Structural Evaluation Procedures and Case Studies of Damage Related to Wind Storms, Tornadoes, and Hurricanes

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Abstract
This paper will discuss structural forensic investigative procedures used to assess wind storm damage, tornado damage, and methods to differentiate between hurricane wind and storm surge damage. Several structures or facilities are considered on a case study basis to determine commonalities and differences in the types and extent of wind-related damages. In several cases, comparisons to storm surge-related damages were conducted as part of the investigation.

This paper will address the factors impacting the types and degree of wind-related damages exhibited by each structure. Wind forces related to hurricanes, tornadoes, and wind storm events vary in strength, duration, and directionality; however, common wind-related damages were observed as a result of the differing wind events. Though commonalities in the types of damage were observed, the extent of damage varied depending on the type of construction, quality of construction, age of the structure, and orientation of the structure to the wind forces.

Investigation Procedure
In determining the cause and extent of distress to a structure damaged by a wind storm, tornado, or hurricane, a protocol of data collection is utilized. Once on site, it is standard to photographically document all observed distress and take plumbness data. Other valuable information in determining the cause and extent of damage include aerial photographs and relevant wind data.

There is no substitute for a site visit shortly after the storm event to accurately document the damage at the site. Being able to observe and document distress prior to repairs being made allows for more accurate data to be collected. Photographs should be taken in a systematic pattern.

Plumbness measurements are taken to check for structural racking. Aerial imagery can be an important factor if the subject site is not observed immediately following a storm event and prior to repairs. Weather data relevant to a specific storm and subject site is important in determining the effects of the wind on the subject structure. The directionality and wind speeds are important factors in determining if the distress observed is consistent with the storm event.

ANALYSIS

Photographs and Graphical Distress Mapping

Reviewing photographs of the observed distress and graphical mapping of distress on illustrations of the structure are important steps in assessing patterns of distress for comparison to storm data. In the event that the subject structure is not evaluated immediately following a storm event, aerial imagery, photographs taken by others, and any repair documents can play an important role in determining the pre and post-storm condition of the structure, and the cause and extent of damage. The comparison of the pre and post-storm aerial imagery can provide useful information on the pattern of distress at the roofing system.

Plumbness

The plumbness measurements are evaluated to determine if an overall pattern of out-of-plumbness exists at a structure which could indicate structural damage to the lateral load resisting system. When analyzing the plumbness readings it is important to look at the overall patterns or trends, such as movement in one direction or twist, which could indicate damage to the structural system.

Weather Data

Weather data relevant to a specific storm and subject site is important in determining the effects of the wind on the subject structure. The directionality and wind speed experienced at a subject structure assist in determining what types of distress would be expected at a specific structure; however, it should be noted that construction defects, design defects, and material defects often result in distress at lower than expected wind speeds.. The directionality and wind speeds are important factors in determining if the distress observed is consistent with the storm event.

Internal Pressure

Velocity pressure used in the design of a structure is outlined in section 6.5.10 of ASCE 7-05. The equation for design velocity pressure (q_z) is given in equation 6-15 of ASCE 7-05 as: $q_z=0.00256\ K_z\ K_{zt}\ K_d\ V^2\ I\ (lb/ft^2)$. K_z, K_{zt}, and K_d are all factors used to modify wind pressures due to structure height, wind directionality, and the surrounding topography. A basic 3-second wind gust speed (V) is also utilized.

The engineer must take the internal pressure coefficient into account per Equation 6-18 in the ASCE 7-05. Figure 6-5 in ASCE 7 provides the internal pressure coefficients for open, partially enclosed, and enclosed structures. The internal pressure coefficient for an enclosed structure is +- 0.18, where the internal pressure coefficient for a partially enclosed structure is given as +- 0.55. This increased coefficient effectively triples the internal pressure in a partially enclosed structure compared to one that is considered enclosed. In addition, ASCE 7 commentary indicates that the internal pressure coefficient could be increased further. "Taken in isolation, the internal pressure coefficients can reach values of +- 0.8 (or possibly even higher on the negative side)." (ASCE 7-05)

