Lessons Learned From Analyzing Tornado Damage

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1. INTRODUCTION

In the past two decades, much has been learned by studying building damage in the wake of tornadoes. Still, there are problems at the basic level in deciding whether the damage was caused by tornadoes or straight-line winds. Past studies of wind damage have frequently revealed that objects were transported along straight paths in tornadoes and followed curved trajectories in straight-line winds. The flight characteristics of objects and the variability of the terrain are only two of the many factors which cause this uncertainty. Thus damage investigators must exercise caution when using a single point of damage to determine the type of wind field.

Assigning F scale numbers to structures based on the degree of damage is a subjective visual procedure. However, when trying to derive the intensity of the winds, it is important to consider how well the buildings are constructed and to recognize weak links or flaws within such structures. Large variabilities in the strength of wood-framed buildings will yield an F scale number with no greater confidence than plus or minus one F scale.

Studies by Minor et al. [1977a] and Minor and Mehta [1979] have dispelled some of the myths associated with tornadoes and the damage they cause. Cooperative efforts between engineers and meteorologists have continued to yield a better understanding of tornado/structure interaction. Still, the process of disseminating this knowledge is slow and confusing. Many of the popular beliefs about tornadoes conflict with what we know today. We still read about opening windows as a tornado approaches, and yet people are told to board up their windows when a hurricane threatens. Tornado safety rules tell us to stay away from auditoriums, but in hurricane situations, officials still place people in them. This confusion stems from a perception that wind damage from tornadoes is somehow different than wind damage from hurricanes. Some of the lessons learned in analyzing tornado damage are the subject of this paper.

2. WIND IS WIND

Aerodynamic forces are induced as air flows over and around buildings. As a result, the greatest outward (or uplift) wind pressures occur around windward walls, roof corners, eaves, and ridges. The damage due to wind typically involves the removal of wall cladding and roof coverings at these locations. Damage surveys by McDonald and Marshall [1983] after tornadoes and Savage [1984] after hurricanes have revealed the same types of building response regardless of the phenomenon creating the wind.

Mehta et al. [1975] and Abernathy [1976] determined that large-span structures, such as auditoriums and gymnasiums, are quite vulnerable in high winds owing to their large surface areas which induce large loads. Such buildings have been just as susceptible to wind damage in hurricanes as in tornadoes. The general consensus now is that people should avoid shelter in auditoriums and gymnasiums during any type of windstorm.

3. BUILDINGS DO NOT EXPLODE

It was once thought that the low pressure within tornadoes caused buildings to explode. This theory was based on the erroneous assumption that a building somehow remains structurally intact after passing the radius of maximum winds on the periphery of the tornado. Furthermore, the theory assumes that the building remained sealed such that the barometric pressure inside the building can become significantly greater than outside.

Studies of tornado damage presented by Mehta [1976] and Minor [1976] indicated that building damage initiates from wind pressure breaching the building, not from low barometric pressure. The wind typically enters the building through broken windows or doors. Evidence of mud, insulation, glass shards, and wood missiles inside buildings that remain partially intact indicate wind had entered the buildings. Openings on the windward side of a building actually increase the internal wind pressures, resulting in additional uplift on the roof (Figure 1). Thus persons are no longer advised to open their windows in advance of a tornado. Another reason is that flying debris will likely break the windows anyway; thus people should use any advance warning time to seek appropriate shelter rather than opening windows.

4. OBJECTS TWIST ACCORDING TO THEIR OWN PROPERTIES

The fact that a tree, house, or object is twisted during a tornado does not indicate that the varying direction of the wind caused the damage. Although the primary wind flow in a tornado at the ground is rotational, the rotating wind field extends over a diameter much larger than the dimension of most objects. The width of an average house is much smaller than the diameter of an average tornado. Thus at any given instant, a building in the tornado path would receive winds that are approximately unidirectional. Tornado damage studies by Minor et al. [1977b] and Minor [1982] have indicated that twisted buildings are usually the result of variations in the strength of foundation anchorage, not the rotating winds. Often the bathroom plumbing provides the greatest anchorage of a house to the foundation, and the house will pivot around this point. McDonald [1971] concluded that a twisted house was more likely the result of different resistances in foundation anchorage rather than the spiraling winds (Figure 2). Such damage has been known to occur even in straight-line winds from severe thunderstorms.

