Storm Surge Damage to Buildings

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1. INTRODUCTION

The destruction of buildings and property in low-lying areas caused by storm surges is common with the passage of tropical storm systems, winter storms, and other large scale storms. This hazard stems from people's desire to live adjacent to large bodies of water which occasionally puts them and their property in harm's way. Storm surge is the change in water level which occurs as water is forced ashore. The magnitude of the surge can be increased a number of ways. Topographic features such as the Continental Shelf along portions of the U.S. coastline can enhance storm surges as wind stresses and waves lead to a "piling up" of water. Also, shallow bays and inlets can channel the water resulting in higher water levels. The angle, speed, and size of a given storm also can have a profound influence on the height of the storm surge. Tides are superimposed on the storm surge, such that the effect is compounded if a storm surge occurs at or near high tide.

There are many myths associated with storm surges. One myth is that there has to be onshore winds to have a storm surge. People who have waited for the strong winds to arrive before evacuating have found their evacuation routes already flooded. Such was the case on Bolivar peninsula in advance of Hurricane Ike. Actually, storm surges can occur when the winds are blowing offshore as the "piling up" of water, sometimes called the "surge forerunner", can outrun the strongest winds. So, another myth is that damaging winds always precede a storm surge.

The purpose of this paper is to discuss the characteristics of building damage associated with storm surges. As water rises, a combination of hydrostatic and/or hydrodynamic forces develop on inundated buildings. Wood-framed structures float in water, and movement of water can undermine and dismantle buildings from below. Recognizing how storm surge damages buildings can help damage investigators better separate wind and water damages.

Much of our understanding of how buildings are damaged by storm surges comes from post-disaster engineering surveys. Some of the earliest published surveys were conducted by the U.S. Army Corps of Engineers (USACE) after Hurricanes Betsy (1965), Beulah (1968), Camille (1970), Celia (1971), and Frederic (1981). The National Academy of Sciences (NAS) published damage surveys after Hurricanes Iwa (1983), Alicia (1984), Diana (1986), Elena (1991), and Hugo (1994). Also, detailed damage surveys have been published by the Federal Emergency Management Agency (FEMA) after Hurricanes Andrew (1993), Iniki (1993), Opal (1996), Fran (1997), Georges (1999), Charley (2005), Ivan (2005), Katrina (2006), Ike (2009b), Isaac (2013), and Sandy (2013), and after the Midwest floods (2009c). The National Institute of Standards and Technology (NIST 2006) issued a survey report after Hurricanes Katrina and Rita. Marshall (2006a, 2006b, and 2010) also published damage surveys after Hurricanes Ivan, Katrina, and Ike. Marshall (2002) also studied storm surge damage from a derecho on a Wisconsin lake. A summary of storm surge damage to various building types is presented.

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2. DAMAGE CHARACTERISTICS

There are two types of forces that water can exert on a building. Hydrostatic forces result when a building becomes flooded. Since wood floats in water, a buoyancy force develops as wood-framed structures become submerged. An object floats when the upward buoyancy force exerted by the water exceeds the weight of the object, or when the density of the object is less than the density of water (~1g/cm^3). An object sinks when the weight of an object is greater than the upward buoyancy force, or when density of the object is greater than the density of water (~1g/cm^3). Sea water is slightly denser than fresh water due to its salt content, thus sea water is slightly more buoyant.

The pressure moving water exerts against a stationary object is far greater than that of a wind gust moving at equal speed. A hundred mile per hour wind exerts a pressure of about 125 kg/m^2 (25.6 psf) against a vertical surface. By comparison, a wave moving at just 4.5 m/s (10 mph) exerts a pressure of about 1020 kg/m^2 (209 psf) against a vertical surface. The difference in pressure is due to the fact that water is much denser than air. At sea level, water weighs about 800 times that of air.

Damage associated with moving water is concentrated in the lowest portions of buildings and typically involves undermining or dismantling the buildings from below. Walls facing moving water can be pushed inward at their bases forming hinges at the tops of the walls. Similarly, the bases of walls on the leeward sides of buildings can be pushed outward (Fig. 1). Thus, buildings can collapse even if they are above the water level. The roof remains upright and floats downstream.

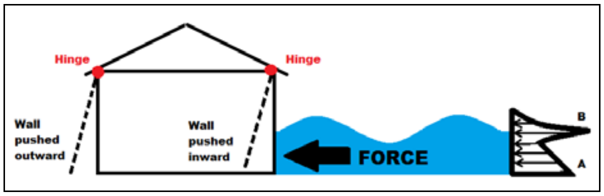

Figure 1. Illustration showing the forces of moving water against a wood-frame building: A) hydrostatic force and B) combination of hydrostatic and hydrodynamic forces in the wave zone. The bases of walls are pushed inward on the upstream sides and outward on the downstream sides of a building. As a result, hinges (red dots) form at the tops of the walls.

