P 2.10 # BUILDING DAMAGE ISSUES IN TORNADOES

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1. INTRODUCTION

The assessment of property damage begins immediately after a tornado. Homeowners, insurance adjusters, contractors, engineers, and architects examine buildings and their surroundings to determine the extent of tornado damage. While catastrophic damage is easy to recognize, the more subtle signs of building distress are not. Many types of building distress that are inherent to different construction materials, are not recognized until after a tornado occurs. Inspectors often erroneously link these conditions to the storm. The purpose of this paper is to summarize some of the more common building damage issues witnessed during the author's inspections of thousands of structures after dozens of tornadoes since 1980.

In order to conduct an accurate damage assessment, it is important to have knowledge of building construction, building materials, and environmental factors, as well as an understanding of wind forces on buildings. Seaquist (1980) addresses some of the inherent deficiencies in building construction and how to recognize such problems. Marshall (1992) and Minor (1982) have addressed some of the fundamental misperceptions with regard to tornadoes and building damage.

2. TORNADO - BUILDING INTERACTION

Tornadic winds encountering a building are deflected over and around it. Positive (inward) pressures are applied to the windward walls and try to push the building off its foundation. Therefore, it is important that the building be anchored properly to its foundation to resist these lateral forces. Negative (outward) pressures are applied to the side and leeward walls. The resulting "suction" forces tend to peel away siding. Negative (uplift) pressures affect the roof especially along windward eaves, roof corners, and leeward ridges. These forces try to uplift and remove the roof covering.

The roof is particularly susceptible to wind damage since it is the highest building component above the ground. Wind pressures on a building are not uniform but increase with height above the ground. Tornado damage to a well-anchored building typically begins at roof level and progresses downward and inward with increasing wind velocities. Thus, the last place structural damage to a building should occur is the interior walls, floors, and foundation.

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Objects susceptible to wind damage on or around a building include television antennas, satellite dishes, unanchored air conditioners, wooden fences, gutters, storage sheds, carports, and yard items. As the wind velocity increases, vinyl siding, roof coverings, windows, and doors become susceptible to wind damage. Only the strongest winds can damage a properly designed and well-constructed building. Marshall et al. (2002) describes the various failure modes in buildings caused by high winds.

3. THE ROOF COVERING

The roof covering is usually the first item on a building affected by strong winds. Obvious damage includes tearing, breaking, and removal of the roof covering especially along windward corners, eaves, and rakes where wind uplift forces are greatest. However, there are a number of roof issues that arise after a tornado. Roofs can have inherent deficiencies due to manufacturing, installation, and weathering that can be mistaken for storm damage. There are also myths and misconceptions regarding how tornadoes affect roofing systems. Thus, distinguishing between tornado damage and pre-existing damage can be controversial.

In order to conduct an accurate assessment of roof damage, it is important to have knowledge of the various roofing materials, installation procedures, weathering effects, as well as an understanding of how wind forces affect roofs. The National Roofing Contractors Association (NRCA, 1996) has published a manual explaining the installation procedures for a number of roof systems. Obviously, the performance of a roof during a tornado depends greatly on the type of product and how well it was installed. McCampbell (1991) presents a number of cases citing specific problems with roof design and installation.

3.1 Wind damage issues to asphalt shingles

Asphalt shingles are composed of a mat material that is either paper (organic) or glass-fiber (inorganic). The mat is saturated with an asphaltic mixture and topped with granules. Roof shingles come in a variety of shapes, sizes, and patterns including three-tab, strip, and dimensional, and they are fastened to the roof deck with nails or staples. It is important that the fasteners be installed properly and placed in the correct positions in order to achieve the greatest wind resistance.

As asphalt shingles age, the asphalt breaks down. The extent of aging depends upon many factors including the quality of the asphalt, shingle color, roof pitch, slope direction, and amount of attic ventilation. Common deficiencies inherent with aged asphalt shingles are blistering, flaking, cupping, clawing, and general granule loss (Figures 1 and 2). In many instances, these anomalies are not discovered until after the tornado, however, this does not mean they were created or even aggravated by the storm.

