4 Observations on Residential Property Protection

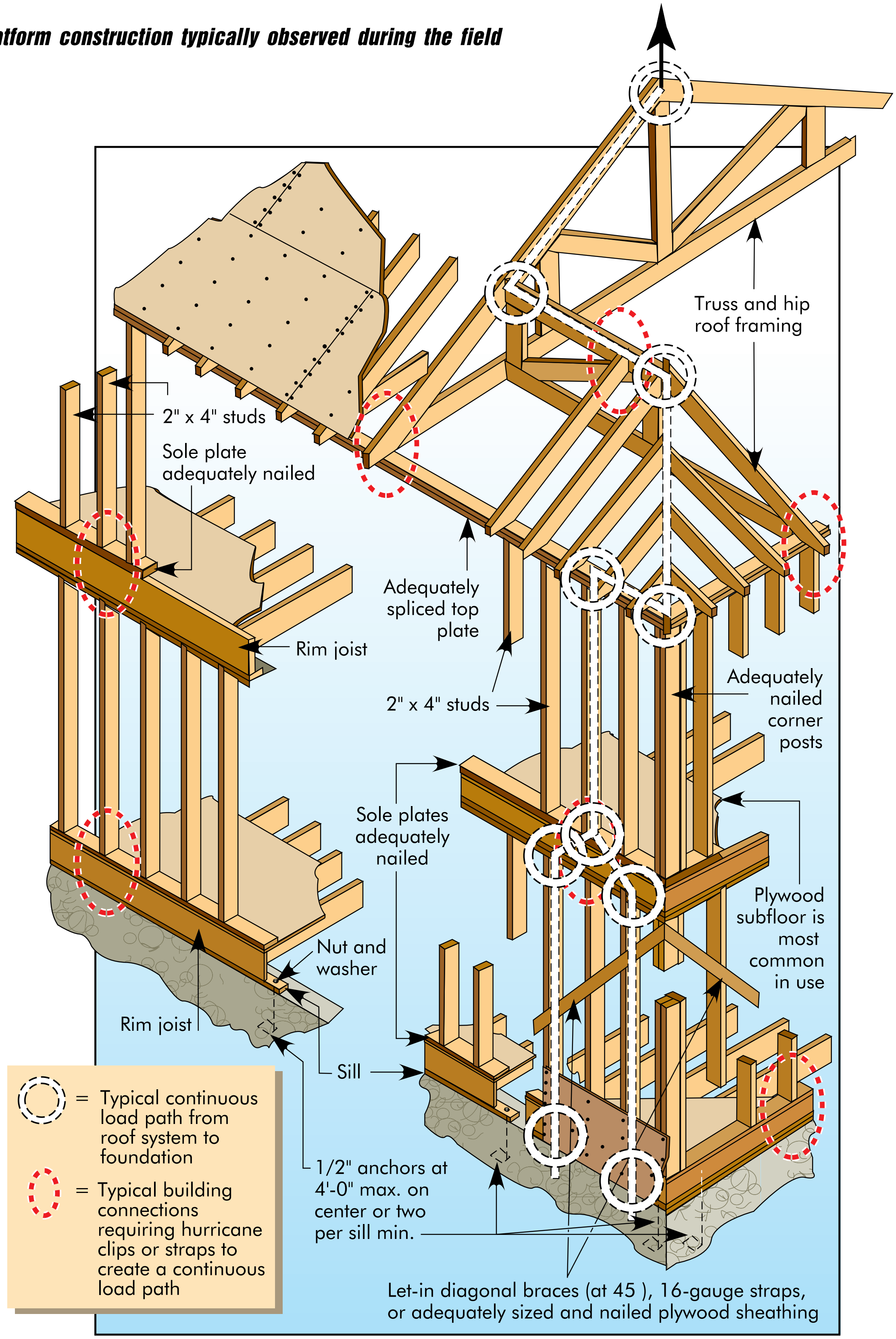
The damage assessment of buildings was divided into residential and non-residential property protection. This section presents the BPAT's observations on residential property protection. Specifically, residential buildings were categorized into three types of housing: single-family, multi-family, and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

The BPAT assessed the performance of primary structural systems of buildings, which are those systems that support the building against gravity loads and the lateral and vertical loads generated by high winds during a tornado or other high wind event. Within a tornado's impacted area, these systems are typically constructed of wood framing, sheathing, anchor bolts, and other connections. In residential applications, the structural system of a house comprises the roof framing and the sheathing bearing walls and sheathing, floor framing, the foundation system, and the connections and fasteners used to fasten these parts of the house together. Roof structure, diaphragms, 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 and strength of the connections between them. Observations were also made concerning exterior architectural systems (e.g., roof and wall coverings, windows and doors, and masonry chimneys).

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," "site built," 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 (typically 1-in by 8-in boards). Platform construction was observed in all cases (Figure 4-1). The buildings observed in Oklahoma were commonly brick veneer and wood frame walls on "slab-on-grade" foundations with some "crawl-space" foundation construction. In Kansas, the buildings were predominantly 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 that assure 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. 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 (where extensive building damage is expected).