In the Northern Hemisphere the greatest wind velocities typically occur on the right sides of cyclonically rotating tornadoes as the effects of translation are added to the rotation. Using computer simulations, Metcalf [1978] has shown that fast translating, weak tornadoes can leave straight-line damage paths. Marshall [1985a] found such straight-line damage trajectories in the debris left behind in the Mesquite, Texas tornado.

In addition, the variations of building strength, orientation, number and type of openings, roof type, degree of shielding, and impact by neighboring objects are known to influence trajectories in the damage path. Thus it is important to study a large area of damage with several points of reference before drawing definitive conclusions about whether a tornado caused the damage. Furthermore, these ideas should be kept in mind when assigning an F scale rating.

5. TYPICAL WOOD FRAME BUILDING FAILURES

Damage investigations by Marshall [1985b] and Liu et al. [1989] have identified certain building connections that have failed in windstorms, particularly at the following locations: (1) wall/foundation, (2) wall stud/bottom plate, (3) roof joist/top plate, and (4) rafter/top plate. Uplift forces are often not considered when the connections are utilized. Each member of a structure should be thought of as a link in a chain; the weakest link usually initiates failure.

Inadequate wall/foundation anchorage has meant failure of large portions of structures. Conventional wood structures, especially rural dwellings, sometimes have little to no anchorage to their foundations. Minor [1981] has shown examples of unanchored buildings that have moved laterally off their foundations in strong winds. See Figure 3. Properly installed anchor bolts in slabs would help secure walls to the foundation and provide greater resistance against lateral movement.

Wooden wall framing usually is straight nailed to the bottom plates. As a result, laterally applied forces distributed over the height of the wall cause rotation of this connection, and the nail ends pull out. A stronger connection would be to install straps and braces to put nails or bolts in shear. Significant resistance to racking failure can be achieved by installing plywood sheets in wall corners of wood-framed structures.

Wooden roof joists/top plate and rafter/top plate connections are usually toenailed. Such connections typically fail in tension, causing large sections of the roof to become displaced (Figure 4). Properly installed straps or braces are needed to place fasteners in shear, not tension, in order to provide greater resistance against uplift (Figure 5). As wind velocities increase with height above the ground, roof systems usually experience strong wind uplift pressures. Conner et al. [1987] showed various illustrations in using straps and tie-downs in securing roofs to perimeter walls. Pull tests conducted by Canfield et al. [1991] have shown a dramatic increase in the strength of the rafter-top plate connection when metal rafter ties were used instead of simple toe nailing.

The best time to install connections to resist uplift forces is during construction. Proper placement of anchors, braces, and connections is essential to anchor floors to foundations, walls to floors, and roofs to walls. Increasing the wind uplift resistance of a building after it is constructed is more expensive, more difficult, and often less effective. Sherwood [1972] presents several construction details showing how to install anchors and braces to resist wind forces.

6. METAL BUILDING PROBLEMS

Studies of metal building performance after windstorms have revealed several weak links within such structures. When failure of a weak link leads to breach of the building containment, the damage to the building increases significantly. An extensive study by Mehta et al. [1971] on metal building performance after the Lubbock, Texas, tornado found that inward buckling of overhead doors frequently led to loss of roof and wall corner cladding. Openings in the windward side of a metal building resulted in increased interior wind pressures, especially when there were no openings on the remaining building faces. Similarly, open bays "catch" the wind, causing increased wind pressures on cladding. Perry et al. [1989] and Ellifritt [1984] have documented similar failure initiation points in metal structures in hurricane damage.

7. UNREINFORCED MASONRY PROBLEMS

The absence of steel reinforcement in concrete block masonry makes such a system vulnerable to lateral wind loads. Even load-bearing block masonry walls have often collapsed owing to the lack of steel reinforcement and cell grouting. Examples of such failures have been shown by Sparks et al. [1989] and Hogan and Karwoski [1990] in both tornado and hurricane damage. Bond beams atop masonry walls have performed poorly in past windstorms. McDonald and Marshall [1983] had attributed the failure of an entire roof system to a failed bond beam system on a masonry structure. Failure initiated as the mortar joint below the bond beam failed in tension.

