3 General Assessment and Characterization of Damage

The general types of damage the BPAT observed as a result of the May3 tornadoes in Oklahoma and Kansas are discussed below. As a result of the site investigations and general field observations, important issues such property protection, personal protection, and sheltering were identified. A more detailed discussion of these issues may be found in Chapters 4,5,and 6 of this report.

3.1 PROPERTY PROTECTION

During the field investigation, the BPAT investigated buildings to identify success and failures that occurred during the tornadoes. Building failures were identified as being directly struck by the tornado, affected by winds outside the vortex of the tornado, or out on the extreme edge of the tornado path. Considerable damage to all types of structures throughout Oklahoma and Kansas was observed. Failures occurred when extreme winds produced forces on the buildings that they were not designed to withstand. Failures also occurred when windborne debris penetrated the building envelope allowing wind inside the building that again produced forces on the buildings that they were not designed to withstand. However, other failures observed were attributed to poor construction, improper construction techniques, and poor selection of construction materials. It was a goal of the BPAT to determine if any of the damage observed to both residential and non-residential buildings was preventable.

3.1.1 Overview Of Buildings Evaluated

The damage assessment of buildings was divided into residential and non-residential sections. Specifically, the residential buildings were categorized into single family housing, multi-family housing and manufactured and modular housing. The non-residential buildings were categorized into the various engineered types of construction observed. These groupings were made to focus on the structural performance of each type of building. In both cases, important observations were also made concerning exterior architectural systems, e.g., roof and wall coverings, windows and doors.

3.1.1.1 Residential Buildings

The residential buildings were categorized into the various types of construction investigated and the structural performance of each type of building was observed. The residential buildings investigated by the BPAT were:

- single- and –multi-family, one- to two-story wood-frame houses
- manufactured and modular homes
- accessory structures

Residential buildings that were directly struck by the vortex of severe and violent tornadoes were substantially or completely destroyed. Residential buildings that experienced a direct strike from moderate tornadoes or experienced inflow winds from severe and violent tornadoes saw a wide range of damage. This damage range observed was broken windows and light building damage, partial loss of roofs and walls, separation of buildings from their foundations and total roof loss, and only remnants of core rooms surviving.

3.1.1.2 Non-Residential Buildings

The non-residential buildings were categorized into the various *engineered* types of construction investigated focusing on the structural performance of each type of building. The non-residential buildings investigated include:

- tilt-up pre-cast concrete walls with steel joists
- load-bearing masonry walls with steel joists
- load-bearing masonry walls with pre-cast concrete hollow core floors and roof slabs
- steel frame
- steel frame with masonry infill walls

The non-residential buildings investigated by the BPAT were typically designed by a design professional and therefore the non-residential buildings that were damaged by the tornadoes experienced different damage from the same tornadoes that damaged residential buildings. Non residential buildings that were directly struck by the vortex of severe and violent tornadoes were substantially damaged or destroyed, however, they were typically not reduced to rubble like the residential buildings. Non-residential buildings that experienced a direct strike from moderate tornadoes or experienced inflow winds from severe and violent tornadoes saw a wide range of damage. This damage range observed was broken windows and light building damage, partial loss of roof and wall coverings, partial loss of roof and wall systems, complete roof loss, and partial upper level damage with minimal lower level damage on multi-level buildings.

3.1.2 Load Path and Increased Loads

Site visits in both Oklahoma and Kansas of wind-induced damage to residential and commercial buildings indicate that internal pressurization is a major contributor to poor building performance under severe wind loading conditions. It is recognized that maintaining the exterior envelope of a building has a large effect on the performance of the elements of the structural system. In spite of loss of a portion of the exterior envelope, the construction must provide a continuous load path in order to increase survivability of the building in events that marginally exceed the design winds.

Primary structural systems are those that support the building against all lateral and vertical loads. Many buildings inspected had structural systems capable of providing a continuous load path for downward acting gravity loads, but were unable to provide a continuous load path for the lateral and vertical uplift forces generated by the tornado winds. The team looked at how this property damage could have been prevented or reduced in all areas of the windfield with the exception of directly under the vortex of violent tornadoes. Figure 3-1 shows a continuous load path in a wood frame (stick built) house.