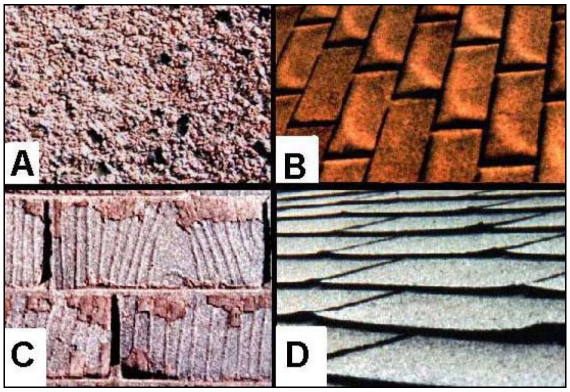

Figure 1. Asphalt shingle deficiencies not due to wind effects: A) blisters, B) clawing, C) granule flaking, and D) edge cupping.

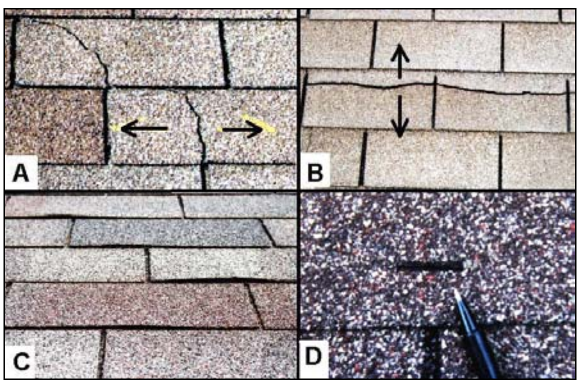

Figure 2. Additional shingle deficiencies not caused by wind effects: A) diagonal splitting, B) horizontal splitting, C) shingle buckling, and D) elevated or protruding fasteners.

Shingle blisters result from poor quality asphalt combined with excessive heat. Granule flaking stems from asphalt shrinkage and subsequent delamination from the mat. Cupping and clawing results from asphalt shrinkage on the top and bottom surfaces of the shingles, respectively. Diagonal and horizontal splitting results from asphalt shrinkage and low tensile strength of the mat. Elevated fasteners occur during the installation of the shingles and can buckle or protrude through the overlying shingles. None of these conditions are caused or aggravated by tornado effects.

Asphalt shingles are not damaged by granule loss during a tornado. The quantity of granules lost due to wind or rain during the storm is a very small fraction of the total quantity of granules on the shingles and within normal tolerances. Generally, about one-third the weight of an asphalt shingle is granules such that the average residential roof has more than a ton of granules. Granule loss occurs from the moment shingles are manufactured, shipped, installed, and during the weathering process. Thus, more granules are initially placed on the shingles than are needed to cover the mat.

An asphalt shingle roof can leak water during a tornado. Many steep roof coverings like asphalt shingles simply shed water and are not waterproof. As a result, wind-driven rain can be forced beneath the shingles and flashings and cause interior damage without damaging the roof covering.

Wind uplift tends to remove asphalt shingles from the roof. This can lead to a combination of disbonding, creasing, and displacement of the shingles (Figure 3). Fasteners secured to the roof deck are usually stronger than the shingles themselves. Therefore, when shingles are torn from a roof during high winds, the fasteners usually remain in the roof deck. Windward eaves, corners, ridges, and rakes are areas that are most susceptible areas to wind damage because of higher aerodynamic uplift pressures in these regions.

Figure 3. Wind damage to asphalt shingles: A) shingles removed from windward slope, B) windward rake damage, C) loose and flipped shingles, and D) impact damage to shingles from flying debris.

3.2 Intentional mechanical damage to roofs

On occasion, some people have tried to simulate wind damage to roof coverings by lifting, tearing or removing the shingles. Such roof damage is normally found on the periphery or outside the tornado damage path. The author has determined a number of factors that can distinguish intentional damage from wind damage.

Intentional damage usually is concentrated in upper portions of the roof, away from roof edges, and frequently avoids ridges. In contrast, wind-caused damage usually is most severe at the roof edges and ridges. Intentional roof damage typically involves removal of a portion of the shingle and leaving pieces lying on the roof near where they had come from (Figure 4). In contrast, wind usually lifts loose debris from the windward slopes. Also, intentional roof damage is sometimes found on roof slopes opposite the direction of the wind during the storm. In addition, objects particularly susceptible to the wind (i.e. television antennas, satellite dishes, trees, etc.) are often found not damaged.

Figure 4. Intentional mechanical damage to roofs in attempt to simulate wind damage: A) torn tab corners upslope away from roof edge, B) closer view showing tab pieces remaining on roof, C) uplifted shakes, and D) closer view of uplifted shakes.

After completing a general examination of the building surroundings, the inspector should draw a roof plan diagram and plot the locations of the roof damages. Any pattern or grouping of shingle marks quickly becomes apparent in the diagram (Figure 5). Note the roof damage occurred on all but one slope, although the windward side of the roof was facing southwest.