During the exposure transition, design wind pressures on the windward wall and roof effectively transition from a positive pressure in the direction of wind flow to a negative pressure, acting in the opposite direction from the prevailing wind. In addition to the pressure reversal on the windward side, the pressures acting on the leeward side and ends of the structure increase by 60% and 63%, respectively. If an internal pressure coefficient of 0.8 is used, this increase in leeward pressure increases by an average of 200% from the values obtained for an enclosed structure. "An opening on the windward face of the building can also lead to a failure by allowing positive pressures to occur that, in conjunction with negative pressures, can 'blow the building apart.'" (FEMA, 2000)

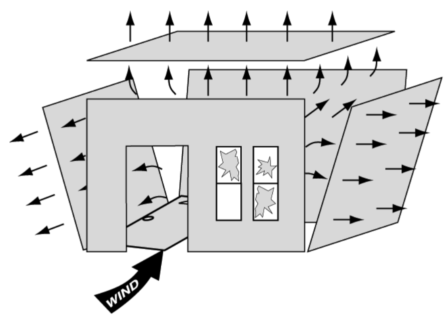

Figure 1. Building Failure Due To Internal Pressurization (FEMA, 2000)

Structures can transition from an enclosed to partially enclosed condition as openings in the building envelope are created. Such openings can be created by flying debris damaging windows and doors. "When glazing is breached by missiles, development of high internal pressure results, which can overload the cladding or structure if the higher pressure was not accounted for in the design." (ASCE 7-05) This immediate pressure increase can have a "popping" effect on the building's connections, significantly weakening and possibly failing them if the connections were not designed to withstand the additional force. "Building failures occur when winds produce forces on buildings that the buildings were not designed or constructed to withstand. Failures also occur when the breaching of a window or door create a large opening in the building envelope. These openings allow wind to enter the buildings, where it again produces forces that the buildings were not designed to withstand." (FEMA, 2000)

Lateral Loads

During a windstorm event residential structures are subjected to lateral loading in the form of wind, storm surge, or a combination of both. If the loads are not successfully transferred, failure of the structure may occur.

The magnitude of lateral loading associated with wind is dependent on the height of the structure above grade and the velocity of the wind. Wind velocity increases at higher elevations above grade. In addition, when the wind velocity is increased, the air pressure exerted on the structure during a given time period increases, thus increasing the magnitude of the lateral force applied on the structure.

Lateral forces related to storm surge are resisted by a structure in a similar manner. As the depth of the storm surge rises, the water on the exterior of the structure creates an increasing lateral force on the structural framing.

Due to the differences in the density of air and water, the lateral loading related to storm surge is typically far greater than that related to wind on a given area. The density of dry air at sea level is approximately 1/800 the density of water. Therefore, if wind and water moving at the same velocity impact a surface, water will impose a force several magnitudes greater than wind.

Case Study 1

Eight school campuses in southern Louisiana were impacted by Hurricane Rita in September 2005. Observations at the campuses were not performed until August 2006. At the time of the investigations, repairs had been performed or complete facilities had been demolished. This made the aerial imagery and photographs taken by others immediately following the storm key in determining the condition of the structures after the storm event.

During the site investigation, photographs were systematically taken to document the condition of the remaining structures. Also, a plumbness survey was taken at the interior and exterior walls at the remaining structures. Post-storm photographs by others and aerial imagery were heavily relied upon in determining findings. Several of the campuses located at various locations along the gulf coast are discussed below.

School A

At School A, approximately three to six feet of storm surge was incurred at the structure. The post-storm photographs taken by others indicated that the south non-structural stack bond concrete masonry unit walls had collapsed in a manner consistent with being pushed inward at the bottom, which is indicative of storm surge damage as shown in Figure 2. Additionally, the post-storm photographs showed that the papers and posters in the classrooms were still attached to the walls, as shown in Figure 3, indicating that the winds were not strong enough to damage the papers taped or tacked, to the walls, much less a CMU wall.


Figure 2. Collapsed CMU walls


Figure 3. Papers still intact at interior

The aerial photos taken shortly after Hurricane Rita indicated that the high gymnasium flat roof was significantly damaged by wind. However, the aerial imagery did not indicate significant damage to the lower flat or metal sloped roofs. The plumbness survey performed did not indicate any evidence that the structure had been "racked" or displaced due to lateral wind pressures.

School B

School B was located further inland and incurred minimal water from storm surge. The post-storm photographs taken by others indicated a large amount of lost shingles at the sloped roofs. The post-storm photographs did not indicate any displaced flat roof membrane at the flat roof areas.

