5 Observations on Non-Residential Property Protection

This section presents the BPAT's observations on non-residential property protection. The non-residential buildings were categorized into the various engineered types of construction focusing on the structural performance of each type of building. Important observations were also made concerning exterior architectural systems (e.g., roof and wall coverings, windows and doors).

A number of non-residential buildings, such as schools, factories, warehouses, and commercial buildings were in the direct path of the tornado vortexes or in the inflow/outflow areas of tornadoes and received damage. In a few cases, damage could be considered non-structural because architectural and decorative materials were the only damage to the buildings; in engineering standards such as ASCE 7, these materials are referred to as *components and cladding*. In other cases, structural damage occurred due to the lack of capacity in the structural system. Failure of a component, because of lack of capacity results in the load getting transferred to the next member component which then fails because of lack of capacity leading to progressive failure.

5.1 Continuous Load Path

A continuous load path from the roof structure to a building foundation is essential for a building to resist not only gravity loads, but lateral and uplift loads generated by high winds as well. Figure 5-1 shows critical connections in the continuous load paths for representative types of non-residential buildings that sustained structural damage. To resist these loads, adequate connections must be provided between the roof sheathing and roof structural support, steel joists or other structural roofing members and walls, and foundation and walls or structural columns. Each of these connections must be capable of resisting uplift and lateral loads as well as gravity loads.

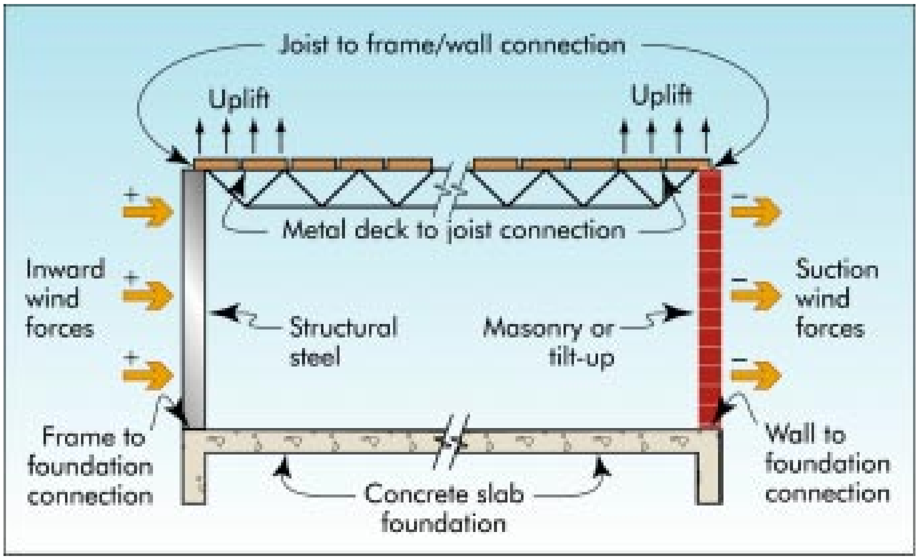


FIGURE 5-1: Critical connections that failed in the load path, resulting in structural damage or collapse.

5.1.1 Tilt-Up Precast Concrete Walls with Steel Joists

Inspection of a damaged tilt-up precast concrete wall building in Moore, Oklahoma, found no deficiencies with connections between the tilt-up walls and the foundation. However, connections between the roof system and the tilt-up walls failed in some buildings. In a commercial building along Interstate I-35 outside Del City, Oklahoma, failure of these connections caused a loss of diaphragm action, which then led to collapse of the endwalls of this building. This will be discussed further in Section 5.2.1. Figure 5-2 is a photograph of this building. The vortex of a violent tornado passed approximately 200 yards from this building, generating inflow winds that removed the roof of this structure. Once the roof of the building was removed and diaphragm action was lost, the endwall that was already being acted upon by outward (suction) wind forces failed.

5.1.2 Load Bearing Masonry with Steel Joists

The BPAT inspected Kelly Elementary School in Moore, Oklahoma, which was in the direct path of the vortex of the violent tornado. The school included a steel frame building in the main section, and a section that was constructed with load bearing masonry walls with steel joists.

This section discusses the damage associated with the masonry wall section of the building; Section 5.1.3 will discuss the steel frame section of the school. Figure 5-3 shows damage to the Kelly Elementary School. A circle indicates the separation between the bond beam and its supporting wall. Connections between the bond beam, joists, and walls were adequate for gravity load, but could not carry the high uplift loads that were caused by winds associated with the vortex of violent tornado.