3. MANUFACTURED HOMES

Manufactured homes typically are wood-framed "boxes" attached to steel frames. Usually, these homes are elevated, leveled on piers, and have various degrees of attachment to the ground. Homes are elevated to provide clearance for accessing plumbing lines. Sometimes metal or plastic skirting surrounds home perimeters to hide the piers. Manufactured homes are accessed via stairs or ramps. Some manufactured homes are set on concrete masonry perimeter foundations. In rare instances, manufactured homes are elevated on tall timber piles or concrete piers.

Manufactured homes often are situated in flood-prone areas. Moving water with debris can push homes off their piers and transport them downstream. Manufactured homes will float but eventually break apart as they strike the shore or other floating debris. FEMA (2009a) details how to prevent manufactured homes from being damaged by floodwaters. They indicate that it only takes 10 to 12 cm (4 to 5 in.) of water above the floor to float an unsecured manufactured home off its foundation (Fig. 2).

Figure 2. This manufactured home was moved off its foundation by moving water (not wind) and was stopped by a tree in Venice, LA. Note flotsam and floating debris on the roof as well as the absence of wind-displaced siding.

4. WOOD-FRAME HOMES ON PIERS

Many wood-framed homes are set on pier and beam foundations. Piers support the floor platform. The piers can be loosely stacked brick or concrete masonry units (CMUs), solid masonry with mortared joints, concrete piers, or steel jacks. Floor platforms are often not anchored to the piers. An unanchored wood-framed building can float when buoyancy forces becomes greater than the weight of the building. Floor platforms act like rafts, especially if the floors are covered with hardwood planks and/or have solid wood subflooring. Buildings with solid wood diagonal wall sheathing or clapboard siding also increase buoyancy. Water lines on the interiors of such wood-framed homes have indicated that it only took a few feet of water above floor level to make the home positively buoyant. Wind and wave action then can steer the buildings much like an adrift sailboat. Buildings have been known to float more than a kilometer until they run aground or are stopped by anchored objects such as trees and fences (Fig. 3). In some cases, some have argued that a tornado picked up and transported the house like in the movie *Wizard of Oz*. However, close examination can reveal otherwise. Look for items still hanging on the walls, and glassware standing upright in cabinets. This indicates the building moved slowly (low speed) and came to rest slowly (low impact). Wind would have broken such items if the building moved rapidly (high speed) and came to rest suddenly (high impact).

Perimeter masonry veneer also can limit building movement. Wood-frames can rise and fall within the confines of the masonry veneer, especially if the masonry is not well attached to the frame. Such buildings rarely return to their original position, leaving distorted flooring and broken piping. Some have argued that aerodynamic wind forces lifted the buildings. However, careful examination of the crawl space can reveal if the building floated. Look for various debris (i.e. flotsam, insulation, branches, etc.) trapped between the tops of the piers and the flooring indicating the building floated during the flood (Fig. 4).

Buildings that are exposed to significant wave action and repeating impacts of floating debris can lose load bearing walls collapsing all or part of the roof. The greatest building damage occurs on the side facing the water. FEMA (1989) points out that such buildings appear "pitched down" toward the water (Fig. 5), a tell-tale sign that water did the damage, not wind. Some have argued that a "downburst" wind crushed the buildings. However, the strongest axis of building construction is downward. The direction of force can be determined by studying failed wall stud connections. Water forces occur at low elevations perpendicular to the downward force direction.

When inspecting the site of a building that is gone, first determine the elevation of the foundation, and whether the building survived prior hurricanes. This information can establish a history of wind and water forces that the building had experienced. It is a good idea to examine other buildings nearby that survived. Check for water lines that appear like bathtub rings in these nearby buildings and compare them to the height of the water level at the building in question. Also, check the severity of wind damage to trees, buildings, and other objects around the site. This comparative analysis can help provide important wind and water information.

Figure 3. This wood-framed house (red outline) floated landward from its stacked CMU foundation (foreground) where it was stopped by trees in Pass Christian, MS. The home was not picked up and transported by a tornado as some have argued.

Figure 4. This wood-framed home in Pass Christian, MS floated within the broken brick veneer shell but did not come back to the same position. This condition was not caused by wind. Note wind did not damage the gable siding or satellite dish.

Figure 5. This wood-framed house was undercut by moving water and debris in Bay St. Louis, MS. The house has the typical "pitched-down" appearance toward the water. Note the absence of wind damage to the roof shingles.