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 wall framing, diaphragms, diaphragm chords, attachments and connections, and foundation systems. If the elements are not adequately tied together or connected, the structural system will fail. As discussed in the following sections, the damage ranged from considerable to total, depending on the type of roof framing, construction methods, and wind load experienced at the building.

4.1.2 Roof and Wall Sheathing

Sheathing in light-frame construction can serve more than one purpose. One is to receive the gravity and wind uplift loads 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 lateral wind 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.

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 fasten-

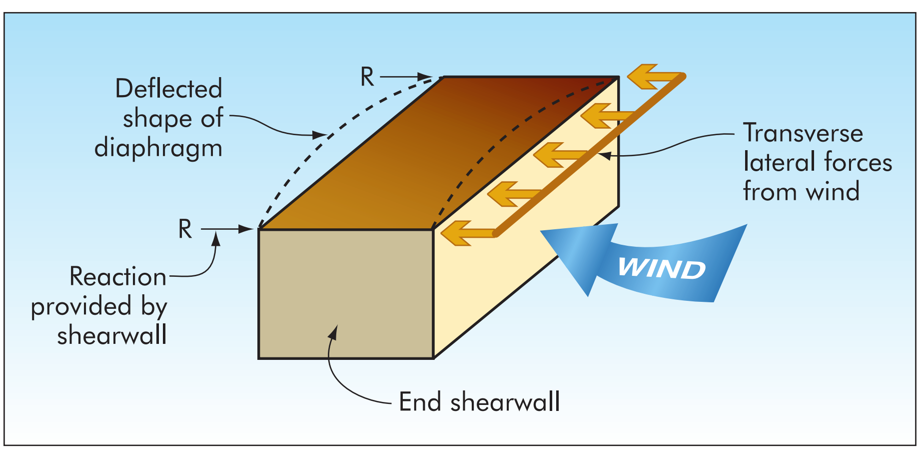


FIGURE 4-2: Lateral load transfer to supporting walls by roof and wall sheathing.

ers observed connecting the sheathing to the supporting rafters or truss top chords were nails or staples. Figure 4-3 shows a typical situation where the stapling of the boards to the rafters or trusses was not adequate to resist the wind uplift. In the application of both the plank and sheet 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 strong tornado.

As wind induced loads reach the top of the walls, the shear has to be transferred to the top plate by some method of fastening. After the fasteners transfers the load from the roof system, 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 and the connection to the wall framing (Figure 4-5) establish the capacity of a shear wall.

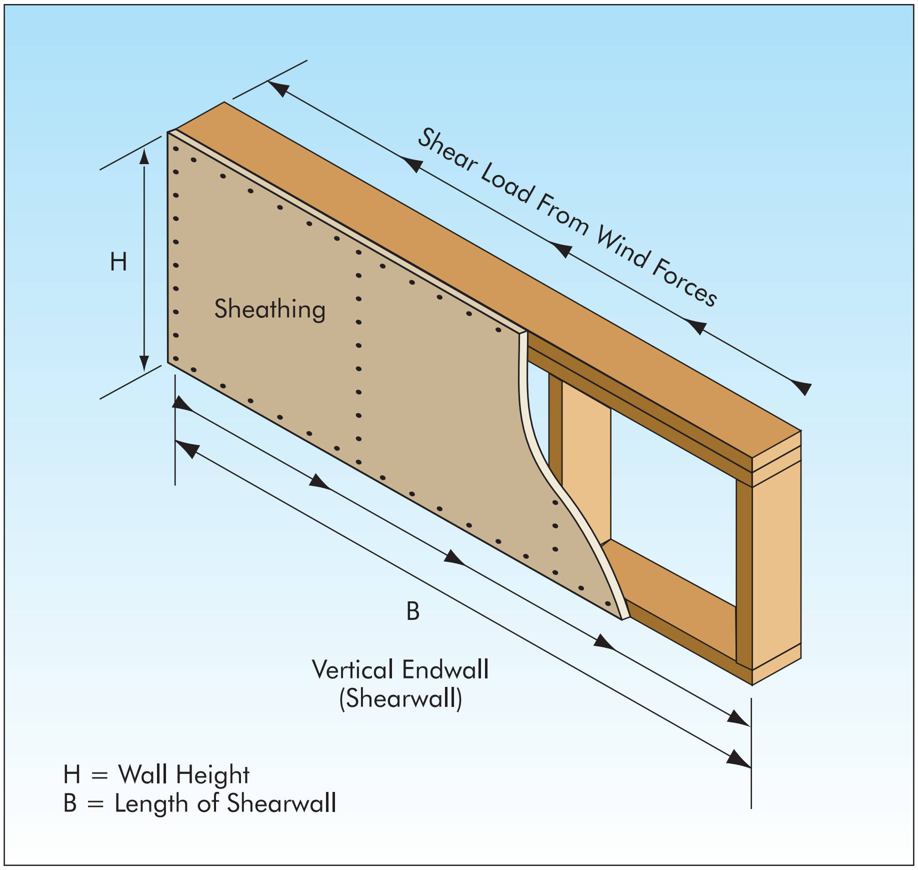


FIGURE 4-5: Shear load carried by wall sheathing.

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 wood fiberboard 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 pressure or a combination of windward/leeward pressure (Figure 4-6).