FIGURE 5-2: Tilt-up precast concrete walls at a storage building located outside Del City, Oklahoma. After the roof joists separated from the walls, this end wall became unable to withstand suction forces and failed.

FIGURE 5-3: Kelly Elementary School, in Moore, Oklahoma, hit by vortex of violent tornado. Damage to school displaying separation between the bond beam and supporting wall and separation between bond beam and roof bar joists.

Figure 5-4 shows a close-up of a joist end over the cafeteria. The circle shows a location where the roof deck was supported for gravity load, but not sufficiently welded for uplift. Below the circle, broken welds can be seen. Some of the welds appeared to provide adequate diaphragm action based on deck material that remained at the welds; the deck appeared to fail at the welds only due to uplift. Spacing of the welds appeared to be consistent with standard weld spacing for deck welds.

Also visible in Figure 5-4 is the lower portion of the exterior wall. As illustrated in the photograph, no effective vertical reinforcement was found in the wall. Consequently, the wall had low resistance to uplift in combination with high lateral wind loads.

FIGURE 5-4: Failed structure showing broken deck welds (top circle), and no effective vertical reinforcement (bottom circle). Kelly Elementary School, Moore, Oklahoma, hit by vortex of violent tornado.

5.1.3 Steel Frame with Masonry Infill Walls

The BPAT visited a regional outlet mall in Stroud, Oklahoma, where most of the roof covering was blown away and significant damage to the building was evident. This mall was struck by a strong tornado that collapsed the central portion of the building's steel frame and damaged many of its masonry and steel frame walls. Figure 5-5 shows standing seam metal roof clips still attached to the purlins in one area of the mall that failed under the uplift loading. It was observed that metal wall panels attached with exposed fasteners performed better than the standing seam roof panels.

Figure 5-6 shows the attachment of columns to the foundation and attachment of the wall bottom plates to slab concrete. At the circle on the right in Figure 5-6, anchor bolts were provided, but the apparent lack of nuts on the anchor

FIGURE 5-5: Metal roof deck (missing in photo) of regional outlet mall, Stroud, Oklahoma, was blown off when hit by a strong tornado vortex.

FIGURE 5-6: Attachment of columns to foundation and attachment of wall bottom plates to concrete slab. Regional outlet mall, Stroud, Oklahoma, hit by a strong tornado vortex.

bolts permitted the column to lift off of the foundation. At the center circle, anchor bolts with properly attached nuts provided a high level of restraint to column uplift. The circle at the left shows a wall bottom plate that was attached to the concrete slab by powder-driven fasteners. Although the plate held at this location, lack of penetration by the nails into the concrete permitted the plate to pull out at many other locations. Additional fastener penetration would be needed to ensure consistent attachment of wall bottom plates to the slab.

Most bolts with nuts exhibited a ductile steel failure as shown in Figure 5-7. This was the failure mode observed in most cases. This was also the failure mode for the anchorages at the steel water tower in Mulhall, Oklahoma. However, some of the bolts observed at the mall did pull out of the concrete foundation, indicating a failure either in the concrete bond or inadequate embedment of the anchor bolts (see Figure 5-8).

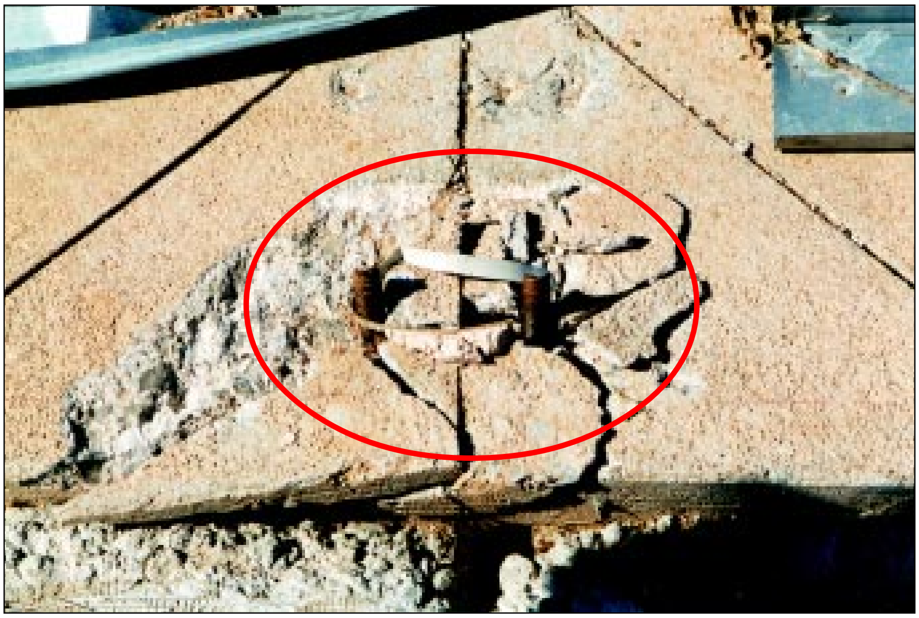


FIGURE 5-7: Column anchors that exhibited ductile failure at the regional outlet mall in Stroud, Oklahoma, hit by a strong tornado vortex.

