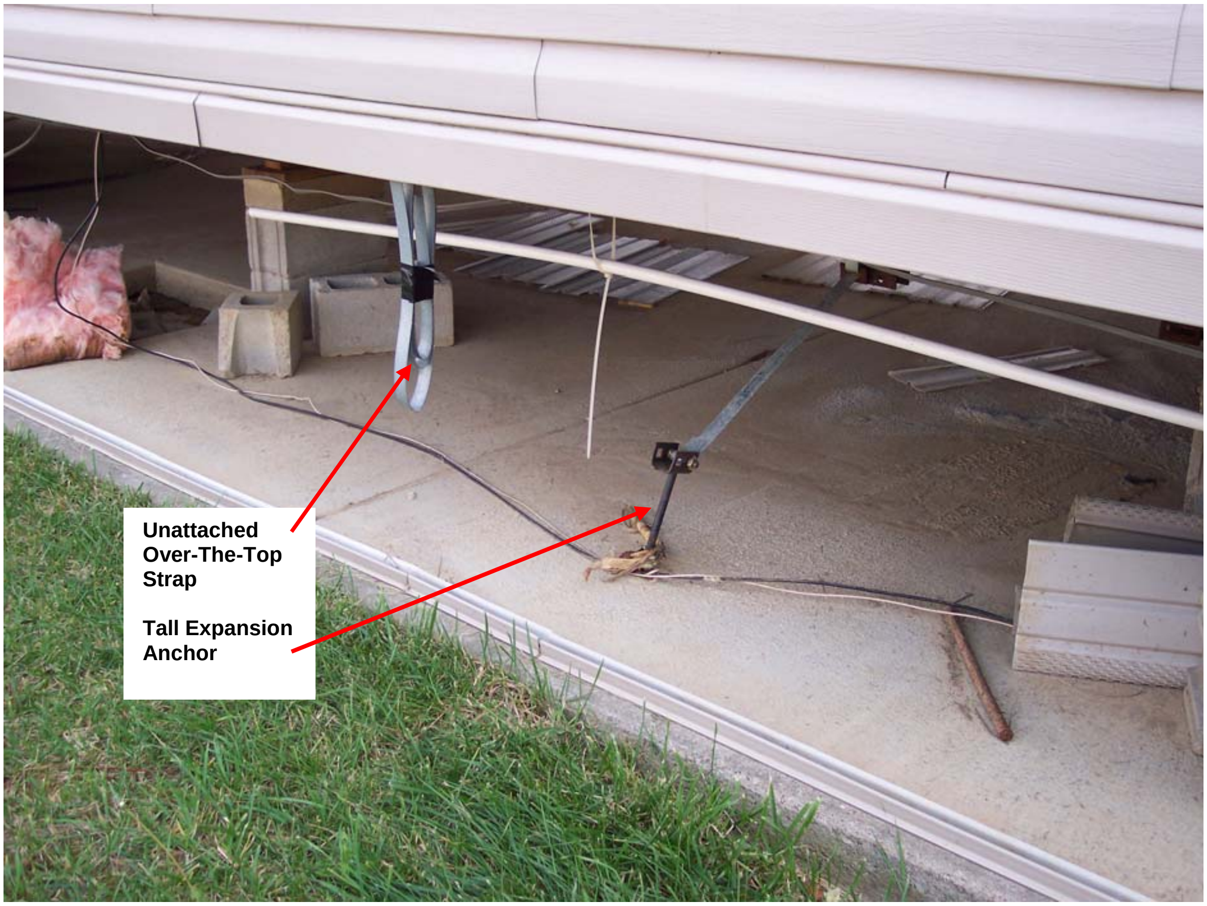



**Figure 3-37. Embedded expansion anchor mounted too high above slab and subject to moment and bending.**

Problems with mobile home tie-down and anchoring systems are not unique to Evansville, Indiana. Where mobile homes have experienced severe wind events, failures of tie-downs and anchors have been witnessed. The broken tie, **Figure 3-38**, and the pulled out earth anchor, **Figure 3-39**, occurred in a mobile home park struck by a tornado in Tuscaloosa, Alabama, December 2000. **Figure 3-40**, taken in Happy, Texas after their tornado in 2002, shows a typical broken tie-down strap.