5. WOOD-FRAME HOMES ON SLABS

Building codes require that wood-frame homes be attached to their concrete slab foundations with anchor bolts, nuts, and washers, or an anchor of similar strength. However, the author has observed framing attached with cut nails, shot pins, and bendable straps which are weaker than anchor bolts. Worse yet, straight-nailed connections between the wall studs and bottom plates offer little upward or lateral resistance. As homes become submerged, buoyancy forces can pull such weak connections apart, resulting in progressive wall failure and subsequent roof collapse. Sometimes the roof remains intact, upright on the house foundation (Fig. 6) or moving water can transport the roof downstream where it breaks apart. In rare instances, the entire house, with its concrete slab foundation, lift together and float away in the rising water (Fig. 7).

As mentioned previously, moving water tends to dismantle buildings from below. Walls facing the water are pushed inward at their bases forming a hinge at the tops of the walls. Walls on the opposite sides of the moving water are pushed outward at their bases. Repeated impacts by floating debris can knock down the walls leading to progressive collapse and removal of buildings. Moving flood water and floating debris can remove building contents as well as the gypsum board cladding on interior walls (Figs. 8 and 9). Some have argued that Bernoulli Effects from high winds are channeled beneath roofs causing damage near the floor. However, items susceptible to wind such as pictures hanging on walls or ceiling light fixtures remain unaffected above the water level indicating that moving water, not wind, did the damage.

Even when buildings are reduced to concrete slabs, evidence still remains about what caused the destruction. Indications that moving water destroyed the buildings involve finding roof structures remaining upright on the ground with roof shingles still intact. Look for items remaining on the slab, such as bent plumbing, nails, or bolts. These items may give an indication of the direction and magnitude of the low-level forces applied to the base of the building. Also look for unbroken debris deposited nearby, such as glass doors, windows, mirrors, dishes, and lights. The author even has found ceiling fans with the intact blades and unbroken glass globes lying on the ground. The absence of damage to such brittle items resulted when the building was dismantled slowly by wave action and these items fell into the water. Once submerged, such items remained protected (Fig 10).

When wind destroys a building, there is usually evidence of windborne debris such as broken roof shingles or roof tiles and insulation downwind. Wind usually takes apart a building from the "top down" whereas water dismantles a building from the "bottom up".

Figure 6. Walls collapsed when this house became submerged in Pensacola, FL leaving the roof upright on the foundation.

Figure 7. This wood-framed home floated along with its concrete slab foundation in Meraux, LA. Buoyancy forces overcame the weight of the building assembly. Wind did not lift the building.

Figure 8. Moving water gutted this wood-framed house on a slab foundation in Long Beach, MS. There was minimal wind-caused damage to the roof shingles.

Figure 9. Wave action and floating debris removed the gypsum board sheathing inside this home, not wind. Note the chandelier remained undamaged.

Figure 10. Storm surge removed the entire building from the property, leaving only heavy items. Unbroken glass items remained on the slab indicating the building was dismantled slowly.

6. WOOD FRAME HOMES ON PILINGS

Many homes in low-lying coastal and riverine areas are supported by tall wood pilings or concrete piers. Wood girders usually are set into notches and bolted to the tops of the timber piles or anchored with steel brackets into the tops of concrete piers. Wood floor joists extend perpendicular to the girders and are either toenailed, strapped to the tops of the girders, or set in joist hangers. The house is then constructed conventionally above floor level.

The extent of rising water damage to a building elevated on timber piles depends on many factors including height of the building above the water, depth of the pilings, and exposure to moving water and wave action. If the building is located on a sandy beach, sand scoured around the pilings can cause the pilings to lean or collapse. Thus, a house above the water level can be damaged or destroyed by moving water if the foundation fails.

Moving water and wave action create both lateral and upward forces on the elevated floor. The first sign of surge damage to the floor is rotation or removal of blocking between the floor joists and landward bending of girders perpendicular to the moving water direction. Upward forces from wave action can sever the connections between the floor joists and the girders. As floor joists work loose and begin to bob up and down in the water, they can leave scrape marks on the girders (Fig. 11). Loose floor joists eventually become part of the mass of floating debris that repeatedly strikes and dismantles the flooring. The force of moving water and wave action literally can push and stack the floor joists toward the landward side of buildings (Fig. 12). This process does not occur all at once but occurs progressively as waves strike the joists. Progressive loss of the floor eventually results in the partial or complete collapse of the building. Portions of the floor or roof can be left hanging precariously while items such as ceiling fans and wall hangings remain untouched (Fig. 13). Eventually, all that remains are the pilings and perhaps a few floor girders.