The construction of exterior shear walls to carry lateral loads requires special design and construction attention when there are large openings such as for

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

garage doors. The exterior walls with garage doors that the team observed were not constructed or designed to act as shear walls. This lack of shear capacity along with roof uplift and other problems discussed in Section 4.1.7 make garages particularly vulnerable to wind damages.

4.1.3 Structural Connections

Post-disaster assessments continue to support the fact that improved connections could result in better performance of building structural systems, and 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 weak-tornado generated winds. It is important to keep in mind that the loads seen by these connections were not known, but the nailed connections observed in most wood frame homes in both Oklahoma and Kansas appeared to be in accordance with connection requirements of the building codes in effect for these areas.

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, the nails and spacing used for the roof sheathing and the use of only nails to fasten the roof framing to the walls provided only minimal resistance to the uplift and lateral forces created by high wind. 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 not meeting minimum building code requirements. Using a nail type or spacing in accor-

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.

dance with current or newer building codes could have produced a sufficient connection for the wind load believed to have occurred at this location.

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 uplift forces, lateral load, and shear transfer, the ability of the structure to withstand the loads generated by moderate winds is increased.

Figure 4-8 shows a seldom seen type of failure caused strictly by uplift of the roof truss attached to the double 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.

Once the wall is erected, the bottom plate should be connected to the foundation or to the floor. 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-bottom plate connection. In this instance, the bottom plate remained anchored to the foundation, but the toe-nailed or face-nailed connection of the studs to the bottom plate were inadequate to resist uplift loads from a violent tornado that struck this Oklahoma home.

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

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

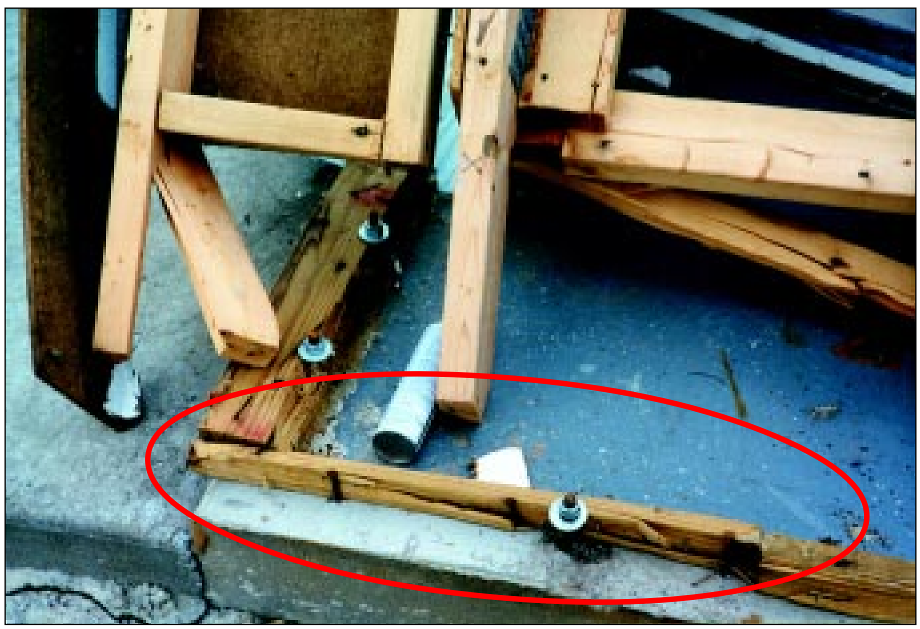
Failures between the bottom plate and the foundation or floor below were observed. Some of these failures occurred when the bottom plate itself failed due to extreme winds associated with the vortex of a violent tornado, as seen in Figure 4-11. In this figure, nails were used to secure the bottom plate to the second story floor system.

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

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. In both Oklahoma and Kansas, bolts, nails, and epoxy anchors were observed securing bottom plates to foundations. In one instance in Oklahoma, straps from the foundation were observed securing the bottom plate to the foundation.

In the event adequate connections and structural elements are provided in the wall system and above, the bottom plate-to-foundation connection is one of the last links in the continuous load path chain that may fail. The BPAT saw many examples of failures at the connection to the foundation. Figures 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 bottom plate. The bottom plate, which was connected to the foundation slab with anchor bolts and nails, has splintered.



4.1.4 Increased Load

Houses are not designed to be open to the wind. When windows break, entry doors fail, or garage doors fail, the internal pressures can increase greatly and work in concert with the outward (suction) forces on the outside of the house, causing structural failures. ASCE 7-98 presents a more thorough engineering discussion of how building openings affect the design for wind loads. A schematic diagram illustrating the increased loads due to a breach in the building envelope was shown in Figure 3-6. 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

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

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 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 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. Shingle damage increased dramatically as the distance from the vortex decreased.

FIGURE 4-14: Asphalt shingles covering a residential roof.

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

4.1.6 Exterior Wall Coverings

Brick veneer over wood framing was a common wall covering in the investigated areas. A large number of houses on the periphery of the tornado tracks lost siding. In many cases (Figure 4-16), 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

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.

missile impacts). A number of houses with vinyl siding were completely sheathed with plywood or oriented strand board (OSB). This allowed a nailing surface for the vinyl siding that was not dependent on the spacing of the framing members (studs). Houses that had walls that were fully sheathed with plywood or OSB generally performed better than houses that used other methods, such as let-in bracing, to brace the walls.