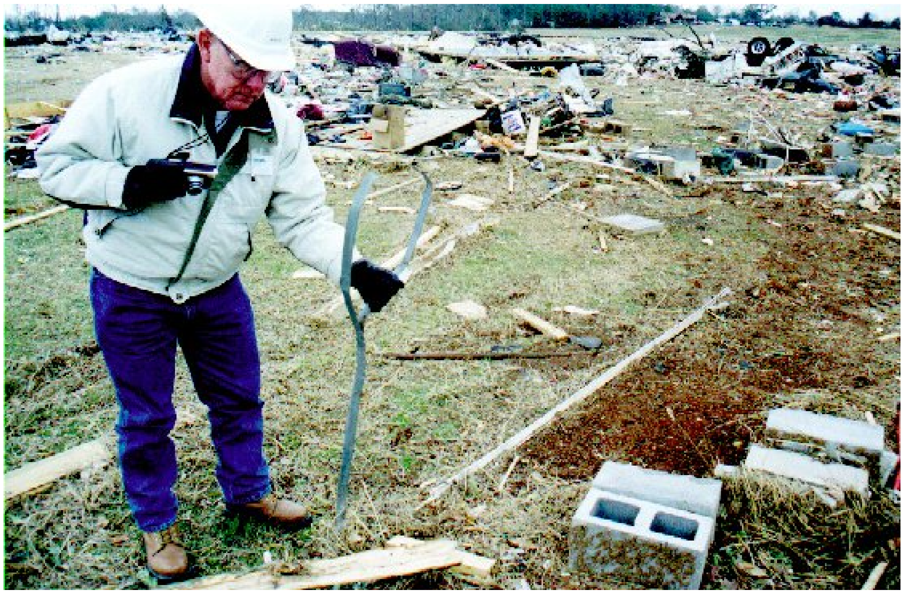


**Figure 3-38. Broken mobile home tie-down, Tuscaloosa, AL, December 2000.**

**Figure 3-39. Earth anchor pulled out of the ground, Tuscaloosa, AL, December 2000.**


**Figure 3-40. Broken mobile home tie-down, Happy, Texas, May 2001.**

## 4.0 Analysis and Conclusions

An investigation of the damage was conducted from the storm's touch down near Ellis Park horse race track to Eastbrook Mobile Home Park to Newburgh (see **Figure 4-1**). The level of damage in all three locations was similar, suggesting that each location was exposed to nearly the same wind speeds. The magnitude and intensity of damage at Eastbrook Park is probably attributable to the "mobile and temporary" nature of mobile homes and their lack or weakness of foundation systems. Virtually every home in the Eastbrook Park that was under the influence of the storm's vortex was destroyed (see **Figure 4-2**). The exceptions were those destroyed mobile homes located in the park northeast quadrant along Lynn Road. Their damage most likely resulted from "backside" winds and debris from the tornado coupled with poor anchoring.

Home along August Drive, Eastbrook Park

Jockey house at Ellis Park Raceway

Newburgh Residence

**Figure 4-1. Comparison of residential destruction at Ellis Park Raceway, Eastbrook Park and Newburgh.**

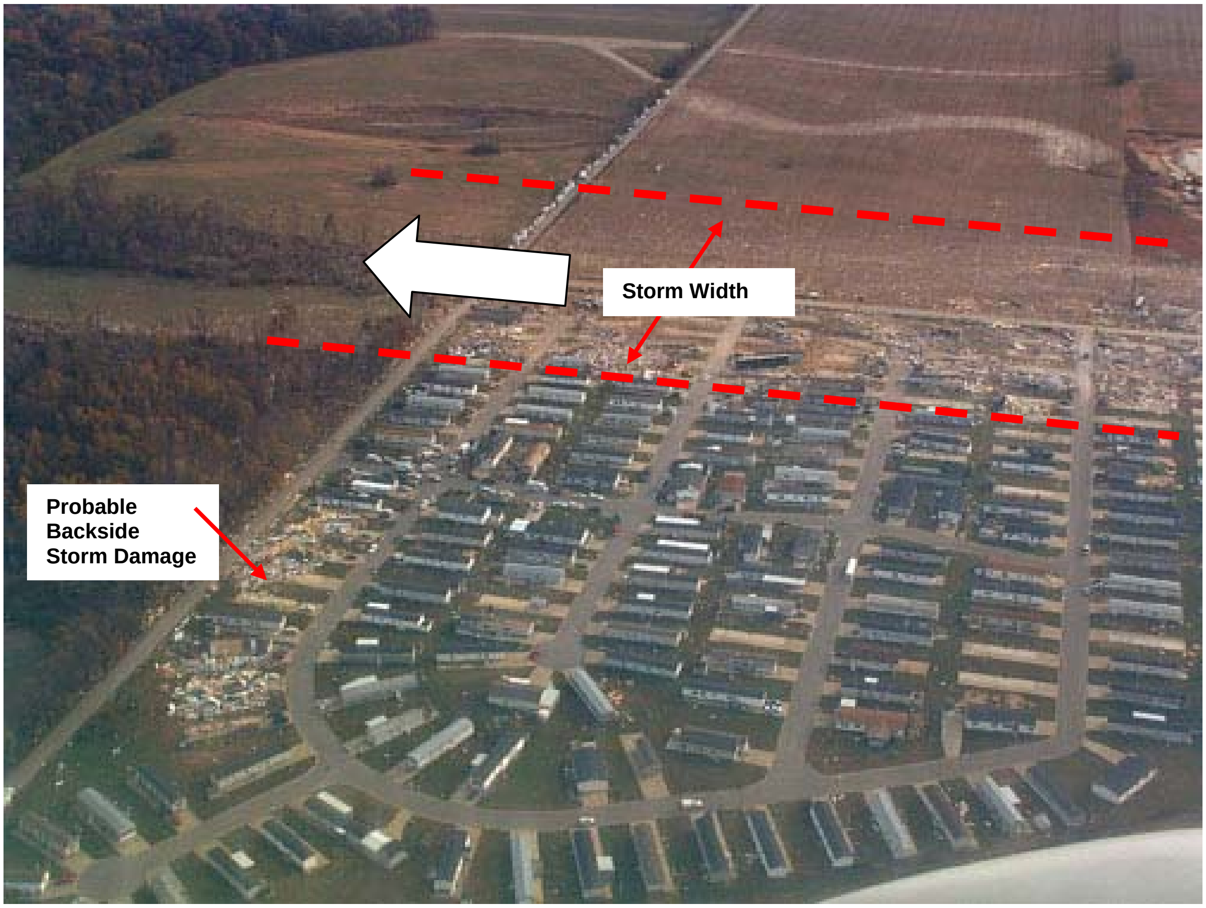



**Figure 4-2. Aerial survey of damage to Eastbrook Mobile Home Park.**

## 4.1 Manufacturing and Construction

As previously stated, Article 3280 merely requires the constructed components of the Zone I manufactured housing unit to be connected to resist the applied loads; however, no guidance to accomplish this task is provided and no maximum stud spacing is specified. Guidance is provided for the Zone II & III units by requiring roof truss-to-stud and stud-to-floor connections to be accomplished with 26 steel strapping located at 24-in. and 16-in. centers respectively. Though not specified in Article 3280, this allocation of strapping spacing would appear to coincide with the stud spacing of these high wind units. **Figure 4-3** illustrates top wall brackets included on a Zone II/III unit located in the Eastbrook Park. **Figure 4-4** shows an older Zone I unit with its roofing removed by the storm. The Zone I roof-to-wall connections are made with randomly located and poorly installed short steel straps.