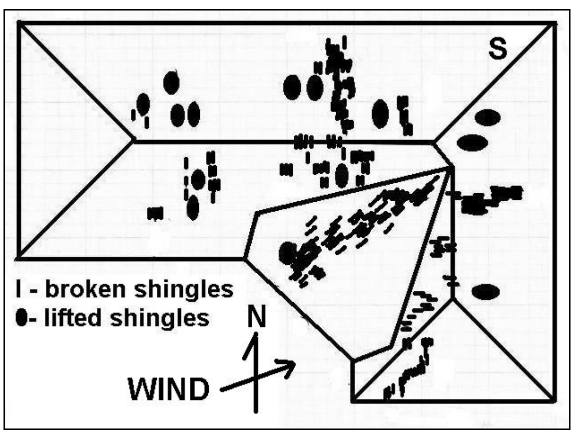

Figure 5. Plot of lifted and broken shingles on a roof intentionally damaged to simulate the effects of wind. The letter "S" indicates an undamaged satellite dish.

4. THE ROOF DECK

The roof deck must support the weight of the roof covering as well as resist wind uplift loads. Therefore, the roof deck must be fastened securely to underlying rafters or joists. Close inspection of the roof deck after a windstorm usually reveals various anomalies such as warped decking or decking that is not fastened properly to the roof structure (Figure 6). In some instances, these deficiencies are erroneously linked to the storm.

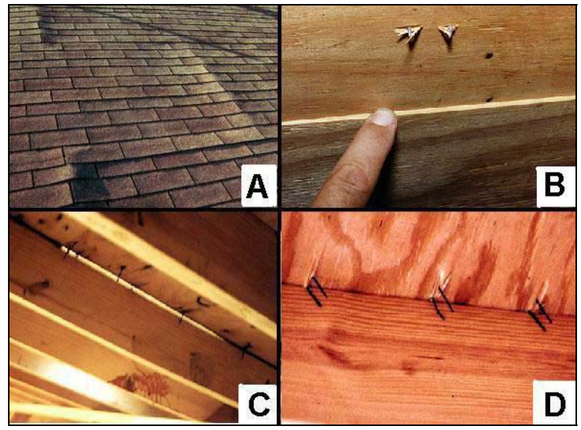

Figure 6. Roof deck deficiencies not caused by wind effects: A) warped decking beneath roof shingles, B) lack of space between deck boards, C) warped decking in attic, and D) decking not fastened to rafters.

There needs to be sufficient spacing between the deck boards to allow for expansion and contraction. Also, aluminum H-clips should be installed in the joints between the roof decking centered between the rafters. If nail guns are used to install the decking, care must be utilized to make sure the roof deck is fastened to the rafters or joists. Otherwise, the roof deck can be removed during the wind (Figure 7.)

Figure 7. Examples of wind damage to roof decking: A) Loss of entire roof deck since it was not fastened to the trusses, B) entire deck sheet with shingles still attached.

5. THE ROOF STRUCTURE

The roof structure must support dead loads that include the weight of the roof as well as live loads such as people walking on the roof, snow, and code-specified wind forces. However, the author has found many deficiencies with wood framed roof structures including: warped purlins or braces, use of low grade material with large knots, knot holes and cracks as well as poor joinery. These deficiencies often are discovered after the storm and erroneously attributed to high winds, low barometric pressure, etc (Figure 8). The cracks and gaps frequently contain dirt and cobwebs, indicating they were present prior to the windstorm.

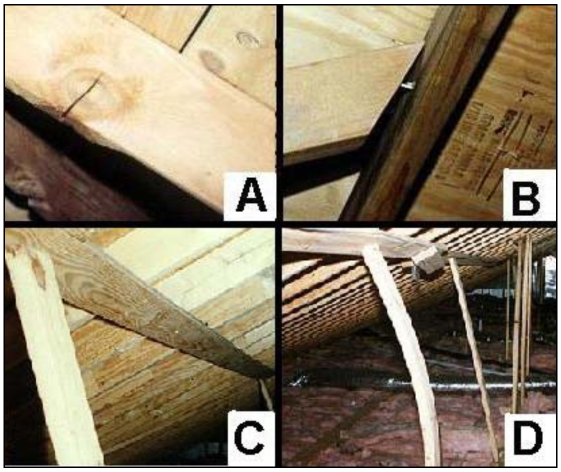

Figure 8. Inherent deficiencies in the roof structure not caused by wind: A) large knot with old crack, and B) gap where rafter intersects ridge beam, C) bowed purlin from lack of support, and D) warped bracing from inadequate bracing.

