Structural Performance of Heritage Buildings During Tropical Cyclones

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Presented at the ISCARSAG Workshop: Earthquakes and Hurricanes Response and Preparedness, Havana, Cuba, May 16-17, 2011

ABSTRACT: This paper describes the performance characteristics of a range of heritage building types, as observed from the author’s extensive field surveys and rehabilitation design work throughout the US Gulf coast. The overall context of risk is discussed, along with observed behavior with examples, and a set of vulnerability indicators is presented.

1 INTRODUCTION

Traditional buildings often constitute a large part of the existing building stock in the areas most vulnerable to tropical cyclones. These older buildings have distinct structural performance characteristics that differ from modern construction. In some important ways, traditional buildings have clear vulnerabilities, such as shallow foundations and a risk of deterioration due to their age. In spite of this, many heritage buildings have survived for over a century in cyclone-prone areas and possess features of construction that are inherently cyclone-resistant (e.g., timber frame construction with its frame-tying methods of joinery).

1.1 Understanding the Risk

Tropical cyclones (also called hurricanes or typhoons) are large scale cyclonic storms that are capable of producing massive destruction in low lying coastal areas. To improve survivability of traditional buildings, an accurate assessment of risk is essential, and this depends on historical records as well as good models for prediction.

Recent major disasters, such as Ivan, Rita, Katrina, Wilma, and Ike in the Atlantic, the 2006-2008 Bay of Bengal cyclones, and others have produced a general perception that the high level of major cyclone activity represents a departure from normal. However, research suggests that the recent active phase (1995–2005) of Atlantic hurricanes is unexceptional compared to the earlier high-activity periods of ~1756–1774, 1780–1785, 1801–1812, 1840–1850, 1873–1890 and 1928–1933, and is actually a return to normal activity (Nyberg 2007).

The widely used intensity scales such as the Saffir-Simpson scale are based on linear increments of wind speed. This single parameter linear-scaling masks the true destructive energy, which follows a logarithmic or power-law curve (Powell and Reinhold 2007), such that a Category 5 storm is 500-times more destructive than a Category 1 (Pielke, et al 2008, Stewart 2007). Also, defining the intensity primarily in terms of wind speed does not necessarily convey the potential for storm surge. Hurricane Katrina, one of the most destructive storms on record with a disaster zone covering some 230,000 square kilometers, technically made landfall as only a Category 3 storm. Recently proposed intensity models consider the total energy in the storm; such models may eventually form the basis of revised category scaling. A self-similar scaling property based on fractals has been proposed by Barton and Nishenko (1997) that more accurately estimates the rate of occurrence and damage-consequence of extreme tropical cyclones.
Officially-defined flood elevations in North America are set by regulatory agencies, and in the past have been defined by the 1% recurrence probability, which is significantly lower than the historical maximum. For example, Hurricane Camille produced a 7m storm surge in 1969, but afterward the revised flood elevation for that area of Mississippi was set at only 3.7m. Thirty-six years later Hurricane Katrina produced a 9.0m surge in the same location. Despite these two very large and destructive storm surge events on record in the same locale, the current official flood elevations have typically been set at only 6.0m, a full three meters short of the recorded surge. Moreover, tropical cyclone risk analysis has sometimes neglected the most severe historical storms as ’outliers’ (Seed, et al. 2006). Barton and Nishenko (1997) have shown that so-called outliers must be considered in analysis because their damage-consequence is so great.

2 STRUCTURAL ACTIONS

A tropical cyclone produces an array of structural actions including wind and storm surge; the latter producing hydrodynamic and hydrostatic pressure, buoyancy, debris impact, and erosion. Important actions that affect the structure before the storm are decay and corrosion, mortar deterioration, foundation movement, etc. Each action has its own distinct character and effects.