**Figure 4-3. Zone II/III unit with roof-to-wall strapping.**



**Figure 4-4. Zone I unit with poorly installed roof-to-wall connectors.**

It is a standard practice and, in many jurisdictions, a code requirement for wood frame construction to include corner bracing to resist racking and shear loads produced by seismic activity or high winds. The *2000 International Residential Code* requires one story structures located in Seismic Category A and B or in wind zones of 100 mph or less to have braced exterior walls "at each end and at least every 25 feet on center, but not less than 16% of the braced wall line."[28] Methods of bracing include diagonally installed wood boards; 5/16-in. wood structural panel sheathing; ½-in. structural fiberboard sheathing; ½-in. gypsum board; particleboard wall sheathing; Portland cement plaster; or hardboard panel siding. Though it would appear prudent for resistance to wind, seismic, and transit loads to provide some type of wall bracing for manufactured housing, no requirement is found in either Article 3280 or NFPA 501. Investigation of the damaged units at the Eastbrook Park revealed units varying from those with no bracing to units having full sheathing bracing. **Figure 4-5** shows a unit with "house wrap" over bare studs, no bracing, and vinyl siding installed directly to the studs. **Figure 4-6** shows a unit with no bracing and Styrofoam substrate. **Figure 4-7** shows a unit with non-structural asphalt sheathing. **Figure 4-8** clearly reveals the corner of a unit without sheathing and bracing. Though devastated by the storm's vortex and moved from its moorings, the fully particleboard-sheathed unit pictured in **Figure 4-9** remained generally connected, thereby affording the occupants some protection. Without adequate bracing mobile home units were frequently devastated by the wind forces (see **Figure 4-10**).


**Figure 4-5. Unit with house wrap and vinyl siding over bare studs.**

[28] Table R602.10.3, Wall Bracing. 2*000 International Residential Code.* (International Code Council, 2000). p. 118.


**Figure 4-6. Vinyl siding over Styrofoam substrate.**


**Figure 4-7. Asphalt sheathing beneath vinyl siding.**

**Figure 4-8. Metal siding over insulated stud space (no substrate).**


**Figure 4-9. Full particleboard sheathed mobile home struck by tornado.**

**Figure 4-10.  Totally demolished unit without wind bracing.**

## 4.2 Tie-downs and Anchoring Systems

Performance of the tie-down and anchoring systems has been previously documented. A numerical analysis was conducted to determine the actual loads placed upon these systems based on wind speeds and system spacing. Calculations for equilibrium were conducted on a standard 16-ft. x 80-ft., 25,000-lb., single-wide mobile home in order to determine the tensile force in the tie-down systems. The tie-down systems were evaluated for four different wind speeds: (1) 86 mph, pressures prescribed by Article 3280; (2) 90 mph, 2000 International Residential Code requirement for the state of Indiana; (3) 150 mph, which corresponds to the NWS lower boundary for the Evansville tornado; and (4) 200 mph, which corresponds to the NWS upper boundary for the Evansville tornado. With the exception of the Article 3280 prescribed pressures (**Table 2-2**), calculations were conducted using the guidelines of *ASCE 7-02, Minimum Design Loads for Buildings and Other Structures*. Calculations included an internal pressure coefficient ($G_{cpi}$ = .18) for a partially enclosed structure and computed based upon Exposure C (open terrain with scattered obstructions) and no topography factor. A diagram of the prescribed Article 3280 pressures is shown in **Figure 4-11** and a general loading diagram of the pressures produced by winds of 90, 150 and 200 mph respectively is shown in **Figure 4-12**. Main Wind Force Resisting System (**MWFRS**) Net Pressures relating to the various wind speeds are shown in **Tables 4-1** to **4-5**. It is unknown whether the high wind zone units observed in the Eastbrook Park were Zone II or Zone III; however, to evaluate their tie-down system, the Article 3280 Zone II unit pressures for 120 mph wind shown in **Table 2-2** were utilized and are distributed per **Figure 4-13**.