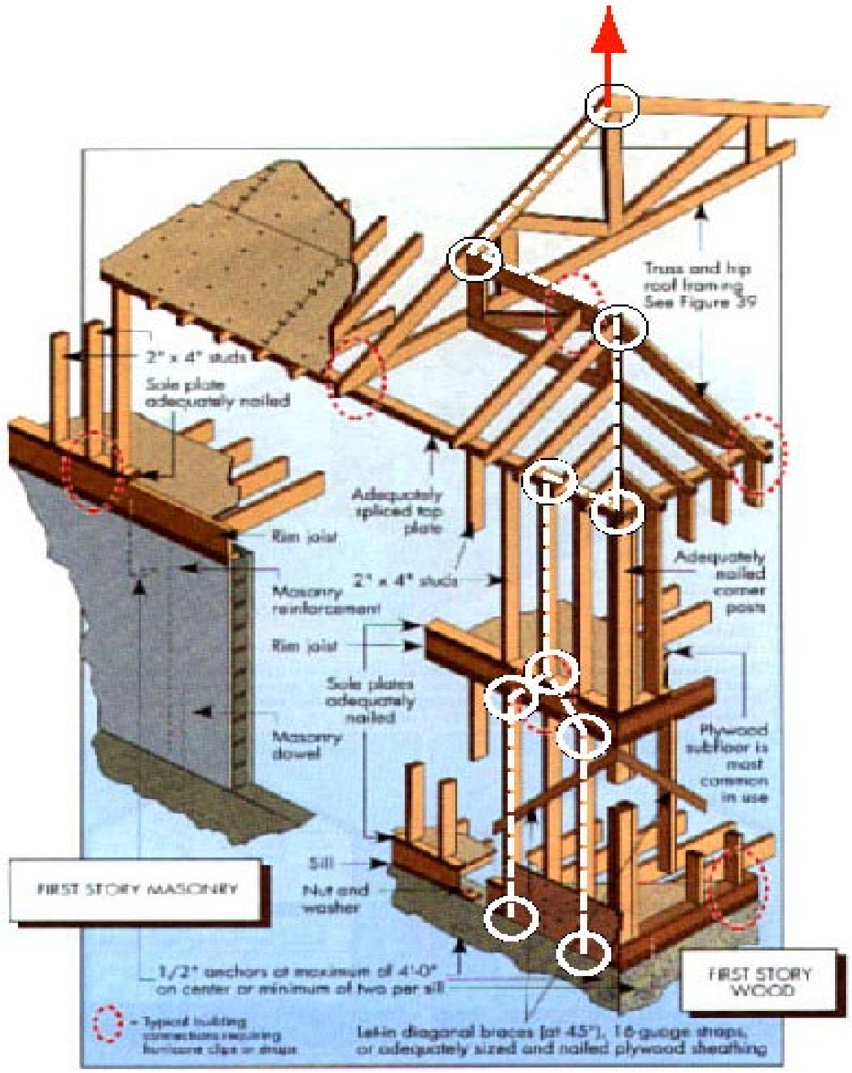


Figure 3-1: Diagram showing a continuous load path for a two-story wood frame building.

A primary effect of high winds flowing around and over a structure is the wind loads that act on the structure. Uplift is the force caused by the wind accelerating around and over buildings and other structures (Figure 3-2). An example of uplift strong enough to move a house off its foundation is presented in Figure 3-3. This house was separated from its foundation when it experienced winds associated severe tornado that passed through this neighborhood in the city of Haysville, Kansas. Although anchor bolts extended from the concrete foundation into the wood floor framing, nuts were not attached to the bolts to provide a continuous load path at this connection point that would have resisted the uplift forces. This deficiency was observed at more than just this one house.