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). The siding on the home in Figure 4-17 was fastened with roofing nails placed at 13.5-in, 10-in, and 20-in along one length of siding. The vinyl pulled over the nailheads. Most of the siding failures observed were in areas that experienced straight inflow winds from the tornadoes that were likely at or slightly above the design wind speeds of the current building codes wind speeds (e.g., 70-80 mph, fastest mile or 90-mph 3-second peak gust).

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., 70-80 mph, fastest mile or 90-mph 3-second peak gust) of the 1997 UBC, 1996 NBC, and 1995 CABO codes.

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.

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 laboratory tested positive 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 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, the positive load derived from ASCE 7-98 is 68 percent higher than the resistance of the door. Had this door met the wind loading derived from ASCE 7-98, this failure may have been avoided. This observation is important because it highlights the advanced guidance given by engineering standards as opposed to the basic guidance given by the model building codes for components and cladding elements such as exterior wall systems, windows and doors, and garage doors.

Most of the doors investigated 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, most likely caused by excessive door deformation (see Figures 4-19 and 4-20). Door failure resulted in increased load on the buildings.

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 1200 feet away from the vortex of the tornado as it moved from the southwest to the northeast of this neighborhood. A partial schematic map of the Greenbriar Eastlake Estates is shown in Figure 4-21. The rectangles represent the average dimensions of homes surveyed with

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

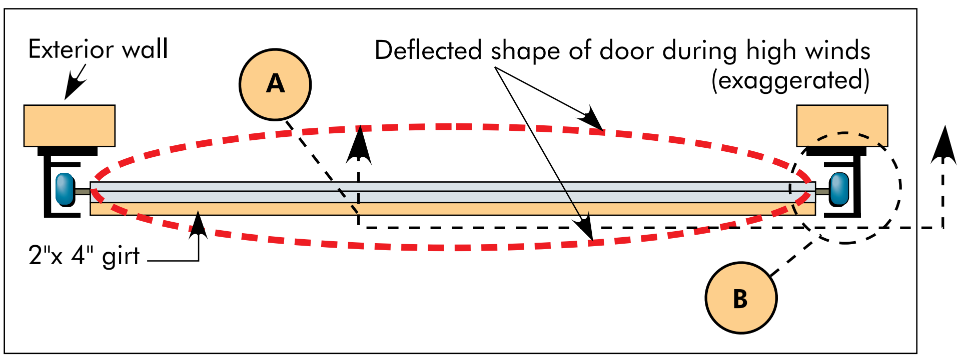


FIGURE 4-19: Plan view of typical garage door shown in Figure 4-18.

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 1-in by 8-in board sheathing with some 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.

FIGURE 4-20: Detail B from Figures 4-19. Garage door failure at track and recommend assembly improvements.