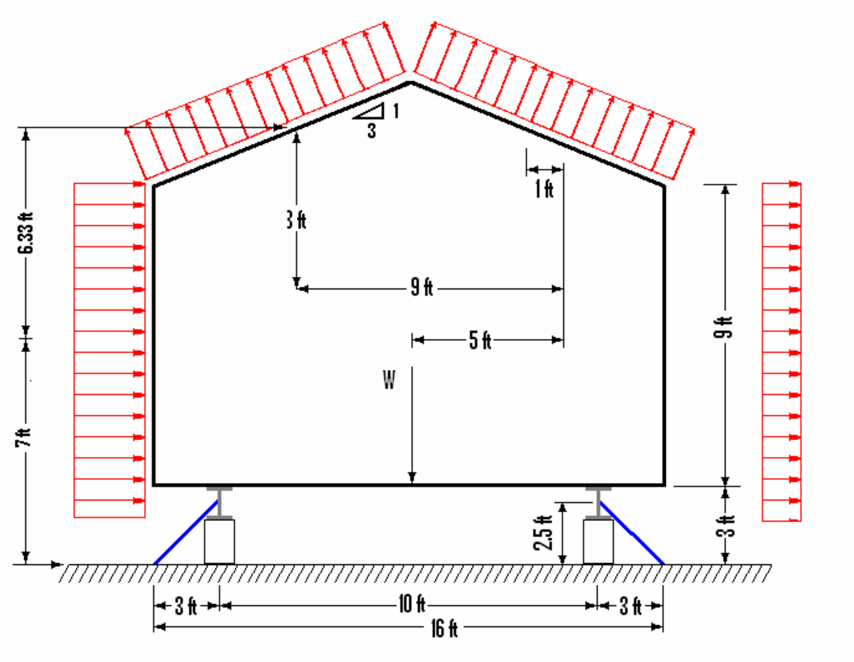



**Figure 4-11. Wind pressure diagram (MWFRS) on mobile home per Article 3280, Standard Wind Zone.**

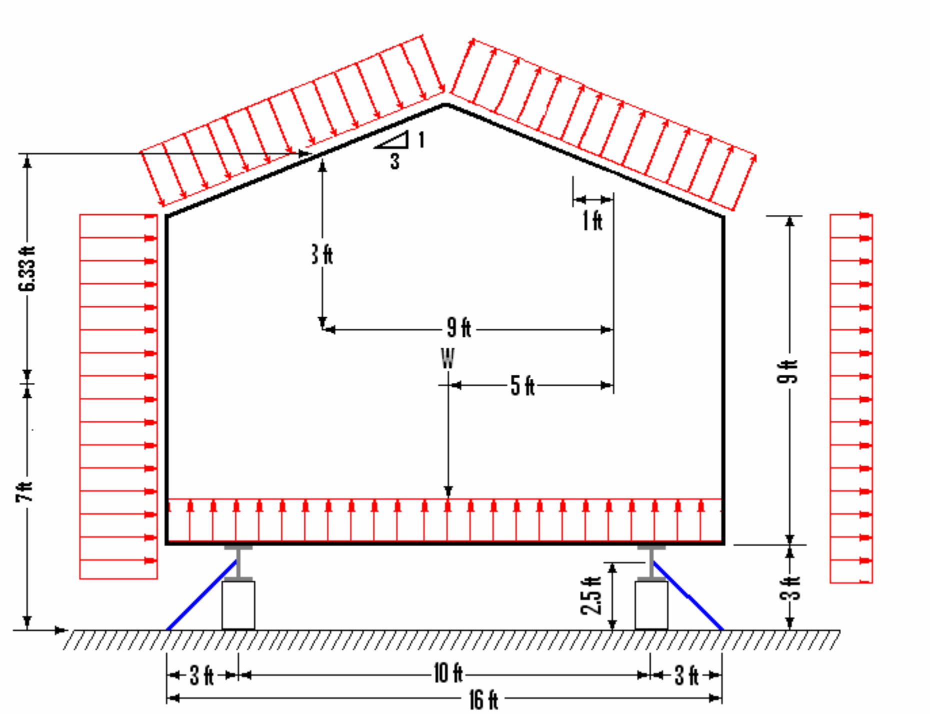



**Figure 4-12. Wind pressure diagram (MWFRS) on mobile home, per ASCE 7-02.**

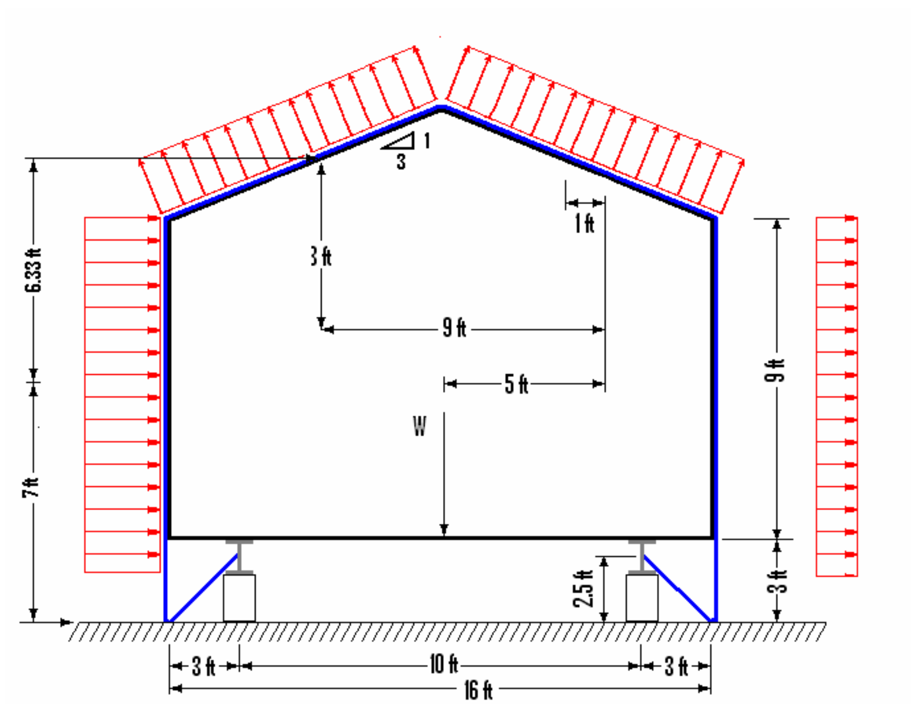



**Figure 4-13. Wind pressure diagram (MWFRS) on mobile home, per Article 3280 Wind Zone II.**

**Table 4-1. MWFRS Net Pressures prescribed by Article 3280 for Standard Wind Zone Units – 86 mph**

| Surface | z (ft) | q (psf) | G | Cp | GCpi | Ext. Pres (psf) | Net w/ + GCpi (psf) | Net w/ - GCpi (psf) |
|---|---|---|---|---|---|---|---|---|
| Windward Wall | 12.0 | 15.0 | | | | | | |
| Side Wall | 13.3 | -9.0 | | | | | | |
| Leeward Wall | 13.3 | -9.0 | | | | | | |
| Side Wall | 13.3 | -9.0 | | | | | | |
| Windward Roof | 13.3 | -9.0 | | | | | | |
| Leeward Roof | 13.3 | -9.0 | | | | | | |