FIGURE 5-8: Column anchors that withdrew from concrete foundation at the regional outlet mall in Stroud, Oklahoma, hit by a strong tornado vortex.

5.1.4 Light Steel Frame Buildings

The BPAT investigated the regional outlet mall that was destroyed in Stroud, Oklahoma. Figure 5-9 shows damage to the outlet mall. In this structure, most of the metal roof panels were blown off by the tornado. In addition, most of the glass curtainwalls at the storefronts experienced failures.

FIGURE 5-9: Stroud Regional Outlet Mall, Stroud, Oklahoma, was struck by the vortex of a weak tornado.

In addition to the building failures at the regional outlet mall site in Stroud, numerous light poles failed. The BPAT documented the failures of these poles and calculated an approximate wind speed at this site from 180-210 mph (fastest mile wind).

5.1.5 Laminated Wood Arches with Wood Frame Roof

Lack of load path resulted in severe damage to the Regency Park Baptist Church in Moore, Oklahoma. This building was approximately one block north and across the street from Kelly Elementary School. The vortex of a violent tornado passed approximately a few hundred yards to the south. Figure 5-10 shows the rigid frames remaining after the roof had been removed by the tornado. Loss of load path between the rigid frames and the roof purlins resulted in severe damage to the facility.

FIGURE 5-10: This church suffered loss of roof due to lack of load path between the rigid laminated wood arches and the roof purlins (missing in photo) that supported roof sheathing. Inflow area of a violent tornado, Moore, Oklahoma.

5.1.6 Masonry Walls with Pre-Cast Hollow Core Floors

In several locations, combined effects of wind uplift and horizontal wind loads caused damage to structures. A continuous load path is often observed in this type of construction at the connection of the floor slabs to the walls. However, at many of the buildings of this type of construction, a continuous load path for uplift and lateral loads did not exist and roof failures and upper level floor failures were observed. Figure 5-11 shows the remains of a motel in Midwest City, Oklahoma, hit by a violent tornado vortex. The circle shows a steel beam

FIGURE 5-11: Motel in Midwest City, Oklahoma that experienced major damage when struck by the vortex of a violent tornado.

that had been deflected inward significantly when the floor slab was lifted during the tornado. There was no positive connection between the steel beam and the floor above.