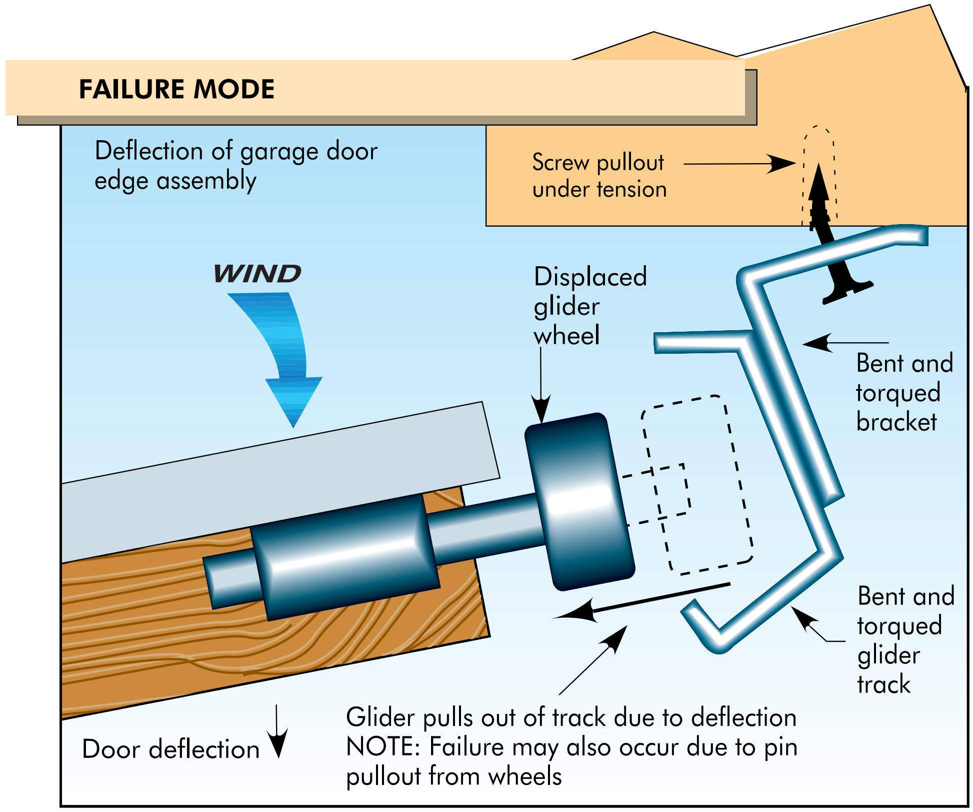
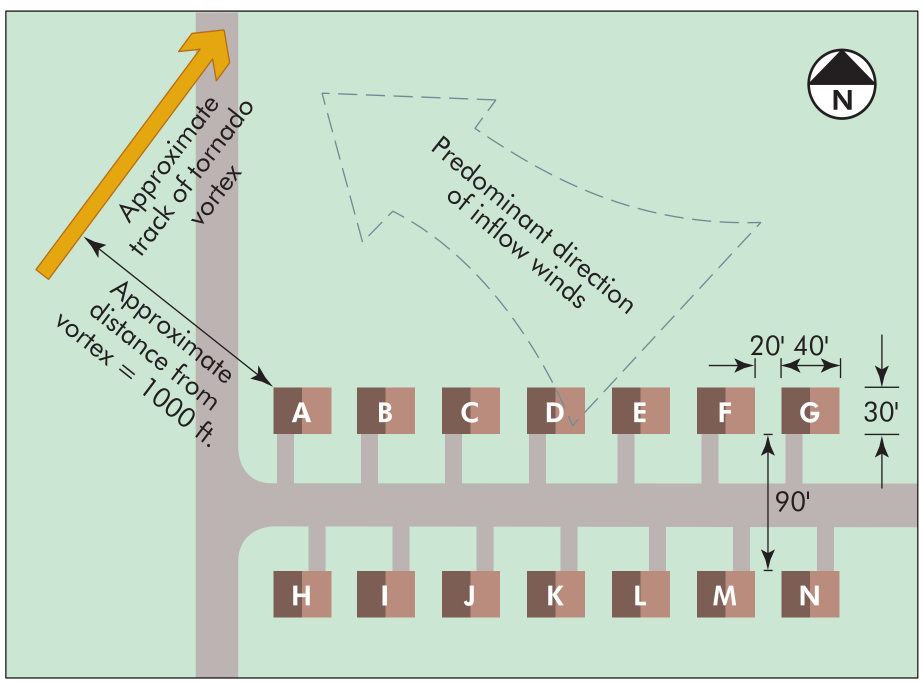


FIGURE 4-21: Partial schematic map of an Oklahoma City subdivision that was affected by inflow winds from a violent tornado.



Homes located at H and A are shown in Figure 4-22. The damage states of the two homes are significantly different even though they are located directly across the street, approximately 95 feet apart, from one another and may have experienced relatively similar wind conditions based on the approximate track location (Figure 4-21). 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 structure and several exterior walls. This was likely due to the failure of the garage door from inward wind forces. For the remaining houses, 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 structure, and the home at location G, which did not lose any roof structure, but did sustain severe roof framing damage due to uplift.

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 4-22 and 4-23. Note that the failed garage door in Figure 4-22 is crumpled up against the car, suggesting a door failure under positive pressure. A partial roof failure (house F) is depicted in Figure 4-23. 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 4-24 and 4-25 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 4-25 was apparent along most of the perimeter of the garage ceiling. Figure 4-26 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 4-22: Home in Moore, Oklahoma, with partial roof loss and garage door in place (H) vs. home with total roof loss due to garage door failure (A) under positive pressure.

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 G located across the street failed in positive pressure, as shown in Figure 4-22 for the home located at A. This door failed under a positive load. Full scale pressure tests on garage doors performed in laboratories have 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).

FIGURE 4-23: Garage door failure possibly resulting in the localized partial roof failure on the left side of this home located in Moore, Oklahoma.

FIGURE 4-24: A view of home G with a garage door that failed due to positive (inward) acting wind loads.

FIGURE 4-25: Roof uplift between garage ceiling/roof structure and exterior wall at home G.

FIGURE 4-26: 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.

4.1.8 Windows and Doors

If the building envelope is breached (e.g., windows, wall and roof coverings), the building may experience rapid pressurization, which may well lead to structural failure (Figure 4-27). The failure of a door or window may start this process. Window failures were commonly observed because windows can be broken by both large and small missiles in addition to the wind pressure acting on the windows. Exterior doors and windows failed from the wind pressures of the tornadoes. Garage doors failed from both wind pressures and debris,

FIGURE 4-27: A missile penetrated this exterior door in Del City, Oklahoma. Interior hollow-core doors typically offer even less missile protection than common exterior doors.

and were less common than window failure. However, when the failure of garage doors occurred, it appeared to have caused additional failures at other parts of the house as was briefly described previously.

Glass in exterior windows and doors, glass storm doors, and glass sliding doors in buildings in or along the track of the tornado vortex rarely survived. It was common for virtually every pane of glass to be broken on all sides of a house. Further from the track of the tornado vortex, it was common to see several broken panes on only one or two sides of the house. As the distance from the track of the vortex increased, the incidence of glass breakage decreased.

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 or garage 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 between roof trusses or framing members, 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.