*No pressure coefficients prescribed by Article 3280.*

**Table 4-2. MWFRS Net Pressure prescribed by Article 3280 for Wind Zone II Units – 120 mph**

| Surface | z (ft) | q (psf) | G | Cp | GCpi | Ext. Pres (psf) | Net w/ + GCpi (psf) | Net w/ - GCpi (psf) |
|---|---|---|---|---|---|---|---|---|
| Windward Wall | 12.0 | 39.0 | | | | | | |
| Side Wall | 13.3 | -30.0 | | | | | | |
| Leeward Wall | 13.3 | -30.0 | | | | | | |
| Side Wall | 13.3 | -30.0 | | | | | | |
| Windward Roof | 13.3 | -30.0 | | | | | | |
| Leeward Roof | 13.3 | -30.0 | | | | | | |

*No pressure coefficients prescribed by Article 3280.*

**Table 4-3. MWFRS Net Pressure – Indiana IBC* Wind Zone - 90 mph**

| Surface | z (ft) | q (psf) | G | Cp | GCpi | Ext. Pres (psf) | Net w/ + GCpi (psf) | Net w/ - GCpi (psf) |
|---|---|---|---|---|---|---|---|---|
| Windward Wall | 12.0 | 15.0 | 0.87 | 0.80 | 0.18 | 10.4 | 7.7 | 13.1 |
| Side Wall | 13.3 | 15.0 | | -0.70 | | -9.1 | -11.8 | -6.4 |
| Leeward Wall | 13.3 | 15.0 | 0.87 | -0.50 | 0.18 | -6.5 | -9.2 | -3.8 |
| Side Wall | 13.3 | 15.0 | 0.87 | -0.70 | | -9.1 | -11.8 | -6.4 |
| Windward Roof | 13.3 | 15<br>0 | 0.87 | -0.14 | 0.18 | -1.8 | -4.5 | 0.9 |
| | 13.3 | 15.0 | | -0.69 | | -9.0 | -11.7 | -6.3 |
| Leeward Roof | 13.3 | 15.0 | 0.87 | -0.59 | 0.18 | -7.7 | -10.4 | -5.0 |

**Figure 1609, Basic Wind Speed (3-second gust), 2000 International Building Code*

**Table 4-4. MWFRS Net Pressure – Evansville Tornado - NWS 150 mph***

| Surface | z (ft) | q (psf) | G | Cp | GCpi | Ext. Pres (psf) | Net w/ + Gcpi (psf) | Net w/ - Gcpi (psf) |
|---|---|---|---|---|---|---|---|---|
| Windward Wall | 12.0 | 41.6 | 0.87 | 0.80 | 0.18 | 29.0 | 21.5 | 36.4 |
| Side Wall | 13.3 | 41.6 | | -0.70 | | -25.3 | -32.8 | -17.8 |
| Leeward Wall | 13.3 | 41.6 | 0.87 | -0.50 | 0.18 | -18.1 | -25.6 | -10.6 |
| Side Wall | 13.3 | 41.6 | 0.87 | -0.70 | | -25.3 | -32.8 | -17.6 |
| Windward Roof | 13.3 | 41.6 | 0.87 | -0.14 | 0.18 | -5.1 | -12.6 | 2.4 |
| | | 41.6 | | -0.69 | | -25.0 | -32.5 | -17.5 |
| Leeward Roof | 13.3 | 41.6 | 0.87 | -0.59 | 0.18 | -21.4 | -28.8 | -13.9 |

** Lower boundary of Evansville tornado wind speed assigned by the National Weather Service*

**Table 4-5. MWFRS Net Pressure – Evansville Tornado - NWS 200 mph***

| Surface | z (ft) | q (psf) | G | Cp | GCpi | Ext. Pres (psf) | Net w/ + GCpi (psf) | Net w/ - GCpi (psf) |
|---|---|---|---|---|---|---|---|---|
| Windward Wall | 12.0 | 73.9 | 0.87 | 0.80 | 0.18 | 51.4 | 38.1 | 64.7 |
| Side Wall | 13.3 | 73.9 | | -0.70 | | -45.0 | -58.3 | -31.7 |
| Leeward Wall | 13.3 | 73.9 | 0.87 | -0.50 | 0.18 | -32.1 | -45.4 | -18.8 |
| Side Wall | 13.3 | 73.9 | 0.87 | -0.70 | | -45.0 | -58.3 | -31.7 |
| Windward Roof | 13.3 | 73.9 | 0.87 | -0.14 | 0.18 | -9.0 | -22.3 | 4.3 |
| | | 73.9 | | -0.69 | | -44.4 | -57.7 | -31.1 |
| Leeward Roof | 13.3 | 73.9 | 0.87 | -0.59 | 0.18 | -37.9 | -51.2 | -24.6 |

** Upper boundary of Evansville tornado wind speed assigned by the National Weather Service*

Equations of equilibrium (∑ Horizontal Forces = 0, ∑ Vertical Forces = 0, and ∑ Moments = 0) were computed for each load scenario (see **Figures 4-11** to **4-13**). Knowing that only one side of the mobile homes tie-downs resist the sliding and overturning forces, tensile forces were computed based upon anchor spacing and compared to the ultimate (150%) prescribed strap load per Article 3280 (3,150 lbs. x 1.5 = 4,725 lbs.). The tabulated anchor spacing relates to the NFPA 225 maximum spacing of 11 ft. and to the 24 ft. spacing allowed by the State of Indiana in 2005. The calculation results are shown in **Table 4-6** and indicate that the maximum tie spacing based upon ultimate load is 15 ft. for the standard Article 3280 unit and 20 ft. for the IBC 90 mph loading. It should be noted that the 90, 150, and 200 mph loadings include pressure reducing coefficients allowed by ASCE 7. The information found in **Table 4-6** clearly supports the NFPA 225 recommended tie spacing for design wind speeds of 86 and 120 mph.

