# 4 Observations on Residential Property Protection

The damage assessment of buildings was divided into residential and non-residential. This section presents the BPAT's observations on residential property protection. Specifically, residential properties were categorized into single-family housing, multi-family housing, and manufactured and modular housing.

The BPAT assessed the performance of primary structural systems of buildings, which are those systems that support the building against lateral and vertical loads generated by high winds during a tornado or other high wind event. These systems are typically constructed of wood framing, sheathing, anchor bolts, and other connections. In residential applications, the exterior load bearing walls (i.e., walls that support roof framing) almost exclusively make up these primary structural systems. Non-loadbearing wall panels (i.e., self-supporting walls only), roof structure and diaphragm, and foundation are components of the building that are also part of this system or affect the performance of the system. The integrity of the overall building and structural systems depends not only on the strength of these components, but also on the adequacy of the connections between them. Important observations were also made concerning exterior architectural systems (e.g., roof and wall coverings, windows and doors).

## 4.1 SINGLE FAMILY CONVENTIONAL CONSTRUCTION

The BPAT observed damage to a large number of wood frame single-family houses, which are commonly referred to as "conventional" or “stick-built” construction. These houses were mostly one- or two-story buildings, many with pre-engineered wood trusses with metal truss plate connectors. Several homes had hip roofs with site-built rafter construction and board roof sheathing. Platform construction was observed in all cases (Figure 4-1). The structures observed in Oklahoma were predominately “slab-on-grade” with some “crawl-space” foundation construction. In Kansas, the structures were predominately wood frame construction placed on a basement or "crawl space" foundation.

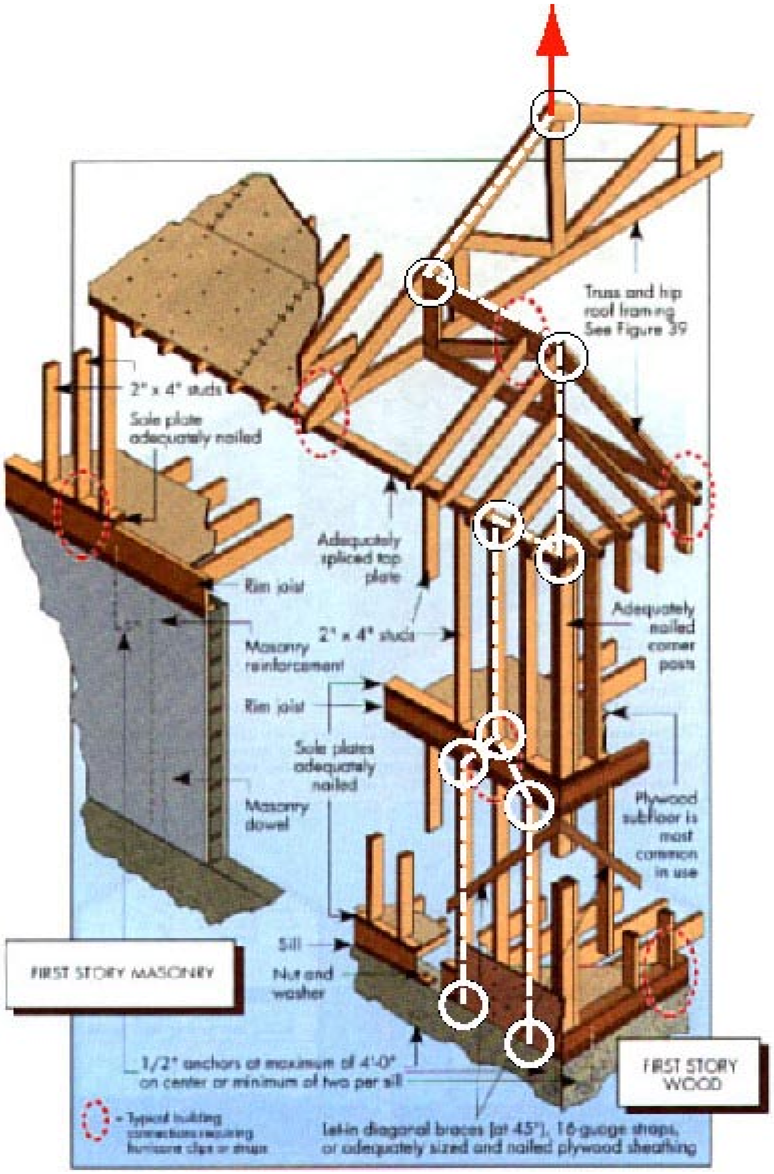


***FIGURE 4-1: Platform construction typically observed during the field investigation.***

### 4.1.1 Load Paths

The preparation of quality construction plans and the assurance of the construction of a continuous load path – from the roof sheathing to the ground – are key to maintaining structural integrity, regardless of the magnitude of the wind loads. Several different building materials and systems are usually involved in constructing and completing this continuous load path, and like a chain, the system is only as good as its weakest link.

Primary structural systems are those that support the building against all lateral and vertical loads. Due to the wind damage observed, the team focused on how this damage could have been prevented or reduced in all areas of the tornado windfield, with the exception of directly under the vortex of violent tornadoes.

Damage or failure was observed in essentially all building elements that constitute the lateral and vertical force resisting systems. Those elements are the roof sheathing, roof framing, load bearing and non load bearing wall framing, diaphragms, diaphragm chords, attachments and connections, and foundation systems. If the elements are not adequately tied together or connected, the system will fail. As discussed in the following sections, the damage ranged from considerable to total, depending on the type of framing, construction methods, and wind load experienced at the building.

### 4.1.2 Roof and Wall Sheathing

Sheathing in light-frame construction serves many purposes. One is to receive the wind and load and distribute or carry the load to its supporting members such as the roof rafters or wall studs. The second purpose is to provide resistance to loads in the direction of the sheathing. This second purpose is illustrated in Figure 4-2, the roof sheathing acts as a horizontal diaphragm and transfers lateral loads to the supporting walls.

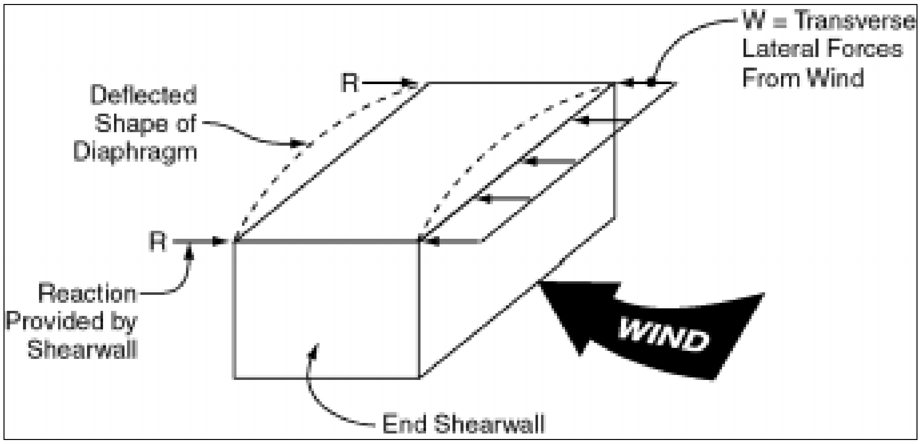


***FIGURE 4-2: Lateral load transfer to supporting walls by roof and wall sheathing.***

Roof sheathing observed in Oklahoma consisted primarily of rough sawn 1-in by 8-in planks placed side by side or 4-ft by 8-ft plywood sheets. The fasteners observed connecting the sheathing to the supporting rafters or truss top cords were nails and staples. Figure 4-3 shows a typical situation where the stapling of the boards to the rafters or trusses was not adequate. In the application of both sheathing materials, it appeared there was a concerted effort to stagger the joints as required by code as shown in Figure 4-4.