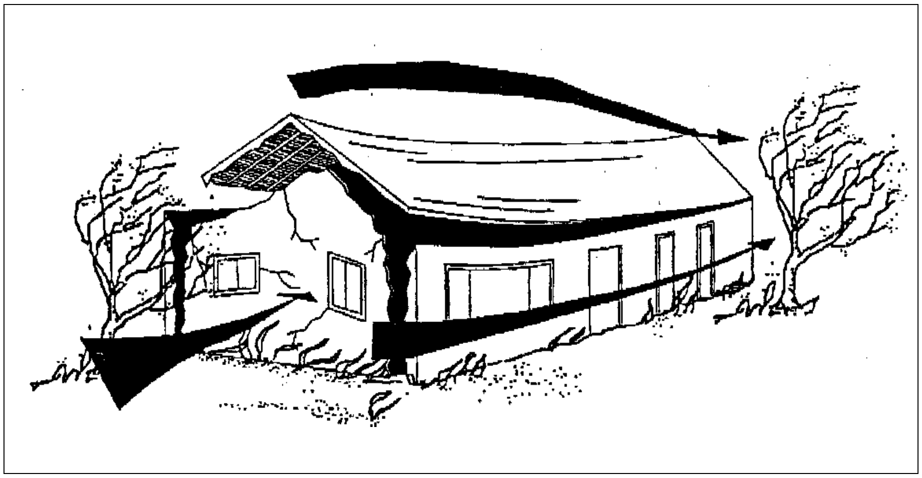


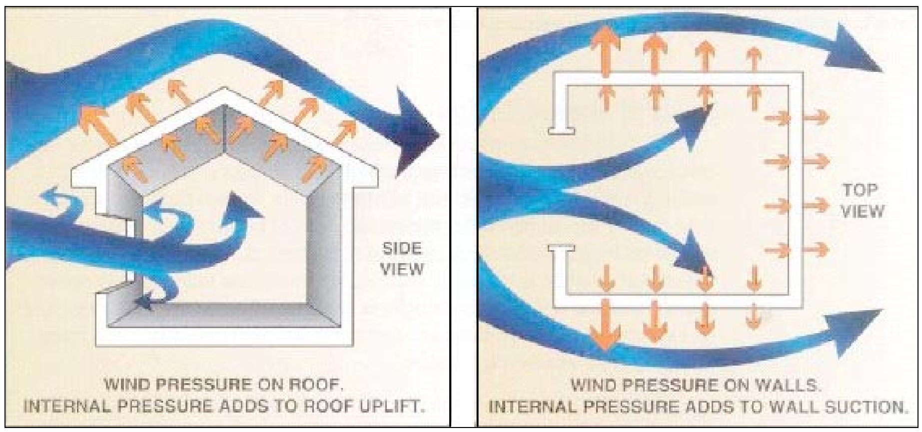
FIGURE 3-2: This building failure is the result of inward wind forces and uplift wind forces acting on a building or structure during a high wind event.

FIGURE 3-3: Wind uplift acting on this house in Haysville, Kansas, resulted in this corner of the building being lifted off its foundation.

The other primary effects of wind are **overturning**, which is discussed in the Manufactured Housing sections of Chapter 4; the **internal pressurization** of a building; the **lateral force** acting inward or positive load created by the wind blowing directly on the face of the building. Most buildings are designed with no dominant openings, such as residential and most non-residential buildings, and a breach in the building envelope due to broken windows, failed entry doors, or failed garage doors may cause a significant increase in the net wind loads acting on the building under severe wind conditions. In such cases the increased wind load may initiate a partial failure or propagate into a total failure of the primary structural system. A schematic diagram illustrating the increased loads due to a breach in the building envelope is shown in Figure 3-4.

Depending on the building size, number of interior rooms, number of stories, size of the breach, etc., laboratory tests, in wind tunnels, indicate that the net increase in uplift on the roof system can exceed a factor of two. The increased load on the roof and wall systems may cause connections between these systems to fail, possibly at wind speeds below the normal design speed. The increased load on the roof and wall systems may cause connections between structural members to fail, possibly at wind speeds below the nominal design speed.

Figure 3-4: Increased loads on roof and walls due to breach in envelope.



Examples of failures of this combination of windward/leeward/internal pressures are shown in Figures 3-5, 3-6, and 3-7.

FIGURE 3-5: Failure of hip roof due to internal pressures and leeward wind forces acting together. This house, which was exposed to inflow winds of a violent tornado, was located in a suburb of Oklahoma City, Oklahoma.

FIGURE 3-6: Failure of this gable wall section was due to wind suction forces of the leeward wall. This house was on the outer edge of a violent tornado path.

FIGURE 3-7 Failure of this exterior wall and roof section in Moore, Oklahoma, occurred when the windows broke and the front room saw an increase in internal pressure. Most of the debris from the roof and exterior wall had been cleaned up prior to this photograph. This home in Moore, Oklahoma, was located on the periphery of a violent tornado track.

Buildings that have significant openings or are mostly open structures are characterized as partially enclosed. Model building codes incorporate provisions, which take into account the effects of internal pressurization on partially enclosed buildings by increasing required design loads. However, residential buildings are typically designed as enclosed buildings and when a breach occurs, for example when a garage door fails, they become in effect partially enclosed buildings and are subject to load wind increases. In many homes inspected, these increased loads may have exceeded the enclosed building's design load specified in the applicable state or local building code, possibly resulting in the structural failure observed.