Wind damage to the roof structure can be subtle or catastrophic depending on how well it is anchored. Flexing of the roof can pull apart nailed connections where braces or collar beams are fastened to the rafters. Stronger uplift forces can pull apart toe-nailed connections where rafters are attached to top plates. Rafters also can be broken at mid-span or where they are connected to the ridge beam, braces, or top plates. In these instances, the exposed fracture surfaces are unweathered and absent of dirt, etc. The author has observed instances where a portion of the roof has been uplifted along with the braces. Such roofs did not return to their original positions, and braces penetrated the ceilings. Downward forces also can overload the roof structure, especially when struck by falling trees. Rafters can be broken and nailed connections pulled apart. Downward movement of the roof structure can cause soffits to move outward from the tops of the walls (Figures 9 and 10).

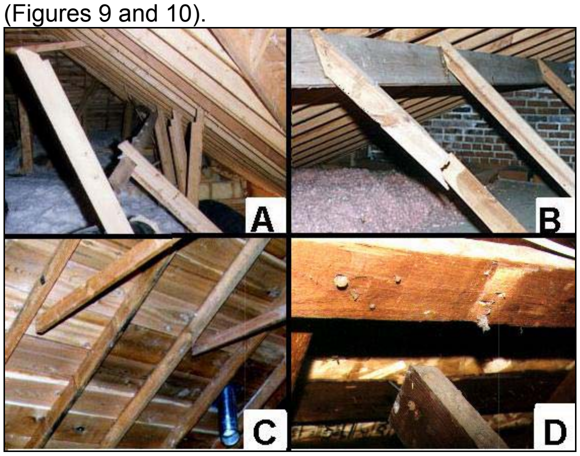

Figure 9. Wind damage to the roof structure: A) failed nailed connections where purlins were attached to rafters, B) broken brace, C) failed nailed connections between collar beams and rafters, and D) failure of nailed connection where brace was attached to purlin.

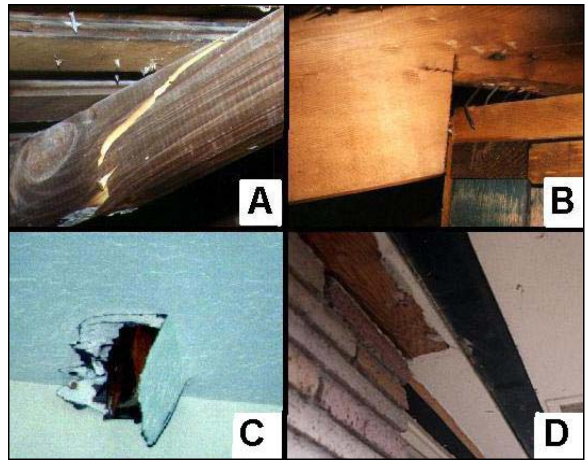

Figure 10. Additional examples of wind damage to a roof structure: A) fractured rafter, B) uplift of rafter from the top plate, C) brace penetrated ceiling, and D) outward movement of soffit when tree impacted roof.

6. GABLE ENDS

Most gable ends on residential buildings do not carry roof loads. These triangular-shaped structures simply "plug" or close off the ends of the attic. As a result, gable ends tend to have minimal bracing and are quite susceptible to wind damage. Positive acting wind pressures push the gable ends inward and break framing members or pulls apart the connections. In contrast, negative pressures pulls the gable ends outward or removes them completely (Figure 11).

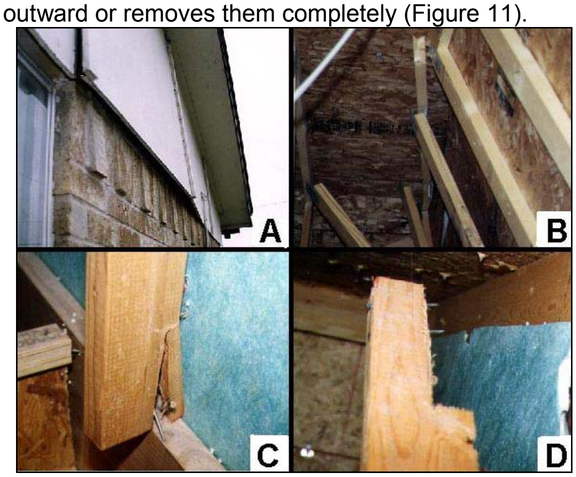

Figure 11. Wind damage to gable ends: A) outward displacement of gable end, B) fracturing of plate connections from positive pressure, C) breaking of gable end stud, and D) pulling apart of nailed connections.