A window 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 may occur. If the interior doors or walls attached to the rooms fail, 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 4-28. This home was located along the periphery of a violent tornado. Other than a small piece of sheathing missing from the roof edge, the roof damage in the back of the home is limited to the loss of roof covering material only. In contrast, several pieces of roof sheathing failed on the front portion of the roof as depicted in Figure 4-29. Note that no breaches to the front exterior wall were observed. Figure 4-30 shows a view of the interior of the same dwelling taken from outside the left-hand window breach seen in Figure 4-28. The photograph of the interior suggests the possibility that internal pressurization may have contributed to the roof sheathing loss. This is suggested by the holes in the ceiling, in particular the right-hand hole above the interior doorway. There was 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 was no evidence of drywall debris on the floor directly below the drywall failure, suggesting the drywall was ejected into the attic. Internal pressurization may have caused the ceiling drywall to fail between the roof structural members that led to the pressurization of the attic space and contributed to the

FIGURE 4-28: Damage to back of home in the Country Place Subdivision in Oklahoma City, was limited to several window failures and roof covering damage. The home was located along the periphery of a violent tornado.

FIGURE 4-29: Front of home in Figure 4-28 where several pieces of roof sheathing failed.

FIGURE 4-30: View of interior of the home shown in Figures 4-28 and 4-29.

sheathing failure shown in Figure 4-29. Drywall debris on the floor in front of the door belonged to the collapsed ceiling drywall to the left and was likely the result of rain water damage entering through the roof.

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.

4.1.9 Masonry Veneer

The BPAT observed brick masonry veneer construction and its failure from moderate wind loads at numerous locations throughout the inspected subdivisions of the Oklahoma City Metroplex and the Willow Lake Estates in Bridge Creek, Oklahoma. Brick veneer often appeared to have withstood the wind forces of the tornadoes, but closer inspection revealed the veneer on many homes, although still standing, was easily moved with light hand pressure (Figure 4-31). In Figure 4-32, 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. On-site evaluation indicated that much of the damage had been caused by straight

FIGURE 4-31: This brick veneer appears to be undamaged but close inspection indicated that this wall could be deflected inward with only hand pressure.

inflow winds associated with a strong tornado, similar to that experienced from severe thunderstorms or other typical design events, and not from a tornado vortex (Figures 4-32 and 4-33).

FIGURE 4-32: Failure of brick masonry veneer construction. The vortex of the strong tornado that caused the winds at this site passed approximately 300 feet from this building in Bridge Creek, Oklahoma.

FIGURE 4-33: Brick veneer failure at the house shown in Figure 4-32.

Informal discussions with the Central Oklahoma Home Builders Association (COHBA) indicated that almost all residences constructed in the last several years in the Oklahoma City 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. However, many of the brick masonry veneer failures observed by the BPAT did not comply with the CABO code with respect to the spacing and anchoring of the masonry ties.

At Country Place and Eastlake Estates in the southwest suburbs of Oklahoma City, the BPAT observed a large 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, including standing wood framed walls, it appeared that most homes with brick veneer failure were outside the vortex of a violent tornado (Figure 4-34).

FIGURE 4-34: Failure of masonry veneer wall of a home located along the periphery of a violent tornado near Moore, Oklahoma.

The BPAT also observed several problems that led to failure of the brick veneer, such as inadequate bonding of mortar to galvanized brick ties, inadequate bonding of mortar to brick, corroded brick ties, and nail pull-out at brick ties. The BPAT observed that brick veneer was generally constructed using 3-in brick. 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 plastic foam insulation 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 4-35, 4-36, and 4-37). Walls with no visible failure could also be pushed over. This occurred when suction loads acting on the walls broke the bond with the ties, but did not result in brick veneer failure.

In Del City and Midwest City, and Oklahoma City, the BPAT observed several more examples of brick veneer (both clay and concrete brick) failure. Most of the failures appeared to have been caused by negative wind pressure (suction) on leeward and side walls (Figures 4-35, 4-36, and 4-37). These walls were also in an area that was in the inflow wind area of a violent tornado, but outside the vortex. The house in Figure 4-38 experienced only brick masonry and window damage when exposed to the winds on the periphery of a violent tornado.

FIGURE 4-35: Inadequate bonding of mortar to galvanized brick ties contributed to this masonry failure at a home in Bridge Creek, Oklahoma.

FIGURE 4-36: Inadequate bonding of mortar to galvanized brick ties, Bridge Creek, Oklahoma.

FIGURE 4-37: Failure of brick veneer wall, Del City, Oklahoma.

FIGURE 4-38: Failure of brick veneer wall, collapsed on the ground. This home, located outside Oklahoma City was on the periphery of a violent tornado.

4.1.10 Masonry Chimneys

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 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. Again, the majority of masonry veneer was single width, 3-in brick.

Chimneys were typically 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, because they ranged in age from 1 to 30 years old. (Figures 4-39 through 4-44).

Basic calculations performed by the BPAT indicated a varying magnitude of wind speeds that caused failure of the different chimneys observed. Using the wind guidance given in the 1995 CABO One- and Two-Family Dwelling Code (the code governing most residential construction in the impacted area) wind speed ranges for some of the chimney failures observed were calculated. The chimney failure in Figures 4-40 and 4-41 (a 32-in by 36-in brick chimney) and the failure of the brick chimney in Figure 4-42 (a 30-in by 30-in chimney) were likely due to wind speeds of no greater than 136-139 mph (fastest mile). Calculations were also performed on a brick chimney (30-in by 42-in) that

FIGURE 4-39: Failure of brick veneer wall of home located along the periphery of a violent tornado in Oklahoma City. Masonry ties are circled.