The plumbness survey performed did not indicate any evidence that the structure had been "racked" or displaced due to lateral wind pressures. However, separations and fractures were typical throughout the plaster, CMU, and brick walls. Mortar joint separations were typical at the corner intersections and above doors and windows. The majority of the separations and fractures had previously been repaired indicating evidence of long-term foundation movement. The CMU at the interior CMU walls were laid in a stack bond pattern with no interlocking of the walls. According to the construction drawings, the vertical cells of the CMU walls were unreinforced except for dowels into the foundation at the bottom of the wall at select locations. The construction drawings only indicated the placement of a single bond beam at the top of the walls. No intermediate bond beams or corner reinforcement were indicated. This lack of reinforcement and bond pattern provided minimal resistance to distress within the wall as a result of normal foundation movement and thermal effects.

School C
School C was located approximately two miles north of the Gulf of Mexico and incurred approximately eight to ten feet of water from storm surge. At the time of the investigation, the structures had been completely demolished; therefore, findings were all based on aerial photographs and post-storm photographs by others. The pre-storm aerial imagery indicated that several temporary classroom structures were located on the campus, adjacent to the main structure. The post-storm photographs by others indicated a large amount of debris in the roof joists. Additionally, the post-storm aerial imagery indicated that the south edge of the roofing was peeled back, consistent with storm surge damage. Based on the pre-storm and post-storm aerial imagery, it was apparent that any temporary classroom structures were completely destroyed by storm surge. Further, the post-storm photographs indicated that the wind-related distress was minor and limited to the higher roof areas of the structure.

School D
School D was located approximately four miles north of the Gulf of Mexico and 12 miles east of School C. School D incurred approximately ten to twelve feet of water from storm surge. At the time of the investigation, the structures had been completely demolished; therefore, findings were all based on aerial imagery and post-storm photographs by others. The post-storm photographs and post-storm aerial imagery indicated limited and minor wind-related damage to the flat roof system. Therefore, it was evident that the majority of the damage was related to the approximately ten to twelve feet of storm surge.

Case Study 1 - Conclusions
The type and quality of construction also impacts the extent of damage experienced at a structure. For example, at School A, the sloped metal panel roofs and lower flat roofs incurred far less damage than did the higher flat roof.

It is critical to document the distress and study the locations and the patterns; including evidence of previous repairs. For example, at School B, a large amount of mortar joint separations were observed throughout the facility; however, the plumbness survey did not indicate a pattern of lateral movement. A study of the locations of the CMU wall distress showed a highly consistent pattern to the distress and also many areas of previous repairs. The type of construction of the walls (stack bond CMU walls) was the primary cause of the distress; wide spread distress was observed within the walls as a result of normal foundation movement and thermal effects.

Finally, all of the schools' wind-related damages varied significantly from campus to campus, even the structures that were located relatively close to each other. Therefore, assumptions cannot be made of the post-storm condition of a structure based only on the condition of surrounding structures. The quality and type of construction; the age; the presence or lack of a good maintenance program; design, construction and material defects; and the orientation of the building all play a central role in how much damage a building sustains from a wind storm.

Case Study 2

Several structures in Plaquemines Parish Louisiana were investigated for wind-related versus storm surge related damages as a result of Hurricane Katrina. Plaquemines Parish was located directly in the path of Hurricane Katrina. The area of Plaquemines Parish investigated is protected by a levee along the west side adjacent to the Gulf of Mexico and by a levee along the Mississippi river to the east. Breaches in the levee system were reported, but the exact location(s) of the breaches were not known.

Adjacent structures in the area were observed to be either heavily damaged with extensive wind distress to the roof, cladding systems, and framing systems, or to be completely destroyed. Many structures were observed to have floated due to buoyancy.

The cladding of the structures as well as the framing, was generally completely destroyed by Hurricane Katrina, as shown in Figure 4. Typically, the brick was observed to have fallen away from each face of the structure while the wood wall framing and windows ranged from partially intact to completely collapsed, as shown in Figures 4 and 5.

Figure 4. Typical condition of remaining structure

Figure 5. Brick veneer distress

Figure 6. Typical roof distress

The roofs of the structures investigated were observed to be completely dislocated from the structure and some of the roofs were observed to have been deposited on the ground, while others were completely gone. Additionally, extensive wind damage was observed to the roof shingles at the displaced roof systems, as shown in Figure 6.