7. EXTERIOR WALL STRUCTURE

Exterior walls are subjected to internal as well as external wind pressures. Inward acting pressures push in the exterior walls. Well-designed buildings usually have shear walls (interior walls that are perpendicular to exterior walls) to transfer the wind forces. However, exterior walls without adequate shear bracing are subject to catastrophic failures. Outward acting pressures tend to pull out the nailed connections at the top and bottom wall plates (Figure 12). Therefore, nailed connections should be designed to resist both inward and outward forces.

Figure 12. Examples of wall failures due to wind: A) base of wall pushed outward, B) failure of bottom plate to wooden floor connection, C) failure of bottom plate to concrete slab connection, and D) failure of wall stud to top plate connection.

8. BRICK MASONRY

Bricks typically are molded from clay and dried in a kiln. There are various types, grades, and qualities of brick. Certain deficiencies can occur during manufacturing. Shrinkage cracks can form in the brick before the material dries. Cracks can also form in the brick as it absorbs moisture and is subjected freeze-thaw effects. Eventually, brick faces detach and erode away. These deficiencies may not be recognized until after a tornado, and can be erroneously linked to the storm (Figure 13).

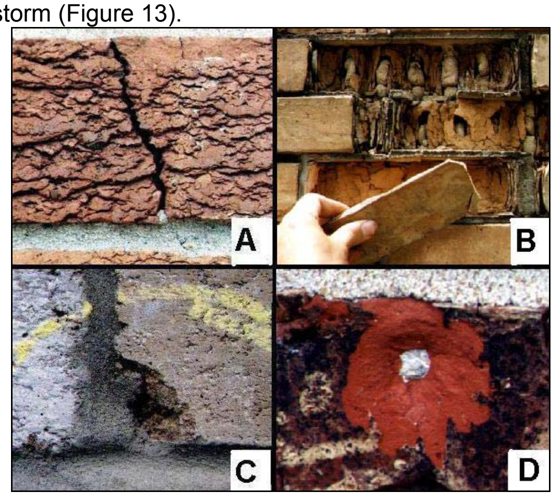

Figure 13. Brick deficiencies not caused by wind: A) shrinkage crack, B) face separation, C) mortar over chipped brick, and D) spalling at a mineral spot.

Brick can be chipped either during shipping or installation. Some bricks are actually tumbled to achieve a random chipped appearance.

Masonry walls should have wall ties to anchor the walls to the frame; however, the author has inspected many buildings that did not have such ties or did not have them engage the masonry. Non-loadbearing brick masonry walls not anchored to the building can be flexed easily when pushed by hand. This does not mean the wall was "loosened" by the wind; it just never was anchored (Figure 14).

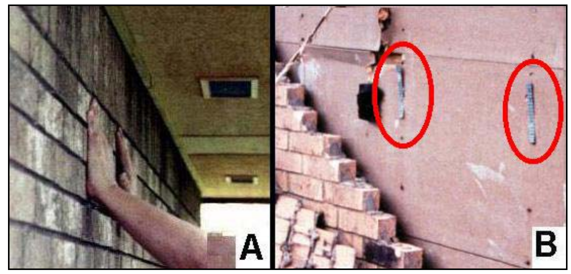

Figure 14. Brick masonry deficiencies: A) masonry wall that could be flexed by hand, and B) removal of brick revealed wall ties (circled) did not engage masonry.

Mortar is a mixture of Portland cement, sand, water, and lime. The lime is utilized to increase workability of the mix. Masonry walls are particularly susceptible to cracking due to differential (up and down) foundation movement. Drainage conditions, locations of trees and downspouts, all affect the soil moisture content. Window and door openings are naturally weak points in the wall where the distress concentrates. Cracks and separations that open with height (V-shape) indicate settlement on either side of the crack whereas cracks tapering closed with height indicate settlement at the base of the crack (Figure 15). Old masonry cracks become discolored with time as they accumulate dirt, paint and debris. In contrast, recent cracks appear fresh and unweathered with broken pieces of masonry along the fractures. The Brick Institute of America (1991) has a number of excellent technical bulletins on masonry wall distress.


Figure 15. Stair-step crack in brick masonry from differential foundation movement. This distress was not caused by the tornado.