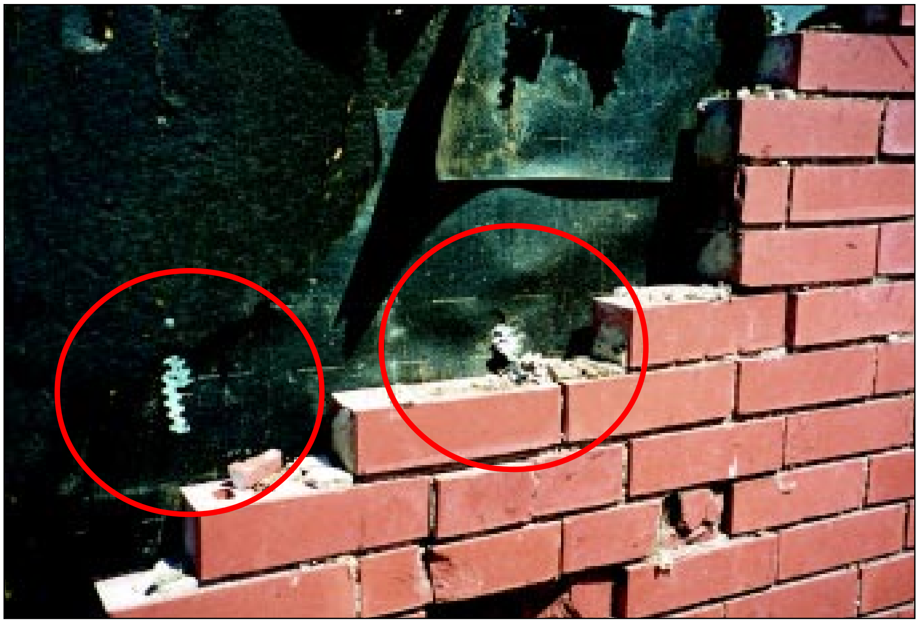


FIGURE 4-40: Failure of brick chimney onto roof of home located along the periphery of a violent tornado, Moore, Oklahoma.

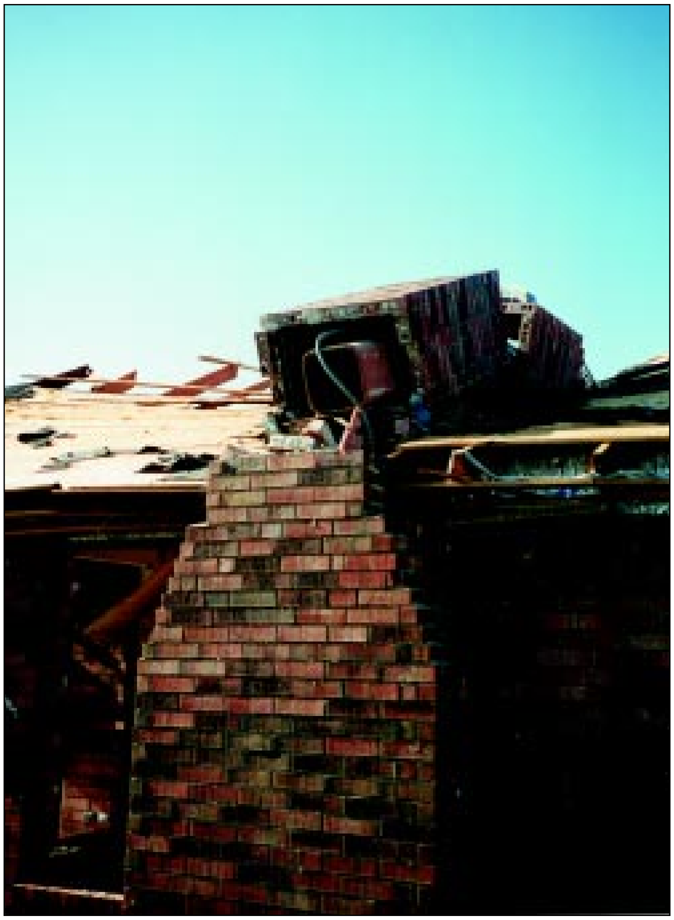


FIGURE 4-41: Close-up view of brick chimney failure in Figure 4-40.

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

FIGURE 4-43: Chimney failure onto roof of single-family attached housing, Wichita, Kansas. This building was located along the periphery of a strong tornado.

FIGURE 4-44: Chimney failure onto roof of single-family attached housing located along the periphery of a strong tornado, Wichita, Kansas.

was similar to the chimneys presented in Figures 4-43 and 4-44. These rectangular chimneys were calculated to have failed at wind speeds ranging from 75-85 mph (fastest mile). No reinforcing bars were observed in any of the chimneys in which calculations were performed.