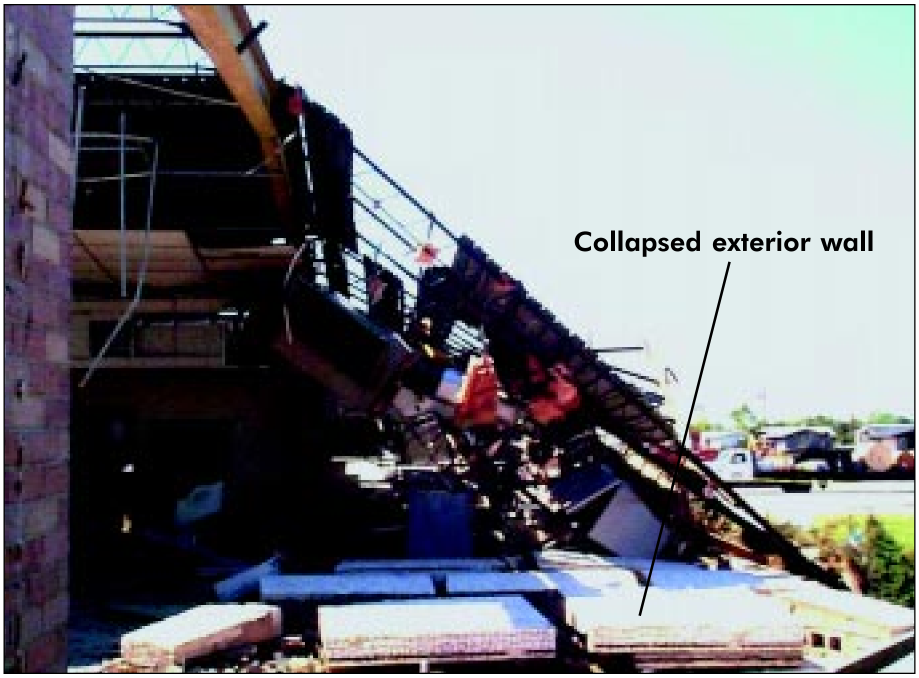
5.2 Increased Load

At a plastics manufacturing plant in Haysville, Kansas, a combination of uplift and horizontal wind caused out-of-plane buckling of the bottom flange of a main girder supporting the roof (Figure 5-12) when the plant site was struck by a strong tornado. One circle shows the column that supports the girder, while the other circle shows the bottom flange of the girder. It can be seen that the bottom flange has displaced significantly sideways in relation to the top flange of the girder. Inspection along the length of the girder indicated that the bottom flange was braced along its length at every purlin except at the location of the supporting column. This lack of bracing permitted buckling and out-of-plane displacement of the bottom flange. However, due to the light gravity loads left on the roof after the wind forces diminished, collapse did not occur.

FIGURE 5-12: Out-of-plane buckling of the main girder supporting the roof created by a combination of uplift and horizontal wind loads. Plastics plant, Haysville, Kansas, hit by violent tornado. This building was in the inflow area of a strong tornado.

Another example of the effects of uplift and horizontal wind forces is seen in Figure 5-13 at Kelly Elementary School in Moore, Oklahoma. The exterior wall collapsed inward, indicating that the roof had lifted up as the wind loads acted inward on the wall. Failure to have a continuous load path from the joists supports into the masonry wall to resist uplift forces contributed to collapse of the wall. The exterior masonry wall is seen lying on the floor beneath the collapsed roof structure.

FIGURE 5-13: Collapsed roof structure and exterior wall at Kelly Elementary School in Moore, Oklahoma, struck by the vortex of a violent tornado.



The Westmoore High School in Moore, Oklahoma, was a relatively new structure that was within 100 yards of the vortex of a violent tornado. A portion of the roof deck and supporting steel joists over the auditorium stage was blown off. Figure 5-14 shows the walls where the steel joists had been attached prior to the tornado. In all cases, welds failed between joist ends and embedments in the walls. This loss of continuous load path permitted the roof to be lifted up off of the reinforced concrete walls.

Figure 5-15 shows the exterior of the reinforced concrete wall at Westmoore High School following the tornado. This 12-in thick by approximately 35-ft-tall wall remained essentially undamaged, except for loss of the metal wall covering, even though the diaphragm action of the roof was lost. The construction of the stage area integrated an I-beam horizontal frame, shown in Figure 5-14, with the reinforced concrete walls. This frame helped to stabilize the walls. Prior to the tornado, the bare concrete had been covered with a decorative metal curtainwall. The entire curtainwall blew off during the tornado, while brick masonry veneer on the lower wall remained, with virtually no damage.

FIGURE 5-14: Roof blown off over top of auditorium at Westmoore High School, Moore, Oklahoma, hit by inflow winds of violent tornado.

FIGURE 5-15: Exterior view of an undamaged reinforced concrete wall, Westmoore High School, Moore, Oklahoma, hit by inflow winds of a violent tornado. Note: decorative metal wall covering was peeled from this wall.

5.2.1 Tilt-Up Precast Concrete Walls with Steel Joists

Lateral support is needed at the tops of exterior walls of commercial buildings with large open interior space, such as warehouses and open office buildings. When the support is lost, wind load resistance is greatly reduced and structural failure often follows.

Figure 5-16 shows a tilt-up concrete wall that failed after loss of a roof diaphragm made up of steel joists and metal deck. This building was located

FIGURE 5-16: Failure of tilt-up concrete wall in Del City, Oklahoma, hit by inflow winds of a violent tornado.

approximately 200 yards from a violent tornado vortex near Del City, Oklahoma. As can be seen in Figure 5-16, the wall was heavily reinforced at the foundation level. However, lack of support at the top of the wall permitted the wall to blow outward and collapse.

Figures 5-17 and 5-18 show the top of the tilt-up precast concrete wall that failed. Figure 5-17 shows that lateral resistance provided by a beam supported by the wall was lost when the beam pulled out of the wall pocket. Failed welds

FIGURE 5-17: Top of failed tilt-up end wall.

FIGURE 5-18: Top of failed tilt-up wall.

tying the roof joist into plates embedded in the top of the tilt-up wall can also be seen in Figure 5-18. Visual inspection showed that only one of the four walls of the building collapsed. The other walls continued to provide lateral resistance because portions of the roof remained.