**Table 4-6. Tie loading based upon spacing and wind speed**

| Wind speed | 11 ft. Spacing | 24 ft. Spacing | Ult. Load Max Spacing |
|---|---|---|---|
| 86 mph | 3,437 lbs. | 7,498 lbs. | 15.0 ft. |
| 90 mph | 2,645 lbs. | 5,770 lbs. | 19.6 ft. |
| 120 mph | 5,728 lbs. | 12,496 lbs. | 9.0 ft. |
| 150 mph | 7,346 lbs. | 16,032 lbs. | 7.0 ft. |
| 200 mph | 13,059 lbs. | 28,495 lbs. | 4.0 ft. |

Based upon the NFPA spacing of 11 ft. and the ratio of the wind velocities squared, the maximum wind speed required to produce failure of the ties is 120 mph for diagonally tied units. It is important to note regarding Wind Zone II & III units that vertical tie straps offer no resistance to lateral movement until significant lateral movement of the unit has occurred; however, once the diagonal ties have broken from the horizontal (sliding) forces, the only resistance to overturning and further unit displacement is the over-the-top ties.

**Standard Wind Speed Units (Wind Zone I):**

Tie-down Strap Capacity at 150% = 1.5 x 3,150 lbs. = 4,725 lbs (Article 3280)

Given : V = 200 mph, Force in Straps Spaced @ 11’ o.c. = 13,059 lbs. (**Table 4-6**)

@ V = 90 mph, Force in Strap = $(90/200)^2$ x 13,059 lbs. = 2,645 lbs. (**Table 4-6**)

Find V at which T = 4,725 lbs. using ASCE 7-02 coefficients

$(V/200)^2$ x 13,059 lbs. = 4,725 lbs.

V = 200 $(4{,}725 \text{ lbs.} / 13{,}059 \text{ lbs.})^{1/2}$ = <u>120.3 mph</u>

$(120.3/200)^2$ x 13,059 lbs) = 4,725 lbs. (check)

**For standard units (Wind Zone I) and ignoring flexure in straps due to longitudinal movement, a strap reaches 4,725 lbs. maximum load at 120 mph.**

Most of the mobile home units in the Eastbrook Park were less than 10 years old. For that period of time, recommended building design loads for buildings were tabulated in the ASCE 7, *Minimum Design Loads for Buildings and Other Structures*. Publications pertinent to this period of time were ASCE 7-95 through ASCE 7-2005. Based on Load and Resistance Factor Design (**LRFD**) theory, failures of engineered construction are expected to begin around (Load Factor)$^{1/2}$ x design wind speed.[29] The factor appropriate for the oldest manufactured home in the park is 1.3 contained in ASCE 7-95; therefore, using that factor, wind induced failures would be expected to begin around $(1.3)^{1/2}$ x 86 mph, which is approximately 98 mph. For site-built, stick frame residential construction, structural failure would begin at 103 mph [$(1.3)^{1/2}$ x 90 mph]. Based upon the observed damage and proximity of damage to the path of the tornado for those structures not immediately under the influence of the tornado vortex, damage to site-built structures and adequately anchored mobile homes with full sheathing was similar (see **Figure 4-1**). The larger structural member sizes, robust connections, and positive connection of the site-built structures to a foundation system provided greater strength and redundancy which accounted for the differences in performance; however, those mobile homes located on the periphery of the storm that were appropriately anchored and had sufficient tie-down strength along with integral unit strength provided by sheathing, mostly suffered components and cladding failures.

Design and analysis of mobile home tie-down systems presumes a near-perfect installation in which the tie-down strap is tight and remains perpendicular to the steel channel under-frame and that the anchor is installed correctly and is sufficient to carry the ultimate load of the strap. The investigators found no perfect installations. The tie-down strap was typically hooked to the under-frame and wrapped around the frame channel, as shown in **Figures 3-25** & **3-34,** and as illustrated in **Figure 4-14 (a, b, & c)**. This method of wrapping the strap creates a sharp bend in the strap that is easily fatigued by the wind buffeting the unit. Failure of tie-downs was typically found at one of these sharp bends in the tie-down strap (**Figure 4-15**).

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[29] Minciarelli F, Gioffre M, Grigoriu M, Simiu E. *Estimates of extreme wind effects and wind load factors: influence of knowledge uncertainties.* J. Probabilistic Engineering Mechanics, (National Institute of Standards and Technology, October 2001), Vol 16, No. 4, p. 331-340.