**FIGURE 4-3: Failed stapling of boards to rafters viewed from home in Moore, Oklahoma.**

**FIGURE 4-4: Although roof sheathing was lost at this Wichita, Kansas, home code requirements of staggering joints in sheathing applications was observed. This house experienced inflow winds from a severe tornado.**

As that load reaches the top of the walls, the shear has to be transferred to the top plate by some method of fastening. After the fastener transfers its load, there will be a force at the top of the supporting wall that is intended to be resisted by the shear wall. The wall sheathing (Figure 4-5) typically establishes the capacity of a shear wall.

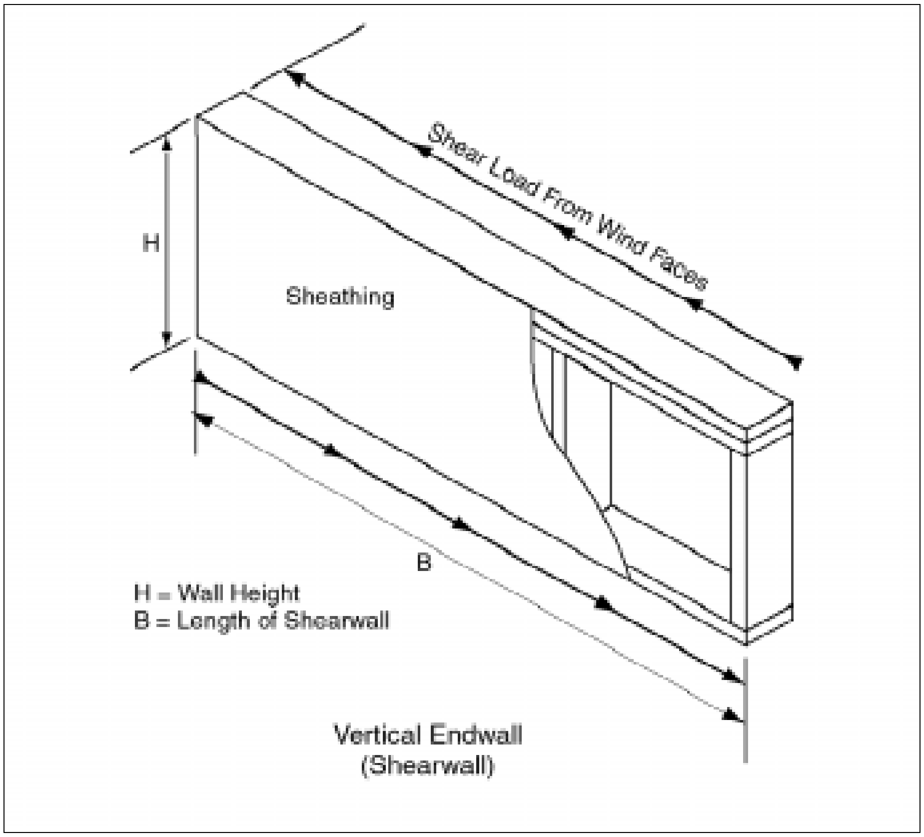


***FIGURE 4-5: Shear load force carried by wall sheathing.***

The force in the wall then must be transferred to the floor below, which in turn must transfer it in a similar manner to the foundation. It is this load transfer mechanism that the BPAT attempted to observe.

Wall sheathing observed consisted primarily of insulated fiber board or combination siding/sheathing. With the exception of garage end walls, it was difficult to ascertain any consistent failure of wall sheathing because it appeared the entire wall was either lifted or blown inward or outward as the result of windward or a combination windward/leeward pressure (Figures 4-3 and 4-4).

One example of an inadequate lateral load-resisting element that was observed was the garage end walls or returns that act as the frame for the garage door. A normal code minimum width for the return is four feet. This one measures 22-in which is clearly inadequate to resist code-required loads. At least one of the model building codes has a minimum width of such panel as 32-in with a special web and special hold anchors. Also, there were a number of cases where the garage bearing walls failed and the garage roof fell to the ground essentially intact. An example of this failure is presented in Figure 4-6 from a house that experienced inflow winds from a severe tornado in Wichita, Kansas.

***FIGURE 4-6: Wall failure due to inadequate lateral load resistance in Wichita, Kansas. The return wall at the garage inadequate to carry loads may have led to this failure.***

### 4.1.3 Connections

Post disaster assessments continue to support the fact that improved connections could have resulted in better performance of building structural systems, attributing to a reduction in loss of life, injuries, and property damage. The BPAT observed a wide range of connection deficiencies or failures in areas subjected to moderate winds. It is important to keep in mind that the loads seen by these connections were not known, but were believed to be with design requirements and safety factors of model building codes.

The wind forces that act on the roof of a building make the roof sheathing to roof framing connection the important first line of defense. Unfortunately, these connections are often overlooked during construction. When the roof envelope is breached (i.e., roof sheathing is blown off), additional damage is likely to occur as wind forces enter the building and act on interior walls not designed for lateral loads. Figure 4-7 shows a typical example of inadequate fastening.

***FIGURE 4-7: Roof truss failure. A single nail (circled) was used to connect each truss to the top plate. This house was in Midwest City, Oklahoma and experienced inflow winds from a violent tornado.***

Working from the roof system down toward the foundation, the next critical connection is the connection between the roof framing and the wall system. The result of failure of this connection is shown in Figure 4-8. If the roof-framing-to-wall-connection was adequate to withstand forces of uplift, lateral load, and shear transfer, the ability of the structure to withstand the loads generated by moderate winds is increased. Forces would now include the dead load of the wall and its coverings and its shear wall capacity; however, this was not the case in this location and the roof was separated from the rest of the house.

***FIGURE 4-8: Failure of a double top-plate. The uplift of the roof truss previously attached to this double top-plate caused separation of the two members that comprise this top-plate.***

Figure 4-8 shows a seldom seen type of failure that may have been caused by a combination of uplift, diaphragm chord forces, and horizontal bending of the double 2-in by 4-in members commonly used as a top-plate. There were few observed failures of the connection of the double-top-plate to the supporting studs below, although one example is shown in Figure 4-9. With platform construction, the walls are typically framed while lying flat on the floor of the house.

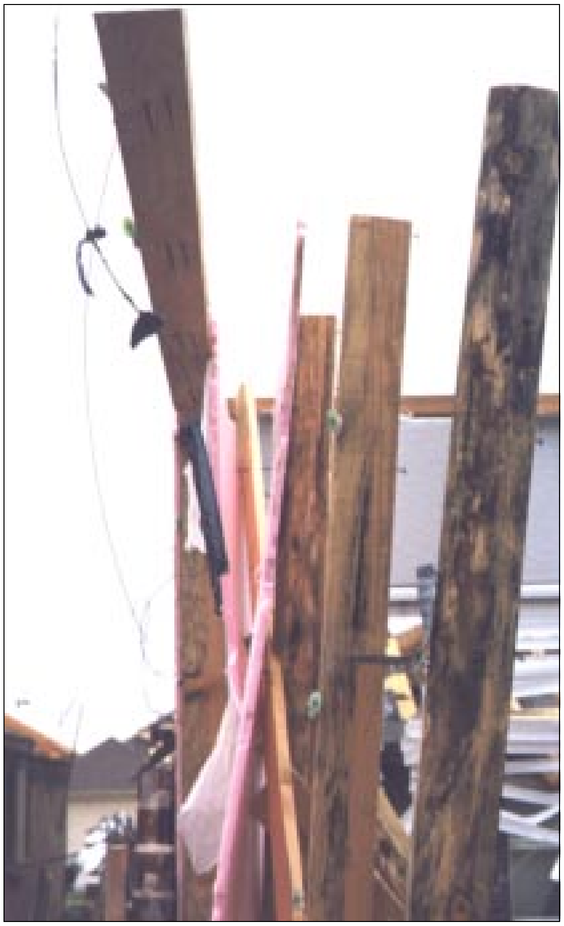


***FIGURE 4-9: Failures of the connection of the double-top-plate to the supporting studs below by home located in Moore, Oklahoma. This home was located along the periphery of a violent tornado.***

Once the wall is erected, the sill plate should be connected to the foundation. In Oklahoma, the foundation was typically a slab-on-grade foundation. In Kansas, basement and crawl space foundations were more common than slab-on-grade construction. Figure 4-10 represents one of many observed failures of the wall-to-sill-plate connection. In this instance, the sill plate remained anchored to the foundation but the toe-nailed or face-nailed connection of the studs to sill plate were inadequate to resist uplift loads from a severe tornado that struck this Oklahoma home.