Overall, measured wind speed information was not available for Plaquemines Parish. It was evident that the wind gust speeds at the sites were in excess of 100 mph; the closest measured wind gust was 114 mph recorded at the Grand Isle Buoy (approximately 25 miles southwest from the structures). Further, the NOAA National Climactic Data Center (NCDC) indicated sustained winds of 127 mph at landfall. Based on observations at the site, the forces from the wind were structurally significant.

The subject structures indicated common evidence of structures that had burst, or effectively exploded consistent with internal pressure build-up. The brick veneer on the structures was typically observed to have fallen outward from each face of the structure, which is consistent with a bursting or explosion of the structure due to high wind forces.

The entire roof system at the subject structures observed in Plaquemines Parish, including the attic framing and decking, were typically dislocated from the structures. Based upon site observations, it was evident that the structural destruction to the structures observed was the result of high wind forces with a subsequent contribution from storm surge.

Case Study 3

A residential structure in North Texas was impacted by high winds and tornadic activity. The damage observed at the subject structure was isolated and the surrounding structures and trees were effectively undamaged, showing the power and selectivity of a tornado.

The north pitch of the structure was severely damaged with large portions of the roof decking and rafters displaced from the northwest and northeast planes of the roof and deposited into the yard at the east elevation (Figure 7). Missing and fractured rafters, ridge beam, and hip and valley members were observed at the north side of the structure as shown in Figure 8. Minimal damage was observed at the south pitch of the roof framing system.

Figure 7. Condition of structure


Figure 8. Roof framing distress

<u>Case Study 4</u>

Over 30 residential structures located on Port Bolivar, Texas were evaluated after Hurricane Ike. The structures evaluated were typically elevated one and two-story structures supported by wood pilings. Elevation heights taken from available FEMA flood elevation certificates were compared with actual in-field measurements of elevated structural components above grade. Based on the comparison of in-field measurements and available survey data, the height of the storm surge was approximated to be in excess of 20 feet above sea level.

Typical observations at the ground level of the structures included undermined concrete seal-slabs, displaced and missing breakaway wall framing, and in some cases, a significant amount of soil scouring and erosion (Figure 9). The exterior siding and any impacted wood framing was typically displaced by storm surge and wave action. In addition, many of the wood pilings were displaced as the deck support framing was removed (Figure 10). Roof distress was typically limited to isolated areas of loose and missing shingles.


Figure 9. Erosion of soil


Figure 10. Missing/displaced framing

A plumbness survey was performed at each structure at the structural wood pilings and at the interior walls of the structure. Only a few of the structures observed indicated lateral movement consistent with structural damages related to lateral pressures associated with either wind or storm surge beneath the structure. In addition, perceptible lateral movement was experienced in two of the structures where an extensive amount of soil scouring was observed below the structure.

The wind speeds at the sites reached approximately 90 – 100 mph (3-second gust). Based on observations and measurements at the sites, the forces from the wind did not cause significant lateral movement of the structures. Additionally, lateral pressures exerted on the structures related to storm surge did not cause significant lateral movement of the structures. Although an extreme amount of destruction was observed on the Bolivar Peninsula, relatively little damage was observed on well built structures that were elevated higher than the storm surge.

CONCLUSION

A protocol of data collection is required when evaluating the cause and extent of distress to a structure damaged by a wind storm, tornado, or hurricane. Photographing and graphically mapping the observed distress at a site creates permanent evidence of the condition of the subject structure and the pattern of distress immediately following a storm event. However, reviewing documentation taken by others is commonly used to re-create the scene.

Wind forces related to hurricanes, tornadoes, and wind storm events vary in strength, duration, and directionality; however, common wind-related damages were observed as a result of the differing wind events. Though commonalities in the types of damage were observed, the extent of damage varied depending on the type of construction, quality of construction, age of the structure, and orientation of the structure to the wind forces.

The case studies presented herein show the different factors that affect the type and extent of distress a structure can experience during a wind event. Significant factors contributing to the extent of damage a structure incurs include the quality and type of construction; the age; the presence or lack of a good maintenance program; design, construction and material defects; and the orientation of the building all play a central role in how much damage a building sustains from a wind storm.

It is critical that proper structural forensic investigative procedures be used to assess damage and collect accurate and significant data. Further, the assessment of damage patterns established from site-specific data, observations, and documentation combined with weather data and other information sources allow for an accurate determination of the cause and extent of damage at a structure.

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