Absence of brick ties to secure masonry veneers has led to wall failures at relatively low wind velocities (Figure 6). Even when brick ties have been properly installed, corrosion and fatigue over time can reduce the performance of such ties.

8. ROOF SYSTEM PROBLEMS

A number of damage studies have been conducted involving the removal of various roof coverings. A common failure initiation point on roof systems occurs where the roof membranes are attached to edges and corners. McDonald and Smith [1990] attributed several roof system failures to the lifting and peeling of metal edge flashings. Uplift of the roof edges allows the wind to penetrate underneath the roof membrane, resulting in pressure rise beneath the membrane and removal of the roof covering.

Another failure initiation point has been traced to the lack of attachment between insulation board and the roof deck. In instances involving the application of hot bitumen on a metal roof deck, it is important that insulation board be installed immediately after application of the bitumen in order to develop a significant bond. A number of roof failures have been documented by the author where the applied asphalt had cooled prior to the installation of the insulation board. In other instances, an insufficient amount of bitumen had been applied to the metal deck. This led to virtually no bond between the insulation board and the deck.

Failure of roof systems has occurred when an adhesive was used to secure the roof membrane to the insulation board. As the membrane was uplifted, failure initiated in the layer of insulation board just beneath the location where the adhesive was absorbed. In this construction the insulation board was inadvertently used to resist some of the wind uplift forces. Similar roof system failures have been documented by Kramer [1985].

9. FLYING DEBRIS PROBLEMS

The presence of flying debris or missiles in the wind field can greatly increase the damage to structures by creating openings in the building where the wind can enter. McDonald [1976] has documented a wide range of missiles found in the damage paths of tornadoes. Among the most common missiles are wooden boards, sheet metal, and roof gravel. Missile drop tests conducted by Thompson [1973] showed that small missiles could penetrate walls with single sheathing at speeds as little as 32 mph (51 km/h).

10. SUMMARY

It is important to consider how well buildings are constructed when interpreting the damage after a windstorm. Variations in damage along the path are not always explained by a change in wind velocity and could be attributed to weak links in building construction. Engineering studies over the past two decades have yielded increasing evidence that the extent and type of anchors, braces, and connections used in buildings correlate well with how buildings behave in the wind. A more accurate F scale rating can be obtained by considering the structural strengths and weaknesses of damaged buildings.