***FIGURE 4-10: Wall framing to sill plate failure. This house in Del City, Oklahoma, experienced a direct hit from the vortex of a violent tornado.***

Failures between the sill plate and the foundation or floor below were observed. Some of these failures occurred when the sill plate itself failed due to extreme winds associated with the vortex of a violent tornado, as seen in Figure 4-11. In this figure, anchored bolts were used to secure the sill plate to the foundation. In both Oklahoma and Kansas, bolts, nails, and epoxy anchors were observed securing sill plates to foundations. In one instance in Oklahoma, straps from the foundation were observed securing the sill plate to the foundation. Another factor observed that contributed to failures of wall systems was that the bottom-plate (sole- or sill-plate) was not integral with the siding or other means of transferring the force. The connection was weak as seen in Figure 4-12.

***FIGURE 4-11: Stud-wall and sole-plate-to-floor failure on a second story wall. This multi-family residence in Wichita, Kansas, was located approximately a few hundred feet from the vortex of a violent tornado and was exposed to inflow winds.***

In the event adequate connections and structural elements are provided above the sill-plate to foundation connection is almost the last link in the chain. The BPAT saw many examples of failures at the connection to the foundation. Figures 4-11, 4-12 and 4-13 highlight these weaknesses. Uplift, racking and moderate windward forces combined to cause separation of this connection.

***FIGURE 4-12: Failure at base of wall between wall studs and sill-plate. The sill-plate, which was connected to the foundation slab with anchor bolts and nails, has splintered.***

***FIGURE 4-13: Failure of this sill-plate to foundation connection occurred at this home outside Oklahoma City, Oklahoma. The vortex of a violent tornado passed very close to this home.***

### 4.1.4 Increased Load

For buildings that are designed with no dominant openings, such as residential buildings, a breach in the building exterior envelope due to broken windows, failed entry door, or failed garage door may cause a significant increase in the net loads acting on the building under severe wind conditions. In such cases, the increased load may initiate a partial failure or propagate into a total failure of primary structural systems. 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., wind tunnel tests 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.

### 4.1.5 Roof Coverings

Virtually all of the residential roof coverings in the areas the BPAT investigated in Oklahoma and Kansas were asphalt or composition shingles (Figure 4-14). Almost all of the shingles were three-tab or laminated, but a small number of T-lock shingles were also observed (Figure 4-15). Shingle age ranged from relatively new to quite old (more than 15 years). It was observed that for homes located near the far periphery of the tornado, damage was typically limited to intermittent shingle damage only. Shingle damage increased dramatically as the distance from the vortex decreased.

***FIGURE 4-14: Asphalt shingles covering roof of residential home.***

***FIGURE 4-15: Several T-lock shingles on this house were lifted and torn. This house was on the periphery of the damage track left from a moderate tornado in Wichita, Kansas.***

### 4.1.6 Wall Coverings

Brick veneer over wood framing was a predominate wall covering in the investigate areas of Oklahoma. A detailed discussion of masonry used for load bearing walls and wall coverings is presented later in this section. Vinyl siding was another common wall covering. A large number of houses on the periphery of the tornado tracks lost siding. In many cases (Figure 4-16), the vinyl had been installed over wood or hardboard siding. In all of the investigated cases, although the vinyl was blown off, the underlying wood or hardboard siding was undamaged (except for missile impacts). The siding of the home in Figure 4-16 was attached with roofing nails. In one area, the nails were 30-in and 21-in apart. The failure of the siding occurred when the vinyl pulled over the nailheads. Additionally, the home in Figure 4-16 suffered some asphalt shingle damage. Houses with vinyl siding that were closer to the vortex commonly had extensive missile damage (Figure 4-17). Pieces of vinyl siding of this home were blown off by wind or torn away by missiles. The siding on this home was also fastened with roofing nails. The roofing nails were placed at 13.5-in, 10-in, 20-in, and 13.5-in along one length of siding. The vinyl siding also pulled over the nailheads. Homes with other siding materials exhibited limited missile damage even though the missile loading was likely similar.

***FIGURE 4-16: The vinyl (white) that was installed over wood siding experienced damage; however, the wood siding was undamaged. The home was located along the periphery of a violent tornado in Wichita, Kansas.***

***FIGURE 4-17: Some pieces of vinyl siding were blown off and in other areas the siding was torn away by missiles. The home was located along the periphery of a violent tornado in Mullhall, Oklahoma.***

Wood siding and hardboard siding and panels were also observed. In a few instances along the periphery of the tornado tracks, blow-off of these materials was observed. However, it appeared that these materials typically exhibited good resistance to wind speeds that were in the range of current design conditions (e.g.,70 mph, fastest mile sustained or 90 mph 3 second peak gust) of the 1997 UBC, 1996 NBC and 1995 CABO codes.

### 4.1.7 Garage Doors

Along the track periphery, it was common to see residential garage door failures (Figure 4-18). The door in this figure likely had a tested load resistance of 12.5 psf; a common test pressure for doors of similar construction. The design load on this door would be 13 psf using UBC 1997 and 18 psf using ASCE 7-98. Hence the load derived from ASCE 7-98 is 44 percent higher than the tested resistance of the door. Had this door met the wind loading derived from ASCE 7-98, this failure may have been avoided. Most of the investigated doors were made of thin metal. Failures were typically caused by wind pressure, rather than by missiles. The most common failure mode observed was the door rollers disengaging from the door tracks. This was likely caused by excessive door deformation (see Figures 18A-18D). Door failure resulted in increased load on the building.