Tilt-up walls at a facility that was located under the vortex of a weak tornado in Wichita, Kansas, survived virtually undamaged, despite loss of metal roof decking. As can be seen in Figure 5-19, trusses spanning the open area maintained enough lateral support for the walls that failure did not occur.

FIGURE 5-19: The tilt-up precast concrete walls in this building did not fail when the roof system failed. The masonry walls shown at the left of the photo were damaged. Note: many roof joists are still in place. Building was located in Wichita, Kansas, and was hit by weak tornado vortex.

5.2.2 Load Bearing Masonry with Steel Joists

In Figure 5-19, damage to a portion of the building having steel roof joists supported on masonry walls can be seen at the left. Walls in this portion of the building collapsed when subjected to the vortex winds of a weak tornado. Even though some diaphragm action was maintained, the masonry walls did not have enough lateral load resistance under the combined uplift and horizontal load of the tornado.

Figure 5-20 shows damage to both interior and exterior unreinforced masonry walls (URM) at Kelly Elementary in Moore, Oklahoma. Wind loads due to the vortex of a violent tornado lifted the roof system until the bond beam atop the URM wall failed. When this bond beam failed, the roof separated from the building and some interior walls failed.

Figure 5-20: Damage to interior and exterior unreinforced masonry walls when bond beams failed at Kelly Elementary School in Moore, Oklahoma. The school was struck by the vortex of a violent tornado.

5.2.3 Masonry Walls with Pre-Cast Hollow Core Floors

At a motel in Midwest City, Oklahoma, which was hit directly by the vortex of a strong tornado, failures occurred between the second floor precast hollow core panels and their supporting walls.

Figure 5-21 shows the location where hollow core planks had formed the second floor. The circle at the right shows a dowel from the masonry wall into grout between the ends of two hollow core panels. One of the panels that had been at the edge of the building was found up on the second level and across on the far side of the building as shown by the circle on the left of Figure 5-21. The wind uplift forces from the tornado were large enough to

FIGURE 5-21: Hollow-core plank formed on second floor of a Midwest City, Oklahoma, hotel that was struck by the vortex of a strong tornado.

overcome the tie-down force provided by the very short dowels. The hollow core planks were been lifted and blown across the width of the building.

Elsewhere along the edge of the second floor of the motel, failure occurred between the hollow core planks and exterior walls of the building. As shown in Figure 5-22, lower plates for the walls had been attached to the hollow core planks using powder-driven anchors. As indicated by the circles, the powder-driven anchors pulled out during the tornado.

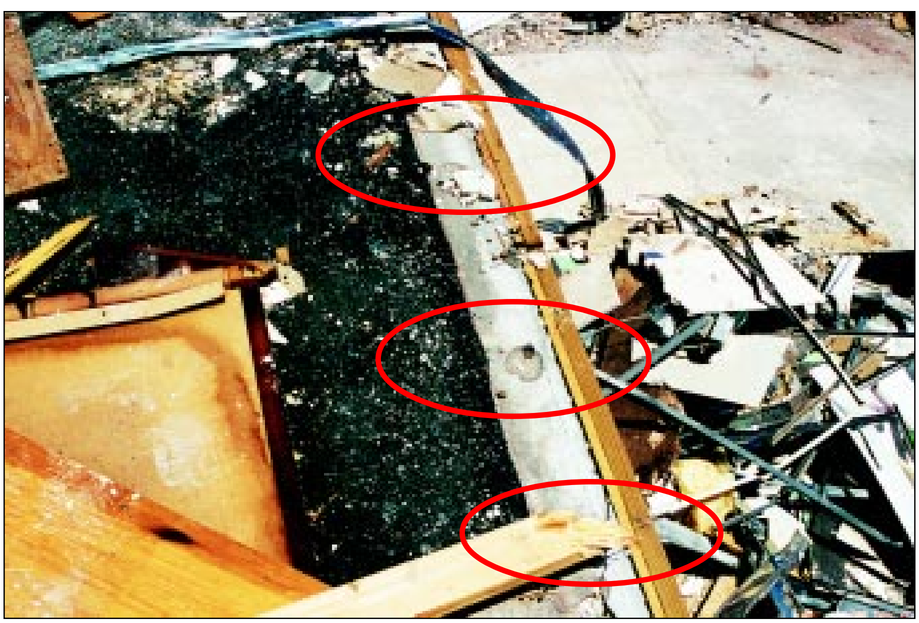


FIGURE 5-22: Attachments of lower plates for wall to hollow core plank using powder driven anchors failed when required to carry loads generated by the winds of a strong tornado vortex. This motel was located in Midwest City, Oklahoma.