2.1 Wind

Wind is the most often accounted for and well-studied of the tropical cyclone actions. The structural analysis for severe winds is established by standards of practice and building codes. Tropical cyclones become structurally damaging to buildings when their winds approach 180 km/h (100 mph). Many traditional structures can survive this level of wind force with moderate retrofitting, which is relatively straightforward. In North America, the wind speed used in design is the highest wind speed probability in a 50-year recurrence. However, these code-prescribed wind forces are much less than what can actually occur in a major storm, where the maximum sustained winds can reach 340 km/h (213 mph). Tornados are often generated in tropical cyclones, with winds reaching 500 km/h. These are not accounted for in ordinary wind-load calculations. (Sparks 2010)
2.2 Hydrostatic Forces

The rate of water-level rise is also an important consideration, especially in estimating lateral hydrostatic and buoyancy forces. Slow-rising water allows hydrostatic forces to equilibrate (water can flow through doors and windows). In Hurricane Rita the maximum rate of water-level rise was approximately 2m/h (McGee et al. 2006). This rate can be accommodated by small floor or wall vents to minimize hydrostatic loading. Buoyancy forces can easily lift a single story wood-framed house from its foundation if it is not properly anchored.

2.3 Storm Surge

Storm surge is the rise in water level caused principally by the wind, with a secondary effect from the low central pressure of the storm. Despite its role as the most damaging and lethal action in tropical cyclones, there is a lack of comprehensive analysis and design procedures for storm surge, even for new structures (Kallaby 2007). In the US, FEMA publishes guidance for storm surge resistance (FEMA 55).

Most storm surge data come from computer models that estimate depth of inundation, not flow velocity. The US agency FEMA uses the SLOSH computer program for large-scale simulation of storm surge. Another promising method has recently been introduced by Ward (2009) using a novel ‘tsunami ball’ approach that is more robust and intuitive than SLOSH and other finite difference/finite element models.

Perhaps the most useful approach for a first approximation for surge depth is the simple estimation formula recommended by Hsu (2006), in which the storm surge is proportional to the central pressure, orientation of the track of the storm, and local bathymetry (shoaling factor). The rapid estimation technique presented can be of great value to those areas with limited access to sophisticated models, and can be adapted for a specific location. Shoaling factor can be estimated from historical data using the same equation, and central pressure is obtained from representative major storm data for the region.
Figure 3. A representative storm surge chart of depth vs time. Onset time is on the order of several hours between the start of the surge and peak depth. Flow velocity is strongest during onset and less during retreat. (Kawata 2004). Peak wind generally precedes the peak surge values by about one hour. (White 2006).

Very little actual surge velocity data has ever been published, and despite attempts by researchers, no data was gathered from Katrina (White et al. 2006). FEMA 55 suggests that surge velocity can be calculated from:

\[ V = \frac{d_s}{t} \] (lower bound) \hspace{1cm} \text{or} \hspace{1cm} \[ V = \left( g d_s \right)^{\frac{1}{2}} \] (upper bound)

where \( d_s \) is the design still-water flood depth, \( t \) is time (1 second), and \( g \) is the gravitational constant (9.8 m/s²). These formulas are based on shallow-water wave theory and do not take into account the details of the site or attenuating effects of obstacles. There is to date no data or fine-scale simulation for surge-structure interaction with which to verify these formulas. It is worthwhile to note that the behavior of coastal storm surge (wind driven) is fundamentally distinct from riverine flooding (gravity driven). For example riverine flood theory holds that obstructions such as buildings and embankments tend to increase flow velocities. It appears from field surveys that in coastal flooding the flow velocities decrease around obstacles due to attenuation of momentum and may not reaccelerate (see Shielding below). Fine-scale modeling in the future may allow studies of surge-structure interaction.

The effect of debris is to amplify the force of the storm surge, both in steady-state by presenting a large tributary area to capture the current, and by producing an impact force. Potential debris includes other buildings, harbor structures, vessels, shipping containers, and trees. Understanding the sources of debris is important in assessing survivability.
Figure 4. The core of this landmark 1840s timber frame house in Mississippi survived Katrina’s storm surge. It is an excellent example of the intrinsic cyclone resistive nature of tradition buildings. Some features include elevated first floor, massive piers, with brick shear walls oriented toward the sea, hipped roof, and timber-frame joinery. During restoration, sensitive retrofit techniques were used to improve future performance.

3 OBSERVED BEHAVIOR

The following are observations about the actual structural behavior of traditional buildings in severe storms. Figure 4 shows an example of a landmark building that barely survived Katrina, and is instructive regarding cyclone-resistive features, including timber joinery, elevation above the ground, and shear resistance of the foundation. Other examples are given below.