A number of non-residential buildings, such as schools, factories, warehouses, and commercial buildings were in the direct path of the moderate tornado vortexes or in the inflow of severe and violent tornadoes and received varying degrees of damage. In a few cases, damage could be considered non-structural because architectural and decorative materials on the exterior and roofing were the only damage to the buildings. Engineering standards such as ASCE 7, identify these element as components and cladding, and provide design guidance for designing to specified regional wind speeds. The failure of an exterior insulating finishing system (EIFS) exterior wall covering and architectural roof parapet is shown in Figure 3-8 at the Regional Mall at Stroud, Oklahoma. This was the only damage experienced by this particular store; however, other significant damage was experienced at the mall that was struck by a moderate tornado and is discussed later in this report.

Figure 3-8: EIFS and metal component damage at the regional outlet mall in Stroud, Oklahoma.

In other cases, structural damage occurred due to the lack of redundancy in the load to resist wind-induced uplift loads. Similar to the residential damage observed, some non-residential buildings did not have a primary structural system capable of providing a continuous load path capable of withstanding the lateral and uplift loads generated by the tornadoes. Other buildings were unable to withstand the wind forces once the building envelope had been breached.

Figure 3-9: This URM wall failed when inflow winds from a severe tornado acted on this building in Wichita, Kansas.

Figure 3-10: The vortex of a violent tornado passed within 100 yards of this plastics manufacturing plant in the City of Haysville, Kansas. The wind forces caused the failure of its primary structural system: a steel frame with masonry infill walls.

3.2 WINDBORNE DEBRIS

The quantity and size of windborne debris (missiles) generated by tornadoes is unequaled by any other type of wind storm. The smaller missiles (e.g., aggregate [stone] ballast from built-up roofs, pieces of tree limbs, pieces of shredded wood framing members) can easily become airborne and break common window glass causing a rapid increase in internal air pressure within a building, which then results in increased load on the building (Figure 3-11). Moderate sized missiles (e.g., appliances, HVAC units, long wooden members) can also become airborne and cause considerable damage to buildings (Figure 3-12). Large high-energy missiles (e.g., columns, joists, trusses, automobiles) are often observed as rolling debris and may become airborne members (Figure 3-13). These large missiles can easily destroy framing members and structural systems of buildings.

FIGURE 3-11: Small missiles commonly observed during the field investigations.

FIGURE 3-12 These medium sized missiles struck and remained embedded within this manufactured home in Wichita, Kansas.

FIGURE 3-13: These trusses and roof covering (still attached to the roof sheathing) was displaced by the winds of a violent tornado and are capable of becoming large, windborne missiles.

3.2.1 Missile Types and Sizes

The majority of the investigated tornado tracks were through residential areas, which were predominantly constructed wood framing with asphalt and composition shingle roofs. Hence, along most of the track, wood framing members (e.g., roof shingles, studs, joists, trusses, sheathing and household contents) were the most common windborne missile types. Many of the framing members and roof shingles were broken, thereby creating an enormous number of small missiles that were only a few inches long. Although small, they had sufficient energy to break glass and injure people. Other framing missiles were quite large and delivered significant impact force. Figure 3-14 shows missile impacts on top the roof of Westmoore High School in Moore, Oklahoma. The missile sticking out of the roof in the foreground is a double 2-in by 6-in. The portion sticking out of the roof is 13 feet long. It penetrated a ballasted ethylene propylene diene monomer (EPDM) membrane, approximately 3-in of polyisocyanurate roof insulation and the steel roof deck. The missile laying on the roof just beyond it is a double 2-in by 10-in that is 16 feet long. The missile in the background that penetrated the roof deck is a double 2-in by 6-in that had a total length of 16 feet. The source of missiles was not determined, hence the distance to their origin is unknown. However, since this school building was located within 100 yards of a violent tornado it is likely that they traveled at least a few hundred feet from a subdivision of the wood-frame houses that were in the direct path of the tornado. Figures 3-15 and 3-16 shows a board missile striking the roofs of residential homes that were located on the periphery of tornado tracks. Figure 3-17 shows a 2-in by 6-in board missile completely penetrating the brick veneer of a residential home. Figure 3-18 shows a 2-in by 6-in board missile penetrating several inches into the freezer compartment of a refrigerator located in a home that was on the periphery of a violent tornado track. The portion that is visible is 4-ft, 8-in long.