5.3 Non-Residential Building Envelopes

In many cases, tornado damage patterns observed demonstrated that additional collapse of buildings was caused by breach of the building envelope. Openings in the envelope caused by loss of roll-up garage doors, entry doors, or broken windows frequently contributed to loss of roofs or walls of the building. The following is based on a limited number of non-residential building site visits by the BPAT.

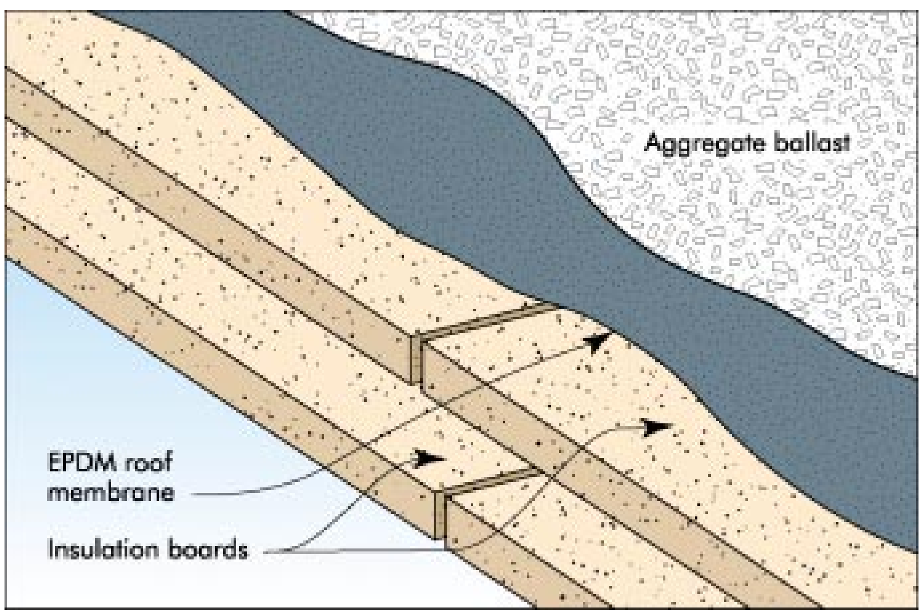
5.3.1 Roof Coverings

The following roof types were observed:

- Ethylene propylene diene monomer (EPDM) with aggregate (stone) ballast
- built-up (aggregate surface and cap sheet)
- metal panel (architectural and structural)
- tile

All of the roofs observed experienced blow-off problems, except for a built-up cap sheet roof that was at the periphery of a tornado damaged area. Windborne missiles punctured some of the roofs. In the case of metal panels on pre-engineered frames, it was not determined whether the panels blew off before or after failure of the supporting frames.

FIGURE 5-23: EPDM with aggregate (stone) ballast roof covering.



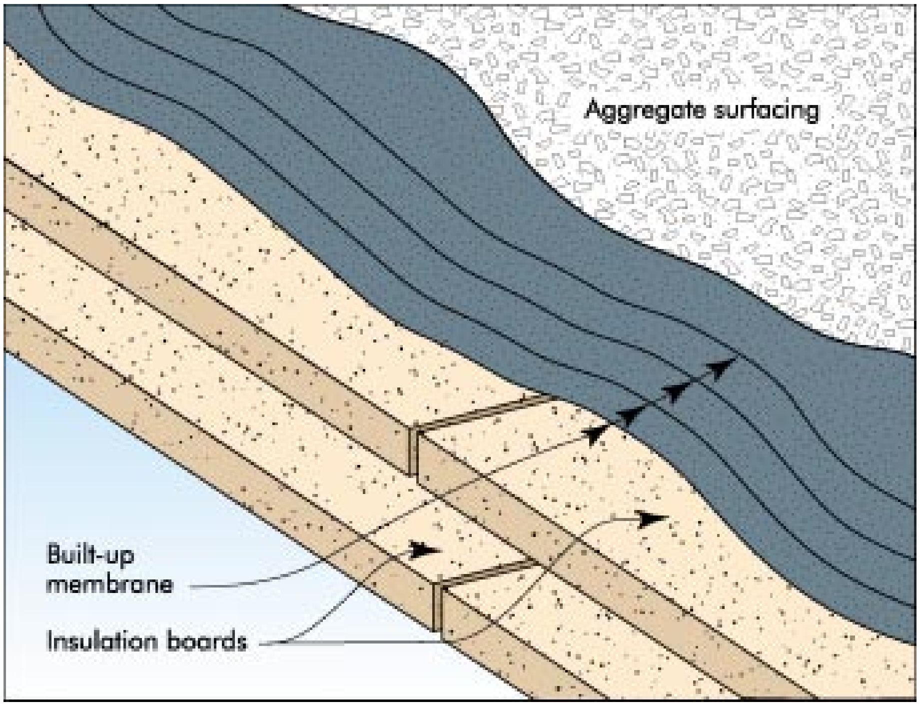


FIGURE 5-24: Built-up (aggregate ballast surface and cap sheet) roof covering.