Frieze boards typically are installed along the tops of brick masonry walls to cover the gap between the masonry and soffit. This decorative trim piece usually is mitered at the wall corners. Any rotation or side-to-side movement of the wall can open the joints in the frieze boards at the wall corners. Analysis of the joints in the frieze boards can give the inspector a history of wall movement. Caulking, paint, cobwebs, etc. in the joints indicates prior wall movement (Figure 16).

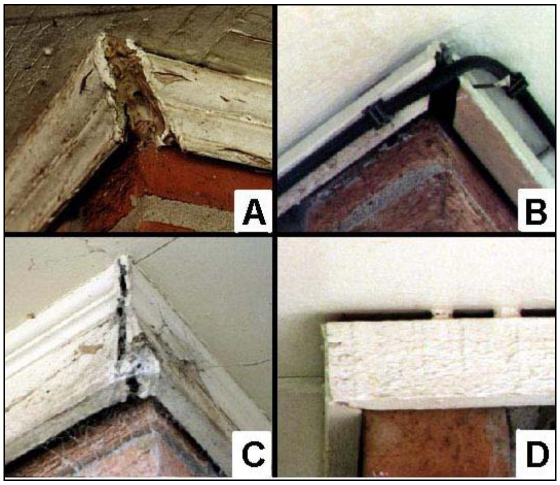

Figure 16. Open joints in frieze boards atop brick masonry walls indicated prior movement as noted by: A) caulking, B) cable spanning joint, C) cobwebs, and D) paint.

Masonry walls are susceptible to wind damage especially if they are non-loadbearing. Such "free-standing" walls are pushed inward on the windward sides and pulled outward on the leeward sides. Movement of the roof structure or gable end can fracture the top course in the masonry. Also, flying debris can strike the walls, breaking the brick and cracking the masonry. Recent fractures in the masonry will be unweathered (Figure 17).

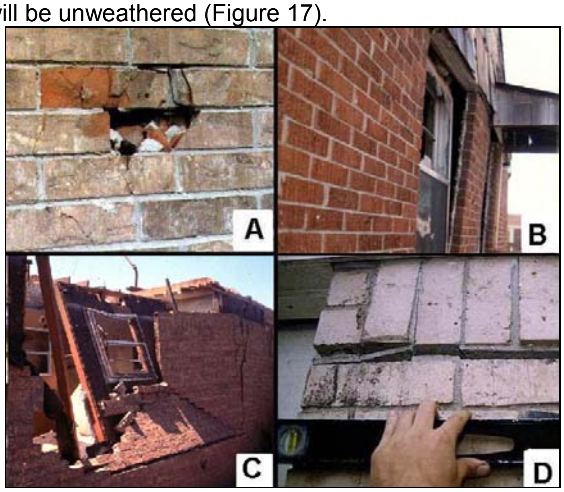

Figure 17. Wind damage to brick masonry: A) impact by flying debris, B) wall pulled outward, C) wall pushed inward, and D) movement in top course of masonry when roof was uplifted.

9. INTERIOR WALLS AND DOORS

Interior walls are frequently gypsum board or plaster. The gypsum board is attached to the underlying framing with nails or screws and plaster is spread over lath that is fastened to the framing. These wall coverings are brittle and record movement. Therefore, shifting of the walls generates cracks emanating from wall and ceiling joints as well as door and window frame corners. These areas represent stress concentration points in the wall. Examination of the wall cracks can reveal whether they are new or old (Figure 18). Dirt or paint in the cracks indicates prior movement. Generally, walls and floors are rarely square, plumb, or level. This is due to a number of factors including installation and soil movement. Walls and ceilings can have a wavy appearance if the underlying wall studs or ceiling joists are bowed.

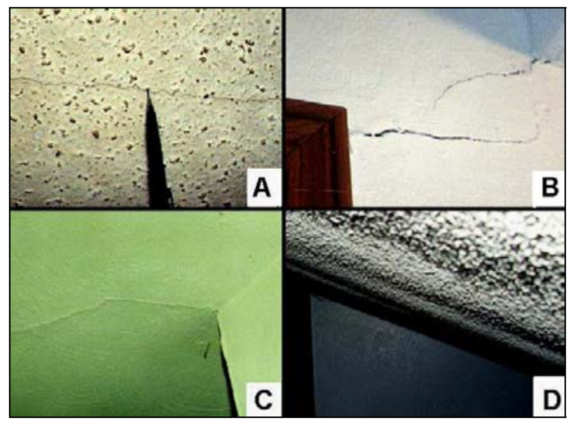

Figure 18. Wall distress not caused by wind: A) hairline crack contains dirt, B) paint bridges cracks, C) cracks patched and painted, and D) wavy appearance to gypsum board ceiling.