***FIGURE 4-18: This double-width garage door failed under a suction load in Moore, Oklahoma.***

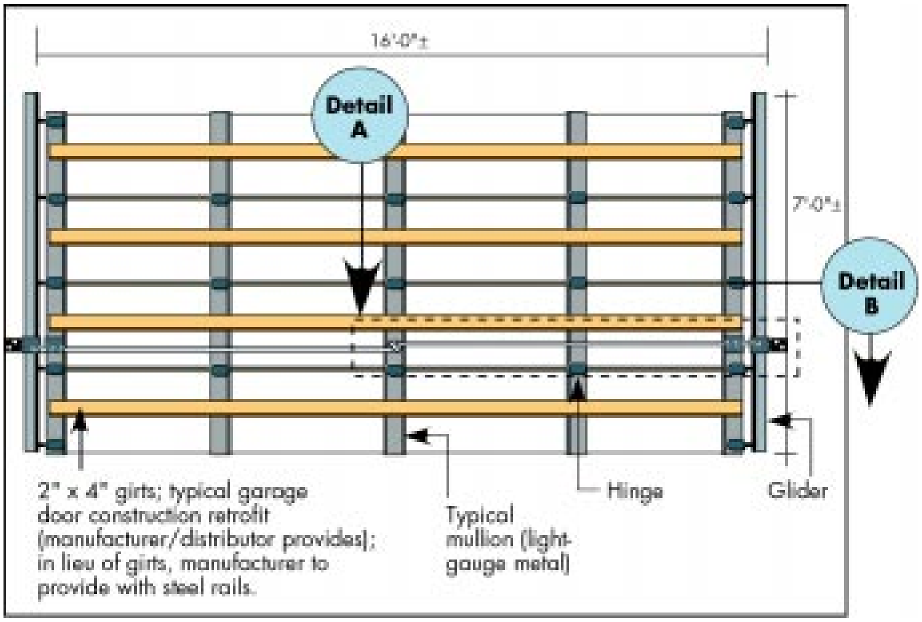


***FIGURE 4-18A:Typical double-wide garage door elevation***

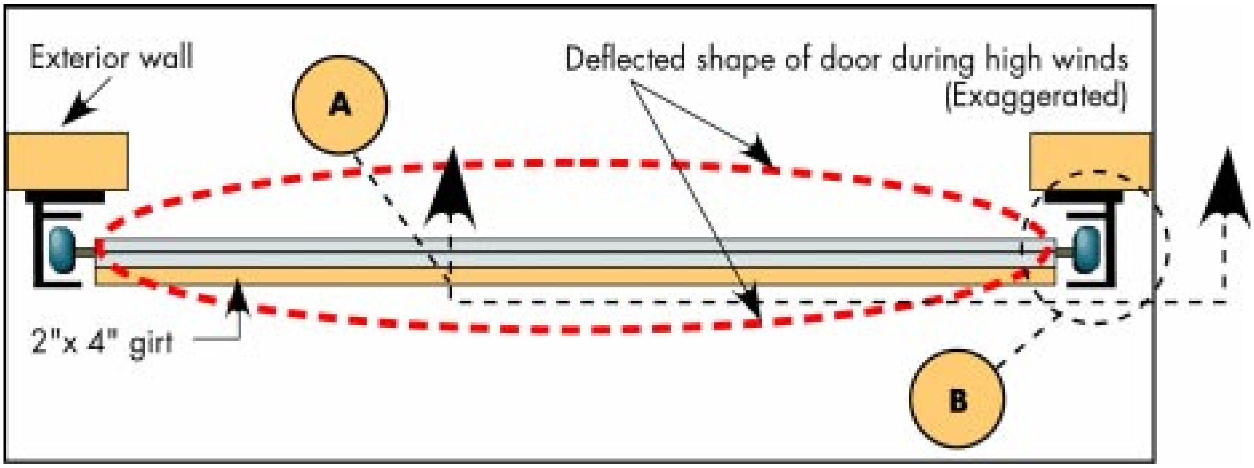


***FIGURE 4-18B: Plan view of typical garage door shown in Figure 4-18A.***

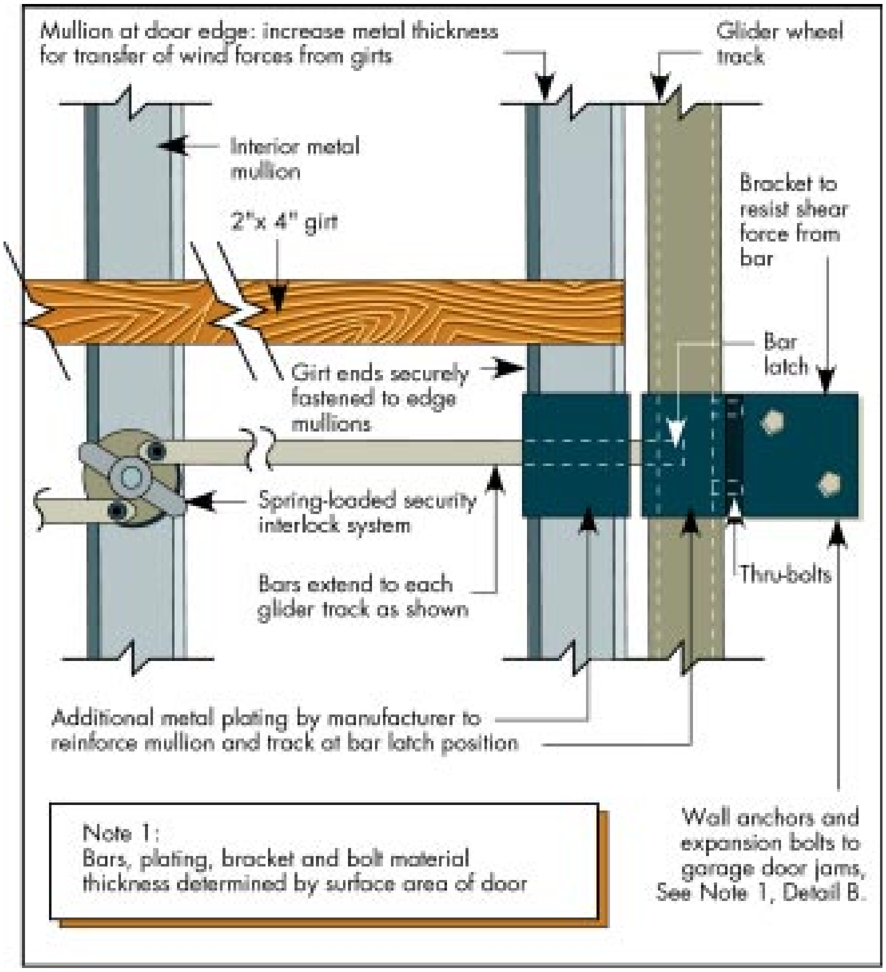
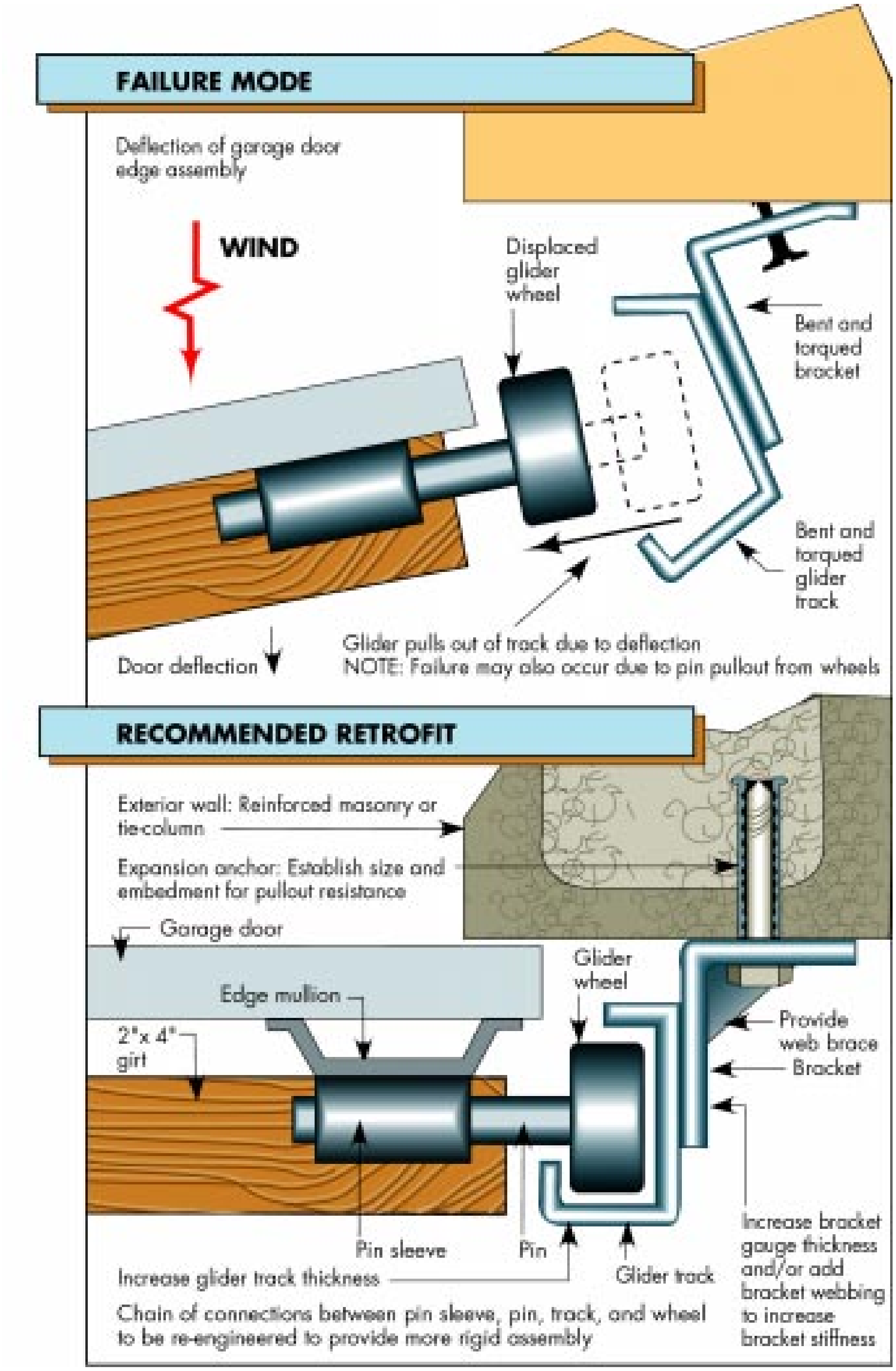