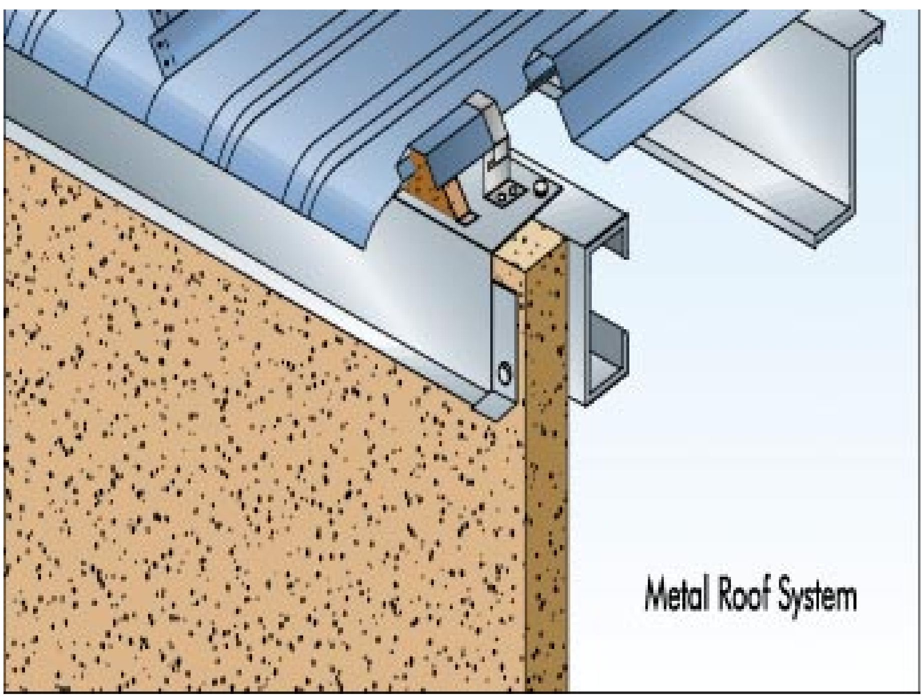


FIGURE 5-25: Metal panel roof covering (architectural and structural), including standing seam.

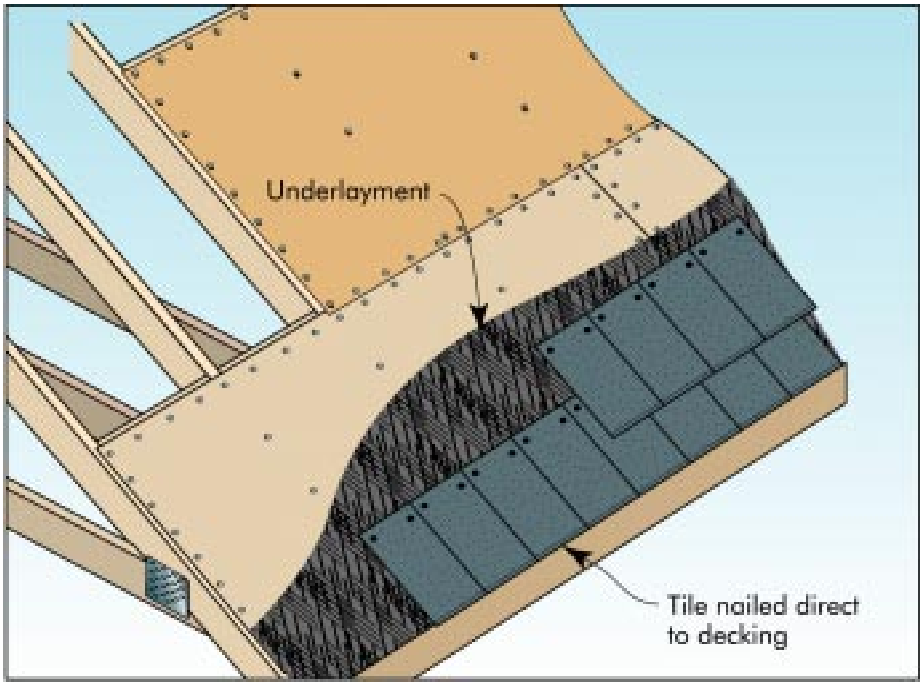


FIGURE 5-26: Tile roof covering.