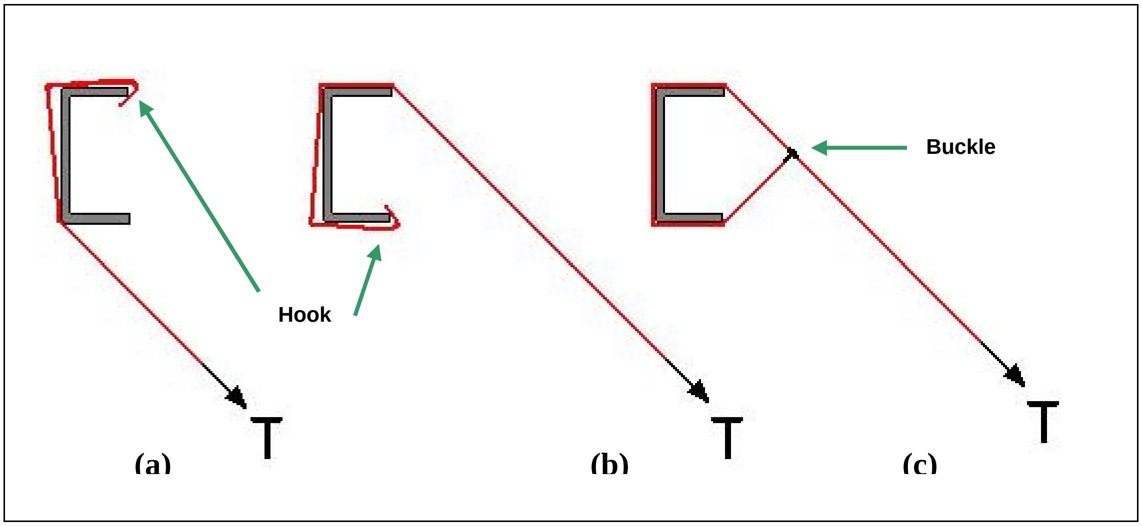


**Figure 4-14. Standard installation method of tie strap to under-frame.**

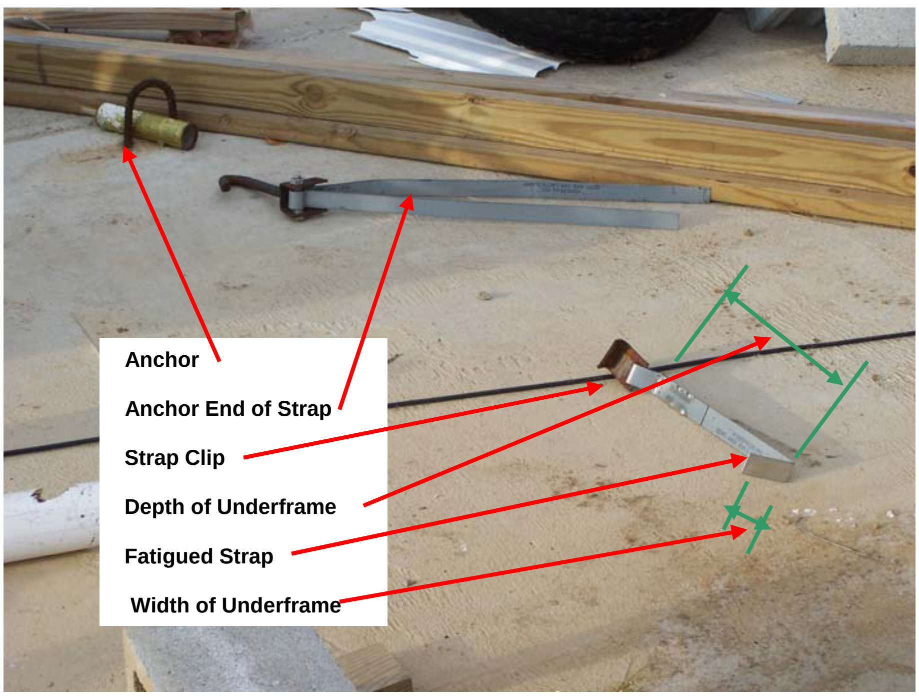


**Figure 4-15. Tie-down strap broken at bend around mobile home under-frame.**

At Eastbrook Mobile Home Park, the investigators rarely observed longitudinal tie-downs installed in the direction of the long axis of the mobile home. Without these ties, the units were allowed to slide longitudinally in the strong multi-directional winds. Longitudinal and lateral displacement of the mobile home unit shown in **Figure 4-16** skewed the strap that was previously perpendicular to the under-frame such that the strap became subject to both tension and bending (see **Figure 4-17**). This condition results in the force applied to the strap by the under-frame being eccentric to the centerline of the strap by a distance, "***e***," as shown in **Figure 4-17.** The stress in the strap at the point of contact with the under-frame becomes the sum of the purely tensile stress and the flexural stress resulting from the moment produced by the tensile force, ***T***, multiplied by the eccentricity, ***e***. The AISI, *Specification for the Design of Cold-Formed Steel Structural Members,* Section 5.1, Combined Axial Load and Bending, require that the sum of the tensile stress and bending stress ratios be less than 1.0.[30] A thin steel strap subjected to tension and bending would, therefore, have a lower tension carrying capacity than a strap subjected to pure tension. The allowable tensile forces for steel strap tie-downs are appropriate for conditions where restraint of the mobile home prevents shifting of the tie-downs from an axis perpendicular to the under-frame steel channel. Where any appreciable shifting of the under-frame occurs, steel straps are apt to fail at significantly lower tensile forces than those for which the tie-down is rated.