***FIGURE 4-18C: Detail A from Figures 4-18 A and B. Recommend reinforced horizontal latch system for garage door.***

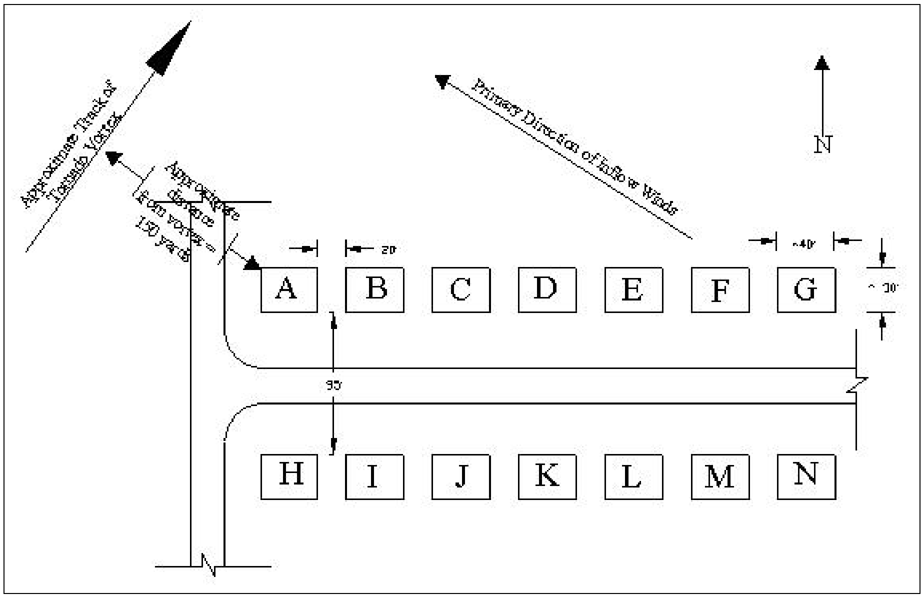
***Detail B from Figures 18***
***e door failure at***
***track and recommend***
***assembly improvements.***



The BPAT conducted an extensive assessment of garage door performance at Greenbriar Eastlake Estates in Oklahoma City. A violent tornado directly struck this subdivision and destroyed many homes. The house in Figure 4-18 was located approximately 200-300 feet away from the vortex of the tornado as it moved from the southwest to the northest of this neighborhood. A partial schematic map of the Greenbriar Eastlake Estates is shown in Figure 4-19. The rectangles represent the average dimensions of homes surveyed with house labels appearing within the rectangles. The homes surveyed in this subdivision are constructed of wood framing with brick veneer. The roofs on these homes were hip, gable, or a combination of the two. The majority of the homes were single-story, some with cathedral ceilings. Most house floor plan configurations are simple L, T, or rectangle shapes. Roof decking was observed to be mostly dimensional lumber with some Oriented Strand Board (OSB) and plywood sheathing. Roof rafter and wall top-plate connections were typically toe nailed with two 16d nails with no added straps or clips. Overall, material quality was observed to be typical for the Oklahoma City area. Windows were observed to be of average quality, as were front, back, and side entry doors. The large majority of the homes observed had single skin aluminum, non-insulated, and non-reinforced double width garage doors.

Homes located at H and A are shown in Figure 4-20. The damage states of the two homes are significantly different even though they are located directly across the street from one another, approximately 95 feet, and may have experienced relatively similar wind conditions based on the approximate track location (Figure 4-19). The home located at H had seven broken windows, primarily at the back of the home as a result of debris generated from a failed wooden fence. It also had one breached glass entry door, and lost approximately 60% of its roof covering. The home located at A lost its entire roof and several exterior walls. For the remaining structures, similar “across-the-street” damage gradients were observed between the homes, A through G and H through N, with the exceptions of the home at location F, which did not lose its entire roof, and the home at location G, which did not lose any roof, but did sustain severe roof framing damage due to uplift. Table 4-1 **(not included at this time)** lists observed damage states for all homes shown in Figure 4-19, illustrating the expected decreasing damage gradient as the distance between home and storm track increases.

***FIGURE 4-19: Partial schematic map of an Oklahoma City subdivision that was affected by inflow winds from a violent tornado.***



Several failed garage doors were observed lying at the back of the garage for many homes A through G, indicating that the garage doors failed due to positive (inward) pressure. These failures of the garage doors are believed to have initiated or contributed to the catastrophic roof and exterior wall failures for homes A through G, a direct consequence of load increase due to a large breach in the building envelope. Examples of this may be seen in Figures 4-20 and 4-22. Note that the failed garage door in Figure 4-20 is crumpled up against the car, suggesting a door failure under positive pressure. A partial roof failure (house F) is depicted in Figure 4-22. In this case the garage door was also found within the garage as shown in the picture inset. The observed location of the failed garage door and the localized roof damage suggests that the failed garage door may have initiated or played an important role in the roof failure. Many of the moderately to severely damaged homes observed had a significant amount of structural damage to the garage area and to the immediate surrounding area, but did not necessarily have the same magnitude of structural damage at the opposite side of the building where no garage was located.

A final example of observed internal pressurization and roof uplift is shown in Figures 4-23 and 4-24 for the house located at G. The garage door failed by positive pressure and was found inside the garage. Figure 4-24 shows strong evidence of the early stages of roof uplift between the garage roof and exterior wall. The ceiling was observed to have pulled away from the exterior wall perimeter, indicating that the whole roof frame was lifted up. The space shown in Figure 4-24 was apparent along most of the perimeter of the garage ceiling. Figure 4-21 shows an exterior view of the roof and wall interface where the initiation of roof uplift was observed. Tension cracks in the brick veneer and a large gap along the length of the right exterior wall between the roof and top plate were also observed.