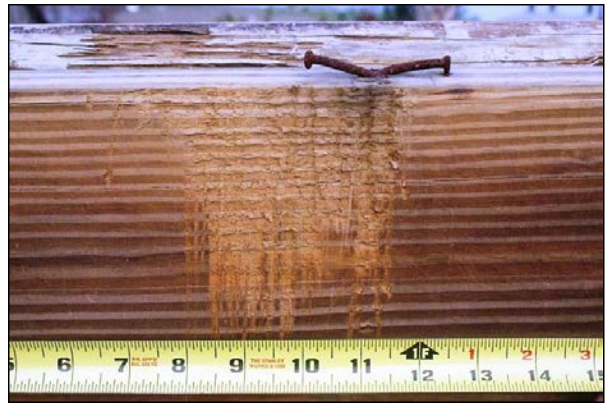

Figure 11. Scrape marks on the side of a floor girder that recorded the bobbing up and down motion of a floor joist that had been toenailed to the top of the girder.

Figure 12. Progressive stacking of floor joists towards the landward side of the building due to the force of moving water and wave action (arrow).

Figure 13. Wave action undermined and removed the floor structure on this elevated wood-framed house on the Bolivar peninsula Note ceiling fans remained intact.

7. MASONRY BUILDINGS

Masonry buildings are vulnerable to damage by moving water as they have little lateral strength. These buildings typically are constructed with brick, hollow clay block, or concrete masonry units (CMUs). Obviously, walls most susceptible to damage would be those perpendicular or broadside to the water flow direction. Collapse of loadbearing masonry walls can lead to partial or total collapse of the roof (Fig. 14). In contrast, wind tends to lift, flip, or remove roof coverings and/or roof structures.

Figure 14. Partial collapse of masonry walls due to moving water and repeated impacts of floating debris in Waveland, MS. There was a 3m water line above the floor inside this building.

8. METAL BUILDINGS

Metal buildings are comprised of steel frames consisting of beams, columns, girts, and purlins. Metal cladding is attached to the frame with sheet screws. Steel columns are attached to the concrete slab foundations with bolts, nuts, and washers. These buildings usually have shallow-sloping roofs.

Lateral forces from moving water and repeated impacts of floating debris eventually buckles and removes the panels and girts in the lowest portions of the walls (Fig. 15). Again, water damage is greatest near the bases of buildings. By contrast, wind damage would be concentrated at roof level. Large canopies and doors also would susceptible to wind damage.

Figure 15. Removal of metal wall cladding and girts due to moving water and repeated impacts of floating debris. This building was in Pass Christian, MS.

9. STEEL-FRAMED BUILDINGS

Steel-framed structures have bolted or welded beams and column assemblies. Walls can be clad with a variety of surfaces to include brick, stone, stucco, etc. Lateral forces from moving water and floating debris impacts literally can gut such buildings, removing partition walls and contents (Fig. 16). Although some people have argued that buildings explode due to low barometric pressure during a hurricane or a tornado, such buildings are not sealed tightly enough to result in significant differential pressure effects.

Figure 16. The first story of this steel-framed building was gutted by storm surge in Gulfport, MS. There was no wind damage to the roof covering including the cupola.

10. CONCRETE-FRAMED BUILDINGS

Concrete-framed buildings have beam and column assemblies poured on site in wood or steel forms. These buildings are quite resistant to the battering effects of storm surges, especially if they are designed with breakaway wall sections. Proper design involves the allowance of water to flow through a building without causing structural damage. Since storm surge occurs at low-levels of buildings, the lower stories are gutted while the upper stories remain intact. In contrast, wind forces become greater with increasing height above the ground/water and affect the roof and upper stories.

In rare instances, catastrophic structural failures can occur with concrete-framed buildings when loadbearing walls or foundations are compromised (Fig. 18).

Figure 17. Moving water removed the interior partitions and contents in the lowest stories of this building in Biloxi, MS.

Figure 18. Catastrophic collapse of what was a five-story concrete-framed building in Orange Beach, AL. Waves removed the load bearing walls.

11. SUMMARY

Knowing how hydrostatic and hydrodynamic forces affect a building can help damage investigators better separate wind and water damage. Basically, water undermines and dismantles a building near its base, whereas wind damage is greatest at roof level as wind speed increases with height above the ground/water. Water weighs much more than air so when it moves, it can exert tremendous forces. It would not be economical to design against the effects of moving water, so it is best to avoid building in flood-prone areas or to elevate buildings above potential flood levels. Breakaway walls allow floodwaters to pass underneath buildings, a successful approach to reduce flood-caused structural damage. However, repeated impacts by floating debris can collapse an elevated building by dismantling the foundation support structure.

When water flows through a building, it removes contents and finish items. The building appears gutted except for items above the water level, such as pictures and light fixtures, which are unaffected. Water flows much more slowly than storm force winds. However, water flowing at the same speed as the wind exerts a far greater force against a structure because water is so much denser than air.

When wood-framed buildings become inundated in water, buoyancy forces can lift the frame from its foundation. A telltale sign of flood damage to such a building is having the roof remaining upright on the foundation. This indicates the supports for the roof structure were removed gradually and the roof settled slowly down into the water.

12. ACKNOWLEDGEMENTS

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