FIGURE 3-14: In the foreground, a medium sized missile, a double 2-in by 6-in, 13 feet long board can be observed sticking out of Westmoore High School's roof, Moore, Oklahoma. A larger missile, double 2-in by 10-in, 16 feet long board is lying in the background.

FIGURE 3-15: Windborne missile striking a house located in Moore, Oklahoma.

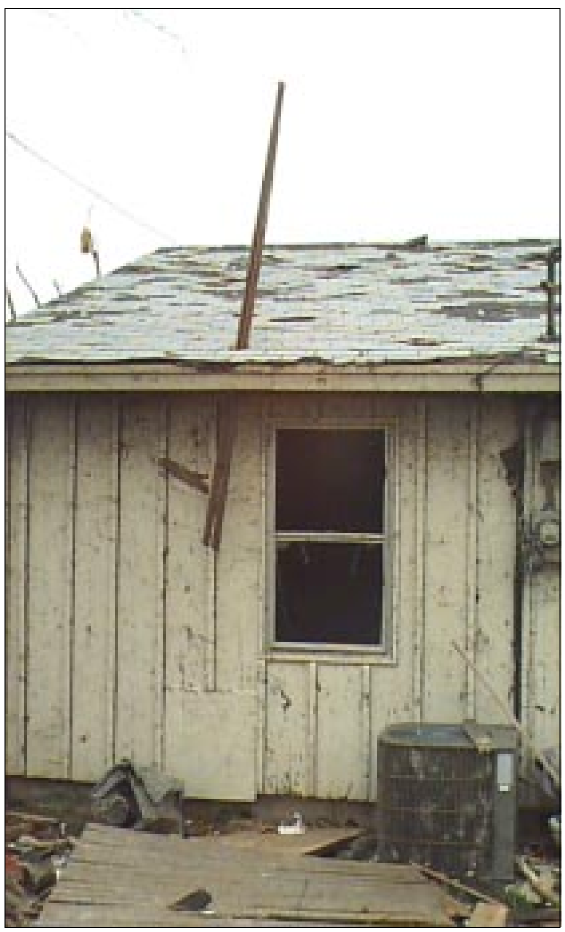


FIGURE 3-16: A missile vertically striking the roof of a home in Mid West City, Oklahoma. It fell nearly vertical illustrating the importance of a strong cover over the top of a tornado shelter to protect against free-falling debris.

FIGURE 3-17: A 2-in by 6-in can be seen completely penetrating the brick veneer of a home in Moore, Oklahoma.

FIGURE 3-18: A 2-in by 6-in board missile penetrating a refrigerator located inside a home the in Country Place subdivision outside Oklahoma City, Oklahoma.

Small-sized missiles also included brick, CMU, aggregate (stone) ballast from built-up and single-ply membrane roofs, roof tiles, asphalt shingles, fences, shrubs, and tree limbs. Moderate-sized missiles included appliances (e.g., hot water heaters, refrigerators, dishwashers), rooftop HVAC units, metal roof panels, car axles and transformers from power poles. Large-sized missiles included automobiles, a power pole (Figure 3-19). The pole was 28-ft, 4-in long and had an 8 ½-in diameter at one end and a 7-in diameter at the other end. From the window, it was roughly 40 feet to the original location of the pole from the window. Manufactured home chassis (one of these penetrated a window of a home), and large propane tanks (Figure 3-20), steel dumpsters, steel deck (Figure 3-21) and trees (Figure 3-22) were among other large missiles observed by the BPAT. Automobiles were observed to have been significantly displaced and destroyed in areas under the vortex of and in the inflow wind field near the vortex of a violent tornado.

FIGURE 3-19: This power pole penetrated a window and extended several feet into the house after traveling approximately 40 feet from its original location. This home was located in Moore, Oklahoma, along the track of a violent tornado.

FIGURE 3-20: Wind displaced this very large propane tank in Bridge Creek, Oklahoma; its original location could not be determined. This area was hit by the vortex of a violent tornado.

FIGURE 3-21: This piece of steel deck landed at the periphery of a violent tornado damage area in Moore, Oklahoma. The building it likely came off of was a few hundred feet away.

FIGURE 3-22: This building was on the periphery of a violent tornado damage area in Haysville, Kansas. One large tree fell near the corner of the house and collapsed a large portion of the roof and the corner walls. A smaller tree caused minor damage on the other corner of the house.