***FIGURE 4-20: Home in Moore, Oklahoma, with partial roof loss (H) vs. home with total roof loss due to garage door failure (A) under positive pressure.***

***FIGURE 4-21: A 2x4 member extends out of the gap that runs the length of this garage wall between the top of the wall and the roof framing***

***FIGURE 4-22: Garage door failure possibly resulting in the localized partial roof failure on the left side of this home located in Moore, Oklahoma.***

***FIGURE 4-23: A view of home G with a garage door that failed due to positive or inward acting wind loads.***

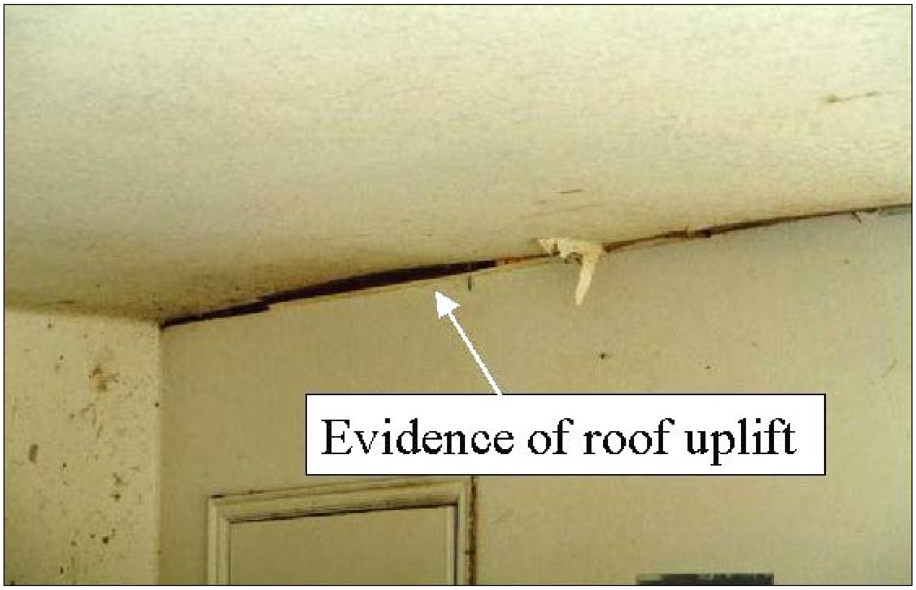


***FIGURE 4-24: Roof uplift between garage roof and exterior wall at home G.***

For several of the homes, H through N, it was observed that the garage doors had sustained permanent deformation due to negative (outward) pressure loads. This observation supports the assumption that the garage doors for homes A through H located across the street failed in positive pressure, as shown in Figure 4-18 for the home located at H. This door failed under a suction load. This door likely had a tested positive load resistance of 12.5 psf. The design load on this door would be 13 psf negative and 11 psf positive using UBC 1997, and 18 psf negative and 14 psf positive using ASCE 7-98. Hence, using a 1.5 safety factor in calculating design loads, the positive load derived from ASCE 7-98 is 68% higher than the design resistance of the door. Had this door met the wind loading derived from ASCE 7-98, this failure may have been avoided. Full scale pressure tests on garage doors have also demonstrated that a typical garage door is significantly stronger in negative (outward) loading than in positive (inward) loading, which may explain why no garage doors completely failed on the homes, H through N (assuming comparable winds).

### 4.1.8 Windows and Doors

Glass in exterior windows and doors, glass storm doors, and glass sliding doors in buildings in or along the tornado vortex track rarely survived. It was common for virtually every pane of glass to be broken on all sides of a house. Further from the vortex track, where winds were either inflow or outflow winds, it was common to see several broken panes on only one or two sides of the house. As the distance from the track vortex increased, the incidence of glass breakage decreased. Glazing failure often resulted in increased wind load on the building from internal pressurization.

Exterior doors typically performed better than windows; however, many were blown out of their frames and others were breached (Figure 4-25).

***FIGURE 4-25: A missile penetrated this exterior door in Del City, Oklahoma. Interior hollow-core doors typically offer even less missile protection than common exterior doors.***

Depending on room size, the existence of interior doors, and the ability of internal pressures to propagate through multiple rooms within the building, the breach of windows or a failed entry door may cause pressurization of only a portion of the building interior and may be often limited to the room where the breach occurred. In order for the breach to increase the overall uplift loads acting on the roof, the internal pressures must be able to propagate through to the attic space. For this to occur, the initial breach and subsequent internal pressurization must also breach through to the attic, typically through the attic entryway. If the attic entry door consists of a set of pull down stairs, the likelihood of attic pressurization is minimal. When the attic opening is a scuttle access, covered with a simple unattached push-to-open panel, the BPAT observed the risk of attic pressurization is dramatically increased. Another way in which the attic can become pressurized is by failure of the ceiling drywall, thus providing an opening to the attic space. Also, depending upon the location of attic vent openings, the attic could be pressurized through the vents.

Thus, a window breach or entry door failure may be unlike a garage door failure where the internal pressure is directly transferred to most of the roof system via the ceiling rafters or to the bottom roof truss chords. When a window or door fails, interior doors may slam closed and contain the effects of internal pressurization to a single room. If the room is isolated from roof framing (e.g., a first story window on a two-story home, very little increase in roof uplift can be expected. If the interior doors or walls attached to the room fail, then the pressurization process will be repeated for adjoining rooms.

Several window failures at the back of the home located in Country Place, a subdivision of Oklahoma City, are shown in Figure 4-26. These homes were located along the periphery of a violent tornado. Other than a small piece of sheathing missing from the roof edge, the roof damage is limited to the loss of roof covering material only. In contrast, several pieces of roof deck sheathing failed on the front portion of the roof as depicted in Figure 4-27. Note that no breaches to the front exterior wall were observed. Figure 4-28 shows a view of the interior of the same dwelling taken from outside the left hand window breach seen in Figure 4-26. The photograph of the interior suggests the possibility that internal pressurization may have contributed to the roof deck sheathing loss. This is suggested by the holes in the ceiling, in particular the right hand hole above the interior doorway. There is evidence to suggest that internal pressure may have pushed the ceiling away from the top of the interior wall where the ceiling drywall failed. Note that there is no evidence of drywall debris on the floor directly below the drywall failure suggesting the drywall was ejected into the attic. This suggests that internal pressurization may have caused the drywall to fail leading to pressurization of the attic space and contributing to the sheathing failure of Figure 4-27. The drywall debris on the floor in front of the entry door belongs to the collapsed ceiling drywall to the left and was likely the result of rain water damage entering through the roof.

***FIGURE 4-26: Damage to back of home in the Country Place Subdivision in Oklahoma City, was limited to several window failures and minor roof damage. The home was located along the periphery of a violent tornado.***

***FIGURE 4-27: Front of home in Figure 4-26 where several pieces of roof decking failed.***

***FIGURE 4-28: View of interior of home in Figures 4-26 and 4-27.***

A more serious effect of a failed or breached window or door is when the pressurization results in the partial or total loss of an adjoining exterior wall. When this failure mode occurs, the breach is often located near a corner where high suction (negative) loads occur on the adjacent wall. The consequence of losing an exterior wall may initiate the partial or total loss of the roof if the wind speed and direction are favorable. Figure 4-29 shows the failure of a portion of exterior wall (leeward side) due to internal pressurization following the breach of a window (windward side).

***Figure 4-29: Box temp. being used as place holder***

### 4.1.9 Masonry

The BPAT observed brick masonry veneer construction and its failure from moderate wind loads was at numerous locations throughout the inspected subdivisions of the Oklahoma City metroplex and the Willow Lake Estates in Bridge Creek, Oklahoma. In Figure 4-30, the north wall of a house had been framed with 2-in by 6-in studs with 1-in by 4-in let-in corner bracing, covered with 1-in thick plastic foam insulation boards and brick veneer. Several studs remained upright, but the brick veneer lay on the ground. Corrugated metal brick ties remained fastened to the studs, and had pulled out of mortar joints. Onsite evaluation indicated that much of the damage had been caused by straight inflow winds near ground level associated with a nearly severe tornado, similar to that experienced from severe thunderstorms or other typical design events and not from a tornado vortex (Figures 4-30 and 4-31).