Investigations revealed poor connections between wood nailers (used for flashing attachment) and the structure at roof perimeters. In one case, roofing nails were used to attach perlite insulation. This type of attachment offered very little uplift resistance.

In at least one observed case, loss of a large portion of a built-up roof with aggregate surfacing resulted in significant water infiltration into a hospital in Stroud, Oklahoma. After the storm, the hospital was closed and the patients moved to a facility about 30 miles away, which significantly reduced the availability of emergency medical services in this area of rural Oklahoma. The characteristics of the damage to the hospital were not indicative of tornado winds. Rather, it is likely that the damage was caused by thunderstorm winds. The failure initiated when the coping lifted off the edge of the roof, in turn, lifting the nailer beneath (Figure 5-27). The nailer was poorly attached to a 4-in CMU that formed the parapet wall. In some areas, the CMU parapet lifted slightly.

5.3.2 Wall Coverings

Brick veneer is discussed in Section 4.1.9. Some metal wall coverings over steel studs collapsed (Figure 5-28). All the metal wall systems at this building that experienced suction wind forces failed at this site. Although it did result in structural failures it exposed some internal areas to tornado winds. Some exterior insulating finishing system (EIFS) failures were observed (Figure 3-10). EIFS wall failures observed were the result of impact of windborne missiles and suction wind forces.

FIGURE 5-27: Nailer at the roof of the hospital in Stroud, Oklahoma. The roof surface in this photo was replaced prior to this photo, but the same nailer was used again during repairs.

FIGURE 5-28: This metal-clad wall covering collapsed and in other areas it was blown completely away.

5.3.3 Laminated Glass

In a few instances, examples of laminated glass performance were observed. In some cases, the glass remained in the frame after missile impact (Figure 5-29). In another case, the glass was punched out of its frame. The school in Figure 5-29 is located adjacent to the Regency Park Baptist Church in Moore, Oklahoma, shown in Figure 5-10. The vortex of a violent tornado passed a few hundred yards south of this building.

FIGURE 5-29: The corner of a table penetrated this laminated glass, but the glass remained in its frame. This school suffered major damage from inflow winds of a violent tornado in Moore, Oklahoma.

5.3.4 Garage Doors, Exterior Doors and Windows

The breach of overhead rollup commercial doors resulted in internal pressurization of several structures leading to significant load increases. Not unlike the residential case, where a breach in the building envelope was observed at a roll-up door, this breach initiated a partial or total failure of primary structural systems. This was particularly true for pre-engineered buildings, which typically had little redundancy in load transfer of their structural systems. Figure 5-30 shows a breached commercial rollup door at a bread manufactur-

FIGURE 5-30: Failure of roof and walls on structure due to increased loads caused by initial failure of a rollup door, Wichita, Kansas.

ing and distribution center in Wichita, Kansas. The building exterior walls were constructed using both CMU and tilt-up concrete panels. The standing seam metal roof panels were on a Z purlin system. The rollup door failure appears to be a result of positive (inward) pressure. The breach may have caused a sufficient enough rapid increase in load to produce failure of the URM wall. Note the location of the failed door near a corner where high suction (outward) pressure is likely to occur on the adjacent wall. As a result of the exterior wall collapse, severe damage to the roof system occurred due to the loss of the load bearing exterior support wall. However, notice that the roof collapsed to the interior of the building, which may indicate that uplift loads acting on the roof were insufficient to cause progressive peeling failure of the roof decking.

Figure 5-31 illustrates another condition in Wichita, Kansas, where breach of the building envelope contributed to additional structural damage. In this case, loss of showroom windows and a rollup door greatly increased loads in the showroom and on the wall at the left of the photograph. These increased loads caused the walls to fail and the roof to partially collapse, thereby greatly increasing structural damage.

Figure 5-32 shows a steel door that appears to have been opened by impact of a heavy object. This door at Kelly Elementary School in Moore, Oklahoma, led into an area where the roof was completely missing. The breached door may have caused an increase in load that propagated damage to that part of the building envelope. A nearby door, which was also heavily impacted, but did not open, was located in an area of the school that saw less damage to the wall and roof of the building.

FIGURE 5-31: Additional structural damage caused by breach of envelope in Wichita, Kansas.

FIGURE 5-32: Damaged door most likely opened by impact with heavy object. Kelly Elementary School, Moore, Oklahoma.