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FIGURES

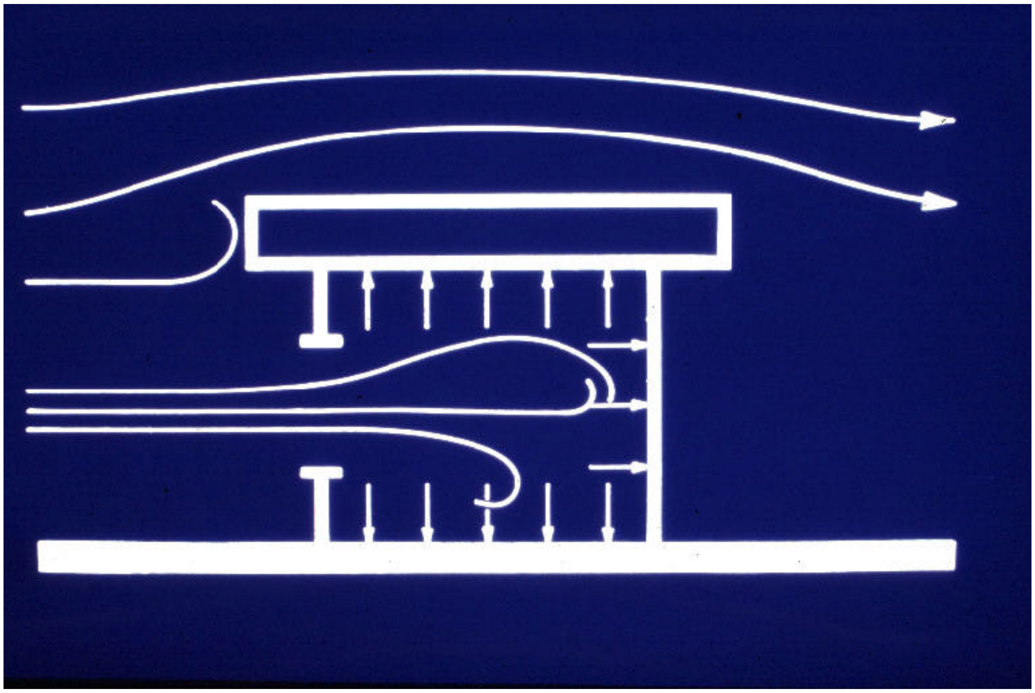

Figure 1. Simplified schematic showing the airflow (long arrows) extending over and into a building with a windward wall opening. The wind pressure on the building's interior actually increases, resulting in additional uplift or outward forces (small arrows). Thus, opening windows when a tornado approaches could actually be detrimental to the structure. Figure courtesy of IDR at Texas Tech University.

Figure 2. This premanufactured home was rotated Off its concrete block foundation during the Hereford, TX tornado. The house actually pivoted about the bathroom plumbing that was the only significant point of floor-to-ground anchorage. The rotation or "twist" of this object was best explained by the variations inherent within the structure rather than rotating wind currents. Note the lack of damage to roof shingles and felt underlayment along the walls indicative of relatively low wind velocities. Photo courtesy of IDR at Texas Tech University.

Figure 3. Lateral displacement of this unanchored home during the Grand Island, NE tornado caused the wooden floor structure to lose support and fall into the basement. Lack of damage to the surrounding trees and roof shingles indicated house movement occurred at wind velocities of probably less than 100 mph (161 km/h).

Figure 4. The roof on this house was not anchored very well and was uplifted during peripheral winds in the Mesquite, TX tornado on December 13, 1994. wind velocities of less than 100mph (161 km/h) can cause such residential damage.

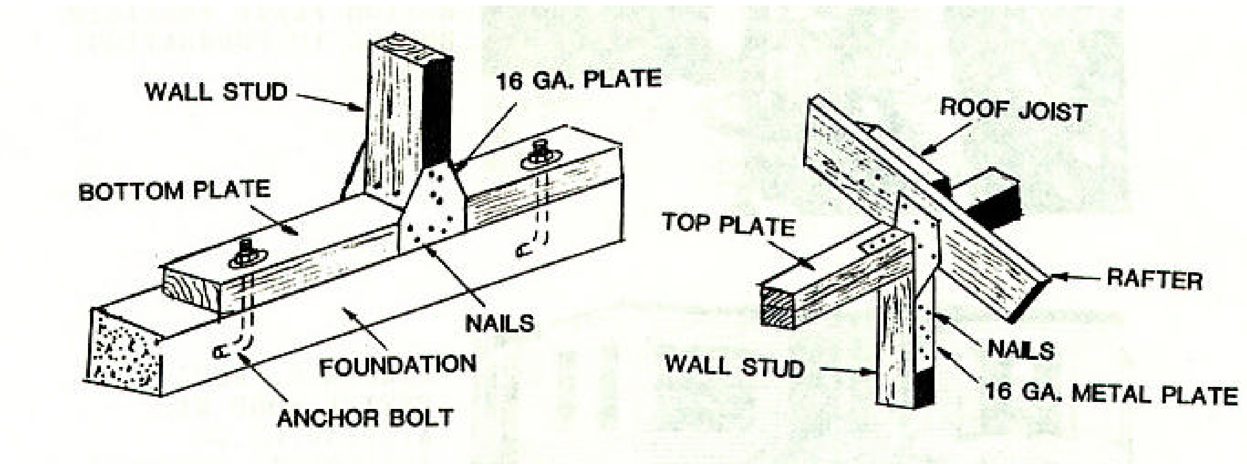

Figure 5. Recommended connection details to resist wind uplift: a) wall-foundation detail, and b) roof-wall detail.

Figure 6. Damage to a two-story brick veneer wall in the Mesquite, TX tornado. There were no brick ties to anchor the wall to the wooden frame. The wall toppled on the leeward or "suction" side.