4.2 Multi-Family Construction

Members of the BPAT inspected the Emerald Springs Apartments in Moore, Oklahoma. The two-story buildings were about 15 years old and constructed of wood framed bearing walls and floors, wood roof trusses, and brick veneer and hardboard siding exterior finish. There was extensive damage of roof systems, primarily caused by wind uplift forces on large (6.5-ft long) overhangs with bottom chords of the roof trusses only toe-nailed to the wall top plate of the load bearing wall. Brick veneer also failed from excessive negative (suction) pressure, and many windows were blown inward by positive wind pressure or broken by small gravel or wood missiles.

There were several two-story apartments in the Wichita, Kansas, area that also had extensive damage to roofs and brick veneer walls (Figures 4-45 and 4-46).

4.3 Manufactured Housing

Damage to manufactured homes was observed in Oklahoma and Kansas. Performance of units on non-permanent foundations utilizing ground anchors and straps were assessed as well as the performance of units on permanent foundations. Although units installed on non-permanent foundations were observed to have performed relatively poorly, units (especially double-wide units) on permanent foundations performed considerably better.

In Bridge Creek, Oklahoma, 11 deaths were reported from a violent tornado; most of these deaths were individuals taking refuge in manufactured housing. Although some manufactured homes were directly hit by the vortex, observed

FIGURE 4-45: Failure of brick veneer at a multi-family housing unit in Wichita, Kansas. This building experienced inflow winds from a strong tornado.

FIGURE 4-46: Failure of brick veneer in multi-family housing located along the periphery of a strong tornado, Wichita, Kansas.

damage to buildings and trees during the site visit indicated that most buildings were impacted by straight inflow winds and not by the tornado vortex.

At several sites in the area, the BPAT observed manufactured houses completely destroyed and separated from the twisted remains of the steel chassis. The chassis and debris traveled distances of 20 feet to over 200 yards 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 6 to 8 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 4-47). This home was not affected by the vortex of a tornado; rather, it was affected by the inflow winds whose violent

FIGURE 4-47: This 14-ft x 60-ft manufactured home chassis in the background of this photo moved about 200 yards from its original anchoring site in Figure 4-49, Bridge Creek, Oklahoma.

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 2 to 3 ft from the anchors (Figure 4-48). The first anchors had been fastened about 12-ft from the east end. Both the number of anchor straps and tensile capacity of the straps were inadequate to resist wind uplift forces (Figure 4-49).

FIGURE 4-48: 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 4-49: 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, and then Wichita, Kansas. There several double-wide manufactured houses damaged by a strong tornado were inspected. 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 of the ground that had been installed about 1 ft into the ground on the northwest end of the home (Figure 4-50). Anchor straps that were still attached to ground anchors and chassis beams were loose, which allowed lateral move-

FIGURE 4-50: Ground anchor of manufactured home pulled from soil. This home in Wichita, Kansas, was located within the inflow area of a strong tornado.

ment of the unit. Anchor depth into the loose sandy soil did not appear to be adequate to resist wind uplift and overturning forces (Figures 4-51 and 4-52) generated by a strong tornado whose vortex passed nearby, but did not directly strike the homes.

FIGURE 4-51: Anchor of manufactured home bent and pulled up from soil. This home in Wichita, Kansas, was located within the inflow area of a strong tornado.

FIGURE 4-52: Strap torn off from chassis of manufactured home. This home in Wichita, Kansas, was located within the inflow area of a strong tornado.

Several manufactured homes 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 4-53 and 4-54) from inflow winds of a strong tornado.

FIGURE 4-53: Manufactured home roof and wall damage experienced due to inadequate resistance to lateral and uplift wind forces associated with straight inflow winds of a weak tornado, Wichita, Kansas.

FIGURE 4-54: Damage to a manufactured home located on the periphery of a strong 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 and chassis had remained on the foundation walls. Although the floors and chassis had remained on the concrete walls, there were no bolts or positive connections between the chassis or perimeter wood joists and the bottom plate, pockets in the concrete walls, or center piers (Figure 4-55). Straps that had been stapled to wall studs and to perimeter joists did not appear adequate to resist wind uplift or lateral loads (Figure 4-56), and fastening of the roof system to walls had been inadequate. Figures 4-46 and 4-56 were taken after demolition and cleanup had begun. The floor system and steel chassis beams (with steel outriggers and steel angle bracing) had been lifted off the foundation by a contractor prior to the photographs being taken.

Several double-wide manufactured housing units in Haysville and Wichita, Kansas, partially survived high wind forces. However, ground anchors were pulled out of the soil, or they were bent over, loosening tie-down straps. Homes shifted laterally from wind forces and fell off un-reinforced 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 4-57 through 4-60).

FIGURE 4-55: Lack of bolts or positive connectors present between the chassis and foundation of a double-wide manufactured house, Haysville, Kansas. The floor framing of the house was still resting on the foundation after the tornado passed.

FIGURE 4-56: A close-up of the manufactured home floor and chassis after it was removed by a contractor from the permanent foundation in Figure 4-55.

FIGURE 4-57: This manufactured home laterally shifted from wind force generated along the periphery of a violent tornado, Haysville, Kansas.

FIGURE 4-58: 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 4-59: 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 4-60: Manufactured home laterally shifted off its dry-stacked masonry block foundation from wind force generated along the periphery of a violent tornado, Wichita, Kansas.