3.1 Concentration of mass over the footprint

The vertical massing of a structure is perhaps the single strongest predictor of its survivability in storm surge (Sparks 2010). Tall, heavy buildings survive more readily than short, light structures. This is true for both framed and unreinforced masonry structures. Even heavy pre-cast bridge spans were displaced because they have a flat shape like a wing. This is because of the hydrodynamic character of storm surge: to lift flat objects and float light-weight ones.

This phenomenon was observed over and over again in various disasters, and also in the historical record. Figure 5 shows a series of photos illustrating the effect of concentration of mass in storm surge survival.
Figure 5. Two series of photos illustrate the concentration-of-mass effect. The upper row shows, starting at the left, a modern concrete bridge completely destroyed, a two-story house surviving amid a debris field of one-story houses, and two masonry buildings remaining on a beach where shorter, lighter buildings were destroyed. Similarly, the second row looks at buildings from past events: a lone house standing in Galveston 1900, a multi-story masonry building after Camille 1969, and a church with surviving tower adjacent to a collapsed on-story wall in Galveston.

Chimneys can also serve to anchor buildings and prevent their displacement. Being unreinforced, it was simply the concentration of mass that resisted the storm surge. The bases of large chimneys may have failed in shear, but still the wood-framed buildings remained more or less in place (see Figure 6).

Figure 6. The concentration of mass in the unreinforced chimney helped keep this listed building in Mississippi from being completely destroyed. It was stabilized and restored.
3.2 Continuity

Timber-frame buildings perform well due to continuous members with few splices. Similarly, balloon framing perform better than platform framing\(^1\) in two and three story buildings, due to the continuity of vertical members across the floor line.

![Figure 7. At left, the top story of a collapsed platform-framed house after Katrina; at right, the ductile behavior of a balloon-framed house, Galveston 1900 (photo from Rosenberg Archives)](image)

3.3 Connectivity

Of course, basic connectivity is essential for survival in an extreme event. Traditional timber frame construction uses joinery techniques that provide good resistance to wind forces. Even in storm surge, timber framed buildings perform better than light-framed buildings due largely to connectivity (joint tying). In previously retrofitted constructions, bolted connections outperformed nailed connections. In general, light-gage-metal wood connectors did not perform well.

![Figure 8. This architectural landmark in Galveston, Texas survived the Great Storm of 1900 which destroyed much of the island. By the year 2007 it had developed severe distress in the upper walls and was retrofitted with steel tie-rods just below the roof level. It subsequently survived Hurricane Ike in 2008.](image)

\(^1\) In platform framing, the vertical members stop at the floor line. In balloon framing, the vertical members are continuous across the floor line.
Figure 9. A nineteenth century bank building survived many storms including the immensely strong Camille in 1969. At some point in its history, the building was retrofitted with tie rods at the second floor level, which helped it avoid complete destruction in the storm surge of Katrina in 2005.

3.4 Walls and roofs

Diagonal sheathing and hip roofs perform well, provided overall stiffness to the structure and in many cases were the final line of resistance to collapse.

3.5 Deterioration

The climate in tropical cyclone prone areas is generally hot-humid with low-lying terrain and a corrosive marine atmosphere. The risk of pre-storm decay is also influenced by socio-economic conditions (inability to make repairs) and micro climate (e.g. prevailing breeze, tree cover, etc.) Obviously, decay and corrosion dramatically reduce resistance, in particular connection strength.

3.6 Foundations

Typical of coastal construction, structures may have post-in-ground, pier-and-beam, or masonry foundations. If the local soils have good bearing and are not expansive, pre-storm foundation damage will be minimal. Unfortunately, stable soils lead to shallower foundations, susceptible to scour and overturning of piers.

Figure 10. Typical shallow brick footing in historic Gulf Coast construction.
On the other hand, in the older constructions, piers were often more massive and their sections were aligned with the storm surge, suggesting a cultural experience with storm behavior.

In the US, FEMA prohibits continuous or enclosed foundation walls. This is because of the higher load transfer to the structure, and because continuous foundations walls are vulnerable to undermining by erosion where storm surge velocities are high. However, many heritage buildings have continuous or enclosed-wall foundations walls and have survived multiple storm surge events, apparently due to attenuation of the energy of the moving water, reducing the hydrodynamic force transferred to the floor structure and interior piers.