There are two ways interior wall and ceiling cracks can be caused by a tornado. One is by flexing of the ceiling and wall framing due to differential pressures as the tornado passes. The other is by increased humidities in the building that occur if the electrical power (air conditioning) is inoperative. As a result, wooden doors and windows may become difficult to open or close after the storm. Such wooden items swell when the moisture content is increased. Luxford (1955) conducted a series of moisture tests on gypsum board nailed to wooden studs. Wall panels were constructed in dry environments where the average moisture content in the wood was six percent. He then subjected the panels to a moist environment where the moisture content rose to 19 percent. In most instances, the nails withdrew, creating slight bulges in the surrounding gypsum board.

Minor wall damage associated with the storm involves nails backing out of the gypsum board or hairline cracks in the wall coverings. Exposed gypsum board around the nails or cracks is not discolored. Such distress usually can be repaired. More significant damages involve the separations of ceiling and wall joints. These occur when the roof joists are uplifted or a wall is pushed inward or outward (Figure 19). In such instances, a detailed structural inspection is warranted.

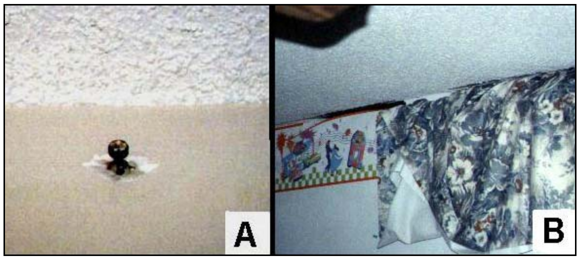

Figure 19. Tornado related damage to gypsum board: A) protruding nail in wall and B) separation of ceiling/wall joint as roof was uplifted (note drapery caught in joint).

The analysis of doors and door frames can give the inspector a history of interior wall movement. Doors often are trimmed to fit within the door frames. Close examination can reveal evidence of planing or abrasions on the doors. Doors binding against their frames may abrade the wood or paint. Relative changes in the door level can be detected by analyzing the position where the door latch meets the striker plate.

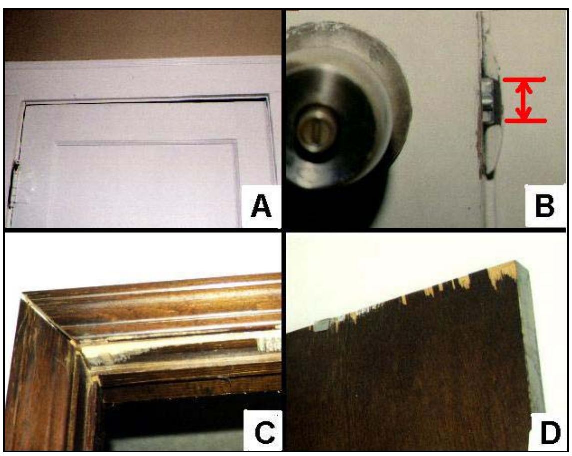

Figure 20. Interior door distress not caused by wind effects: A) gap at top of door yet side of door fits well, B) no relative movement between door latch and painted striker plate, C) wear marks on door frame, and D) evidence that top of door was planed.

10. THE FOUNDATION

The foundation is typically the last place in a building to experience distress from a tornado. There are six common types of house foundations in the United States: 1) concrete slab, 2) pier and beam, 3) poured concrete wall, 4) concrete masonry wall, 5) stacked brick or block, and 6) timber piles or masonry and concrete columns. In general, homes on concrete slab foundations usually are found in the south and southwest United States. Homes with basements or crawl spaces usually have poured concrete or masonry walls and are found in the northern portion of the U.S. Houses on stacked brick or blocks are found typically in rural areas, especially in the southern United States. Timber piles and masonry or concrete columns support homes in coastal or flood-prone areas.

The foundation must bear the weight of the building and also resist any movement of the soil beneath or around it. Over the years, the author has found a number of inherent problems in building foundations ranging from inadequate support to distress from soil movement. Many of these conditions are not identified until after the tornado and then are incorrectly attributed to the storm.