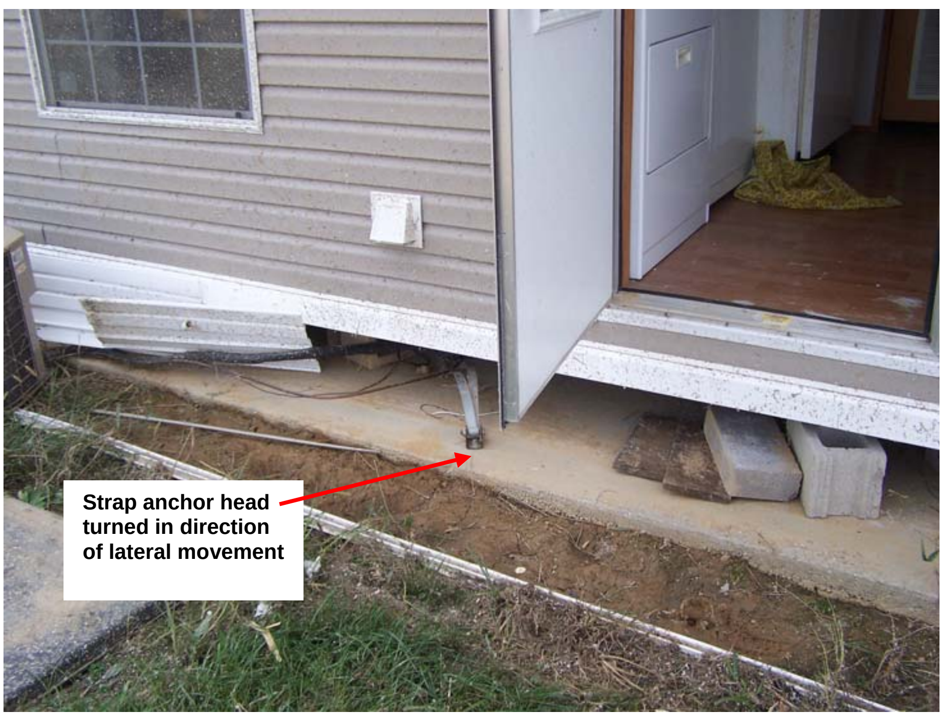


**Figure 4-16. Unit laterally displaced, skewing the tie-down strap resulting in strap failure.**

[30] *North American Specification for the Design of Cold-Formed Steel Structural Members, 2001 Edition*: (American Iron and Steel Institute, Washington D.C., 2001), p. 85.

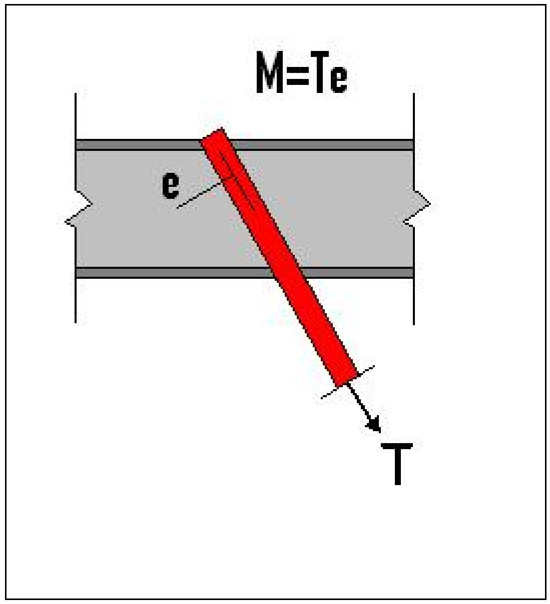


**Figure 4-17. Illustration of tie-down strap in tension and bending due to the eccentricity (e).**

Anchors to which the tie-downs were connected failed frequently. Cam-type ratchets failed, releasing the strap (**Figure 4-18**); anchor heads sheared (**Figure 4-19**); and anchor bolts sheared (**Figure 4-20**).


**Figure 4-18. Failed tie-down anchor ratchet.**


**Figure 4-19. Anchor head sheared.**


**Figure 4-20.** Sheared anchor bolt.

## 5.0 Summary and Recommendations

In the early morning hours of Sunday, November 6, 2005, residents of the Eastbrook Mobile Home Park were awakened by a devastating tornado that destroyed over 110 homes, killing 18 mobile home residents and injuring scores of others. Given the varying degree of damage to the predominately new unit-occupied Eastbrook Park, the investigators sought to study the effectiveness of manufacturing methods and unit installation systems. Within the bounds of reasonable engineering and technical certainty, and subject to change if additional information becomes available, the following is the professional opinion of the investigators:

1. Structural members are required by Article 3280 to be ultimate load tested. This process has led the manufactured housing industry to minimize member sizes to strictly meet the loads but lacks the structural redundancy of its site-built, larger stick-frame housing counterpart. Article 3280 and NFPA 501 should require larger or stronger structural members with more robust and extensive structural connectivity of framing to increase the level of redundancy.

2. Mobile home units that were fully sheathed with a wood substrate material performed far better than those units without sheathing. Revisions to the construction standards for all zone units should include “full house” wood product sheathing for the resistance of racking and shear forces.

3. Zone I units should be constructed with connecting clips at each stud as is currently required for the Zone II/III units.

4. The tie strap looped around the under-frame is a major source of unit failure. A better method of connecting tie-straps to the under-frame must be developed and required by Article 3280 and NFPA 501. Longitudinal strapping is essential to the stability of the unit in multi-directional winds of a windstorm and must be included in the new connection designs.

5. States, counties, and municipalities, including Indiana, should strictly enforce the NFPA 225 guidelines and inspect installations for compliance.

6. States, counties, and municipalities, including Indiana, should require all over-the-top ties (Zone II/II units) to be installed along with the diagonal frame ties, regardless of the installation wind zone. Although over-the-top ties do not contribute to the lateral stability of units, they contribute significantly to the robustness of units lacking the attributes for redundancy referred to in opinion item 1.

7. Buffeting winds can loosen manufactured housing foundation systems. Home owners should periodically inspect their home piers, tie-downs and anchors to maintain a tight installation. Standards should limit the height of stacked masonry piers and provide for concrete filled masonry or other types of structurally stable taller piers.

8. Both Article 3280 and NFPA 501 should require that Standard Zone (Zone I) units be designed to the same 90 mph wind speed as required by ASCE 7 for site-built structures and that the designs for all three zone units (I, II, & III) should utilize ASCE 7 pressure coefficients.

In summary, the writers believe that the investigation of mobile home general performance outside of the influence of the tornado vortex was marginally acceptable if the unit was properly constructed and installed. Given the implementation of the above recommendations, it is therefore reasonable to believe that mobile homes can be constructed and installed to resist Zone I, II & III wind speeds of 90 mph, 120 mph and 130 mph.

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