3.2.2 Windborne Missile Quantity

In areas where buildings were totally or nearly totally destroyed by a violent tornado, missiles were in such great quantity (Figure 2-23) that they often made a layer of rubble completely cover the ground (Figure 2-24). In many houses, the floors were covered with small tree branches and fragments of broken framing members. Figures 3-25, 3-26, 3-27, and 3-28 give some idea of the number of missiles that were flying during the storm.

FIGURE 3-23: Wood framing members and plywood sheathing near the periphery of a violent tornado damage area in Moore, Oklahoma, displaying quantity of flying debris.

FIGURE 3-24: Debris generated by the vortex of a violent tornado in Moore, Oklahoma creates a layer of rubble across the ground.

FIGURE 3-25: Close-up view of roof insulation boards (the boards are 4-ft by 8-ft) at Westmoore High School. This roof is approximately 35 feet above grade. Some of the missiles only caused superficial damage to the insulation, but several others had sufficient force to make large gouges in the insulation.

FIGURE 3-26: This house was on the periphery of a violent tornado damage area in Moore, Oklahoma. Two large missiles struck this area of the roof.

FIGURE 3-27: Several missiles struck the wall of this house in Del City, Oklahoma, including a medium sized piece of debris in the center of the picture. For scale, the square metal fastener plates near the board corners are 3-in by 3-in.

FIGURE 3-28: Several missiles struck and perforated the interior wall of this house in Moore, Oklahoma.

3.3 PERSONAL PROTECTION AND SHELTERING

The purpose of a shelter is to provide a safe refuge in the event of a tornado or an extreme wind storm. The BPAT observed three types of shelters as follows:

1. residential
2. group
3. community

The residential shelters included above-ground in-resident shelters as well as storm cellar and basement types (Figure 3-29). The group shelter observed included one at a manufactured housing park and one at a plastic manufacturing plant. Community shelters observed included one at a manufactured housing park and another at a high school. Shelters are further discussed in Section 4.3.

FIGURE 3-29: Underground residential shelter, viewing door and stairway leading down to shelter. This shelter was located outside a residence.

3.4 LOCAL, STATE, AND FEDERAL REGULATIONS

Building codes and regulations for both residential and commercial/industrial buildings varied because of the states involved. However, regulations dealing with manufactured housing fall under U.S. Department of Housing and Urban Development (HUD) preemptive construction and safety standards.

The design and construction of manufactured housing has been governed since 1976 by Federal preemptive standards which are enforced by HUD under Federal Regulation and through a Monitoring and Enforcement Contractor, the National Conference of States on Building Codes and Standards (NCSBCS). Recently, the HUD Standard has been placed under a consensus process administered by National Fire Protection Association (NFPA). Another tool used by HUD to regulate the manufactured home industry is the Federal Manufactured Home Construction and Safety Standards (MHCSS),

3.4.1 Oklahoma

Throughout the State of Oklahoma, two of the models building codes in the United States are utilized on a city by city basis. In the incorporated areas affected by this storm, the National Building Code (NBC) promulgated by the Building Officials and Code Administrators International, had been adopted. The 1996 edition of the NBC (1996 NBC) was currently adopted by most communities for all construction other than detached one and two family buildings. The 1995 Council of America Building Official's (CABO), One and Two Family Dwelling Code is the currently adopted code for detached one and two family dwellings.

Buildings that suffered damage during this event which were located in the unincorporated areas, were not covered by a model building code.

3.4.2 Kansas

Most communities in the State of Kansas have adopted the 1997 Edition of the Uniform Building Code (1997 UBC) as promulgated by the International Conference of Building Officials (ICBO) for commercial and industrial buildings. The UBC then defers to the CABO One and Two Family Dwelling Code for detached single family residential occupancy (Classified as R-4). The City of Haysville has adopted the 1994 UBC and Wichita and the unincorporated areas of Sedgwick County have adopted the 1997 UBC.

Wichita has local ordinance provisions which address sheltering. These ordinance provisions state that as of April 15, 1994, all manufactured home parks of ten or more manufactured home spaces are required to have storm shelters (above or below grade). For parks with 20 or more manufactured home spaces that did not have a shelter as of April, 15, 1999, a shelter must be provided by April 15, 1999. The ordinance also indicates that the shelter must be designed by a licensed engineer or architect to applicable codes and laws including the UBC, ADA, and FEMA's National Flood Insurance Program (NFIP).