***FIGURE 4-30: Failure of brick masonry veneer construction. The vortex of the severe tornado that caused the winds at this site passed approximately 30 feet from this building in Bridge Creek, Oklahoma.***

***FIGURE 4-31: Brick veneer failure at the house shown in Figure 4-30.***

Preliminary discussions with Central Oklahoma Home Builders Association (COHBA) in Oklahoma City indicated that almost all residences constructed in the last several years in the Bridge Creek area had framed walls and brick veneer on all four sides. COHBA also indicated that this construction complied with the 1995 CABO One and Two Family Dwelling Code.

At Country Place and Eastlake Estates in the southwest suburbs of Oklahoma City, the BPAT observed an increasing number of 1- to 5-year-old homes with brick veneer failures. The wind speeds at these locations could not be determined. However, based on the team's observation of the damage and debris, plus wood framed walls remaining standing, it would appear that many homes with brick veneer failure were subjected to moderate tornadoes or straight inflow wind forces and were outside the vortex of a violent tornado (Figures 4-32 and 4-33).

***FIGURE 4-32: Failure of masonry veneer wall of a home located along the periphery of a violent tornado, Moore, Oklahoma.***

***FIGURE 4-33: Failure of masonry veneer wall, close-up view, Moore, Oklahoma. This home was located along the periphery of a violent tornado.***

The BPAT also observed several problems that led to premature failure of the brick veneer, such as inadequate bonding of mortar to galvanized brick ties, inadequate bonding of mortar to brick, and nail pull-out at brick ties. The BPAT observed that brick veneer was generally constructed using 3-in brick, which appeared to be a dense brick of low porosity. Location and number of brick ties varied considerably, from 16-in on center vertically and horizontally, to ties at top, midheight, and near bottom of walls. There were several walls with up to 1.5-in to 2.0-in gaps behind brick and with brick ties only inserted ¾-in to 1.0-in into mortar joints. Most ties were fastened through foamboard sheathing into studs with one 6d common nail per tie.

In many cases, sections of brick veneer wall panels could be easily pulled loose by hand, and where brick veneer was left standing, it could easily be pushed in with hand pressure (Figures 4-34, 4-35 and 4-36).

***FIGURE 4-34: Inadequate bonding of mortar to galvanized brick ties, Bridge Creek, Oklahoma.***

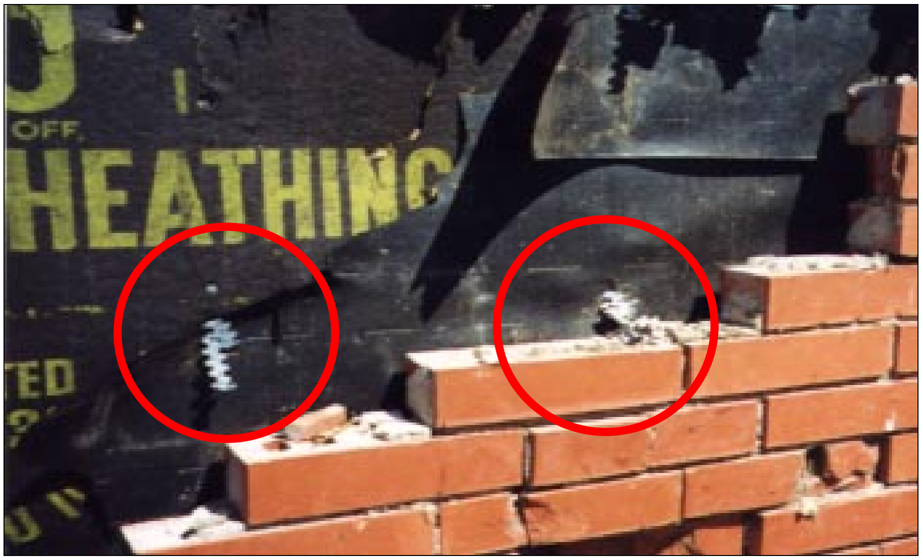
***FIGURE 4-35: Inadequate bonding of mortar to galvanized brick ties, Bridge Creek, Oklahoma.***

***FIGURE 4-36: Failure of masonry veneer wall, Del City, Oklahoma.***

In Del City and Mid West City, in the southeast suburbs of Oklahoma City, the BPAT observed several more examples of brick veneer (both clay and concrete brick) failure. Most of the failure appeared to have been caused by negative wind pressure (suction) on leeward and side walls (Figures 4-36, 4-37, 4-38, and 4-39). These walls were also in an area that was in the inflow wind area of a violent tornado, but outside the vortex.

***FIGURE 4-37: Failure of masonry veneer wall, viewed collapsed on the ground. This home, located in Oklahoma City was in the vortex of a violent tornado.***

***FIGURE 4-38: Failure of masonry veneer wall of home located along the periphery of a violent tornado in Oklahoma City. Masonry ties are circled.***



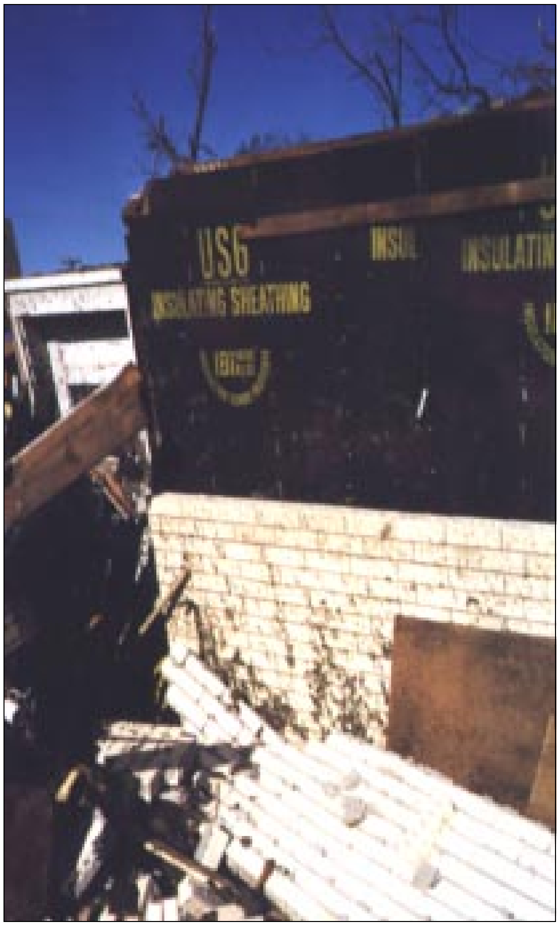


***FIGURE 4-39: Failure of masonry veneer wall of home located along the periphery of a violent tornado, Del City, Oklahoma.***

In Moore, Oklahoma, at a subdivision south of Westmoore High School that was in the direct path of a violent tornado, newer homes located in the periphery of the damaged areas approximately a few hundred feet from the vortex had failures of brick chimneys and brick veneer walls. Brick chimneys snapped off near the eave and crashed through the house roof, breaching the building envelope and placing occupants at risk of injury or death from falling masonry and other debris. Masonry veneer walls appeared to fail from suction (negative) loads pulling the veneer away from the stud framing. Again, the majority of masonry veneer was single width, 3-in brick. Chimneys were 28-in wide by 24-in deep and made of 3-in brick, with a 10-in by 10-in clay tile flue in the center, leaving a large gap between flue and exterior brick. The height of chimney was about 8-ft above eave height. No vertical or horizontal reinforcement was present. Ages of houses did not appear to make any difference on bonding of mortar to brick ties or bonding of mortar to brick., as some were 30 years old and others only one year old. This type of chimney construction should perhaps be limited in its maximum unsupported height, even when considering nominal (non-tornadic) design wind loads(see Figures 4-40 through 4-42).