10.1 Concrete Foundations

Concrete foundations tend to crack during or after curing as they shrink. The extent of shrinkage cracking depends primarily on water content of the mix and placement of control joints. Environmental factors such as the rate of hydration and evaporation can affect the severity of shrinkage cracking. For these reasons, shrinkage cracks are fairly common in concrete foundations. Shrinkage cracks are usually small in width, less than an eighth of an inch, but can extend several feet in length.

Many buildings are constructed on thin concrete slabs with shallow footings and therefore are susceptible to differential foundation movements due to cyclic moisture changes in the underlying soil or settlement. Concrete slabs float on the ground and rise and fall with expansion and contraction of the underlying soil. As expansive soil dries around the foundation perimeter, the perimeter of the building settles relative to the center leading to distress in the interior and exterior finishes. Mitered corners at frieze boards open and interior doors bind. Cracks in plaster and gypsum board frequently emanate from the corners of door and window openings. Slab cracks can extend through brittle finishes like ceramic tiles bonded to the slab.

An examination of the crack interior often will determine whether the crack is new or old. Cracks become discolored with time as they accumulate dirt, paint or debris (Figure 21). Edges of the cracks become rounded with continued wear. Water entering the cracks can lead to rusting of reinforcing steel and the resulting expansion can lead to spalling (removal of the concrete).

In contrast, cracks caused recently do not have these characteristics. Recent cracks appear fresh and unweathered with broken pieces of the concrete along the fractures. Concrete slab cracks associated with wind usually are found in the direct load path of a failed building component (Figure 22).

Figure 21. Cracks in concrete slab not caused by wind: A) center crack and B) close-up view showing dirt in crack.


Figure 22. Cracks in concrete slab caused by the rotation of the steel column that failed in the wind.

10.2 Pier and beam foundations

Many homes are constructed on pier and beam foundations. The piers can be constructed from a variety of materials including brick, concrete, concrete masonry, or wood. Shallow piers rest on the ground surface or on small pads. Deep piers can extend 20 feet or more depending on soil conditions. Homes on pier and beam foundations can experience the same types of distress from differential foundation movement as homes on concrete slabs.

An examination of the crawl space can reveal inherent deficiencies with the foundation such as cantilevered or poorly supported beams, tilted piers, wood rot, etc. (Figure 23). Such deficiencies were not caused by winds during the tornado. It stands to reason that any significant shifting of the home on its foundation would likely break pipes that extend through the floor. Usually, homes on pier and beam foundations have little to no anchorage. Therefore, the structural frame or floor is more apt to shift off the foundation, leaving the foundation in tact.

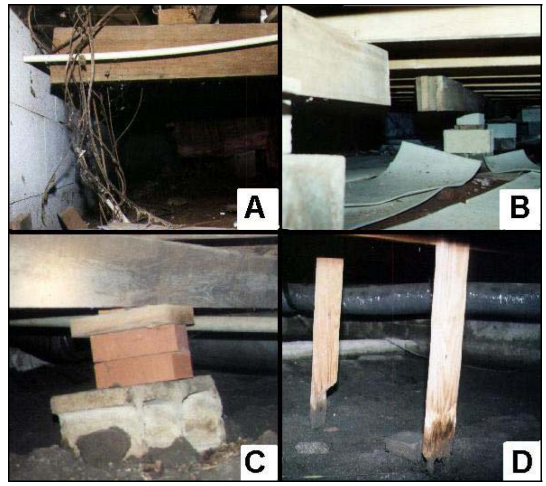

Figure 23. Pier and beam foundation problems not caused by wind: A) cantilevered beam, B) non-continuous beam, C) tilted pier, and D) rotted piers.

11. SUMMARY

In this paper, the author has discussed certain issues with assessing damage to a building after a tornado. The information presented herein has been assembled from more than twenty years of inspecting buildings in the aftermath of tornadoes. Since most buildings are not constructed perfectly, inherent deficiencies usually can be found like walls that are not plumb or square, and floors that are not level. Seasonal soil movement causes cracks in brittle wall materials and long term weathering causes roofs to wear out.

Many people generally do not find these "less-than-perfect" conditions until after a tornado occurs when they closely examine their surroundings. Cracks, gaps, and other anomalies invariably will be found in certain building components that have never been observed before. In order to differentiate between inherent building deficiencies from those caused by a tornado, a careful examination of the building is needed by a qualified individual. It is important to have knowledge of building construction, building materials, and environmental factors, as well as an understanding of wind forces on buildings.

A number of examples were presented herein illustrating the differences between inherent deficiencies in buildings and those caused by strong winds. It is hoped that damage assessors can utilize such information to better determine the extent of storm related damage to a structure.

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