*FIGURE 4-40: Failure of brick chimney onto roof of home located along the periphery of a violent tornado, Moore, Oklahoma.*

*FIGURE 4-41: Close-up view brick chimney failure in Figure 4-40.*

***FIGURE 4-42: Failure of brick chimney onto top of home located along the periphery of a violent tornado, Moore, Oklahoma.***

## 4.2 MULTI-FAMILY CONSTRUCTION

The majority of single-family housing construction in areas of Kansas devastated by the May 3 tornadoes was of older construction with exterior cladding other than brick masonry. However there were a few homes and several two-story apartments with brick veneer that had extensive damage (Figures 4-43 through 4-47).

Most of the observations for single family structures are applicable to multi-family (low rise, condo and garden apartment) construction with the addition of an example of a large overhang.

***FIGURE 4-43: Failure of masonry veneer.***

***FIGURE 4-44: Failure of masonry veneer at a multi-family housing unit in Wichita, Kansas. This building experienced inflow winds from a severe tornado.***

***FIGURE 4-45: Failure of masonry veneer in multifamily housing located along the periphery of a severe tornado, Wichita, Kansas.***

***FIGURE 4-46: Chimney failure onto roof of single family attached housing, Wichita, Kansas. This building was located along the periphery of a severe tornado.***

***FIGURE 4-47: Chimney failure onto roof of single family attached housing located along the periphery of a severe tornado, Wichita, Kansas.***

## 4.3 MANUFACTURED HOUSING

Damage to manufactured homes was observed in Oklahoma and Kansas. Performance of units on temporary foundations utilizing anchors and straps were assessed as well as the performance of units on permanent foundations.

In Bridge Creek, Oklahoma, approximately 50 miles west of Oklahoma City, 11 deaths were reported from a violent tornado; most of these deaths were individuals taking refuge in manufactured housing. While some manufactured homes were directly hit by the vortex, estimates of wind speed based on observed damage to buildings and trees during the site visit indicated that most buildings were impacted by straight inflow winds and not by the vortex of a tornado.

There were several sites in the area that were observed to have the manufactured house wood framing completely destroyed and separated from the twisted remains of the steel chassis, and the chassis and debris at a distance from the original anchorage site. Ages of homes could not be determined; no data plates or labels could be found. Most of the manufactured homes in this location were single-wide, 14-ft by 60- or 70-ft units, originally connected to the ground by helical ground anchors and galvanized steel straps fastened to the steel chassis beams.

Foundation support was typically provided by ungrouted (dry stacked) concrete masonry unit (CMU) piers at six to eight feet on center under each chassis beam. The total number of anchors per home varied considerably, from four to eight per home. The most spectacular failure observed was a 14-ft by 60-ft manufactured home chassis found about 200 yards to the northeast of its original anchorage site (Figure 4-48). This home was not affected by the vortex of a tornado, rather, it was affected by the inflow winds whose violent tornado vortex was approximately 300-400 ft away from this home. At the original site, vertical and diagonal straps remained attached to the ground anchor, but had failed about two to three feet from the anchors (Figure 4-49). The first anchors had been fastened about 12-feet from the east end. Both the number of anchor straps and tensile capacity of the straps were inadequate to resist wind uplift forces (Figure 4-50).

***FIGURE 4-48: This 14-ft x 60-ft manufactured home chassis in the background of this picture moved about 200 yards from its original anchoring site in Figure 4-49, Bridge Creek, Oklahoma.***

***FIGURE 4-49: Failed straps at the anchorage of a manufactured home in Bridge Creek, Oklahoma. This site was 300-400 feet from a violent tornado vortex.***

***FIGURE 4-50: Strap anchoring failure most likely led to the displacement of this chassis, Bridge Creek, Oklahoma.***

After completing several site visits in the Oklahoma City metroplex, the BPAT visited Mulhall, Oklahoma, about 50 miles north of Oklahoma City. There were several double-wide manufactured houses damaged by a severe tornado. One 28-ft by 60-ft home had rotated on its piers, 2-ft to the east at the north end and 1-ft to the west at the south end. Three helical anchors were pulled out that had been installed about one-foot into the ground on the northwest end of the home (Figure 4-51). Anchor straps that were still attached to ground anchors and chassis beams were loose, which allowed lateral movement of the unit. Anchor depth into the loose sandy soil did not appear to be adequate to resist wind uplift and overturning forces (Figures 4-52 and 4-53) generated by a severe tornado whose vortex passed nearby, but did not directly strike the homes.

***Figure 4-51: Ground anchor of manufactured home pulled from soil. This home in Wichita, Kansas, was located within the inflow area of a severe tornado.***

***Figure 4-52: Anchor of manufactured home bent and pulled up from soil. This home in Wichita, Kansas, was located within the inflow area of a severe tornado.***

***Figure 4-53: Strap torn off from chassis of manufactured home. This home in Wichita, Kansas, was located within the inflow area of a severe tornado.***

Several manufactured homes had lost plywood roof sheathing and roof trusses, and some only lost asphalt roof shingles. Fastening of the roof sheathing and roofing materials was inadequate to resist wind uplift (Figures 4-54 and 4-55) from inflow winds of a severe tornado.

***Figure 4-54: Roof and wall damage experienced due to inadequate resistance to lateral and uplift wind forces associated with straight inflow winds of a moderate tornado, Wichita, Kansas.***

***Figure 4-55: Damage to a manufactured home located on the periphery of a severe tornado, Wichita, Kansas.***

In Haysville, Kansas, the BPAT visited the Sunset Field Addition on South 65th Street near the historic district, where several double-wide manufactured housing units were constructed on permanent concrete crawl space foundations. It was reported that roofs and several walls of the units had been destroyed, but that the floors had remained on the foundation walls. Later, during demolition, the floor system and steel chassis beams with steel outriggers and steel angle bracing had been lifted off the foundation. Although the floors had remained on the concrete walls, there were no bolts or positive connections between the chassis or perimeter wood joist and the sill-plate, pockets in the concrete walls, or center piers (Figure 4-56). Straps that had been stapled to wall studs and to perimeter joists did not appear adequate to resist wind uplift or lateral loads (Figure 4-57), and fastening of the roof system to walls had been inadequate.

***FIGURE 4-56: Lack of bolts or positive connections present between the chassis and foundation, Haysville, Kansas.***

***FIGURE 4-57: A close up of the manufactured home floor and chassis after it was removed from the permanent foundation in Figure 4-56.***

Several double-wide manufactured housing units partially survived high wind forces. However, ground anchors were pulled out of the soil, or they were bent over, loosening up tie-down straps. Homes shifted laterally from wind forces and fell off unreinforced and ungrouted CMU block piers. In some cases, tie-down straps with metal clips for attachment to chassis beams were loose and lying on the ground (Figures 4-58 through 4-61).**(location and wind?)**

***FIGURE 4-58: This manufactured home laterally shifted from wind force generated along the periphery of a violent tornado, Haysville, Kansas.***

***FIGURE 4-59: View of anchor strap and attachment indicating lateral shifting of a manufactured home, Haysville, Kansas. This home was located along the periphery of a violent tornado.***

***FIGURE 4-60: View of anchor strap and attachment indicating some lateral shifting of a manufactured home located along the periphery of a violent tornado, Wichita, Kansas.***

***FIGURE 4-61: Manufactured home laterally shifted from wind force generated along the periphery of a violent tornado, Wichita, Kansas.***