3.7 Diaphragms

Lowest-floor diaphragms are often not considered especially important structurally; the emphasis is usually the upper floors and roof. However, in storm surge, the lowest-level floors become structurally significant in several ways: resisting radial compression, tying the walls together, bracing the interior cross walls. Where floor diaphragm float up, the walls move either inward or outward, and with the loss of the floor diaphragm, the buildings warp and may be destroyed. Where the floors remain intact, the building has a higher chance of survival.

Figure 11. Despite heavy damage to this floor diaphragm in an 1840s timber frame house, there was sufficient attachment remaining at the exterior walls to keep the building from being destroyed. It was eventually rehabilitated.

3.8 Interior cross walls

The presence of interior cross walls is always correlated with improved performance in tropical cyclones, even if they are oriented perpendicular to the direction of the wind and surge. There are several reasons for this. The provide shear capacity when oriented in-line with the flow, and resist secondary buckling when oriented perpendicular.
Figure 1. Built in 1795, this French colonial building survived Katrina storm surge due to its mass (two-stories in the rear) and substantial cross-walls.

3.9 Protective Civil Works

Natural and constructed shore features can provide significant attenuation to the energy of the storm surge. Such natural features include barrier islands, reefs, and wetlands. Manmade seawalls, breakwaters, submerged breakwaters, artificial reefs, and sandy beaches can reduce wave forces and greatly improve survivability. In Japan, these kinds of measures were introduced after 1956 and have greatly reduced damages from tsunamis and storm surge (Kawata 2004). The 2011 tsunami, however, overtopped the barriers with its 30-ft (10m) wave.

The island of Galveston, Texas is an example of large-scale response to the near total destruction of the city in the 1900 storm. Determined to protect itself from future devastation, the city of Galveston constructed a sea wall approximately 17 feet (5.2 m) high which is now over 16 km long. Dredged sand was used to raise the city of Galveston by as much as 17 feet (5.2 m) above its previous elevation. Over 2,100 buildings were raised in the process,(35) including masonry churches weighing as much as 3,000-tonnes.

Figure 12. Hydraulic dredging was used in Galveston after the 1900 storm to raise elevation of the entire city behind the new sea wall. Every remaining structure was raised accordingly.
3.10 Shielding by seaward structures:

Structures that remain intact and do not become part of the debris field serve to attenuate the energy of the moving water, protecting other structures in their shadow. This shielding effect is similar to the shielding from wind that is provided by adjacent structures. However, in the case of storm surge, the forces are much higher and there is greater risk that the most seaward structures will be heavily damaged or destroyed. Usually some of the seaward buildings are destroyed and become moving debris, causing severe damage to the buildings behind them. If however, the seaward building stock remains intact, then the shielding effect will offer protection to the buildings behind. This suggests that new seaward structures can be designed to fully resist storm surge, thereby providing a protective shadow to more vulnerable heritage structures. New constructions of reinforced concrete as little as three stories in height can resist storm surge. (Sparks 2010)

4 VULNERABILITY INDICATORS

Findings from field observations suggest the possibility of a simple set of vulnerability indicators to form a qualitative index for use by owners, engineers, and building authorities in rapid assessment of cyclone risk (Sparks 2010). The following relative scoring system in Table 1 is suggested as a qualitative measure of cyclone vulnerability, using ‘macro’ indicators including the number of stories, wall type, etc, which generally can be determined without detailed analysis.

Such indicators can be useful in identifying and monitoring vulnerability, for developing an improved understanding of the contributing factors, for prioritizing strategies to reduce vulnerability, and for measuring the effectiveness of those strategies.

While it would be possible to assign numerical weights to each category and combine the scores into a single aggregate index, such an index may obscure detail and group together structures with dissimilar risks.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>More Vulnerable</th>
<th>Less Vulnerable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stories</td>
<td>1 story</td>
<td>2 story</td>
</tr>
<tr>
<td>Cross-walls</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Wall thickness</td>
<td>300mm</td>
<td>400mm</td>
</tr>
<tr>
<td>Wall Framing</td>
<td>Platform</td>
<td>Balloon</td>
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<tr>
<td>Sheathing</td>
<td>Lap siding only</td>
<td>Horizontal boards</td>
</tr>
<tr>
<td>Vertical ties</td>
<td>None</td>
<td>Foundation</td>
</tr>
<tr>
<td>Wall-to-floor ties</td>
<td>None</td>
<td>Some</td>
</tr>
<tr>
<td>Elevation</td>
<td>&lt; 4m</td>
<td>4m – 7m</td>
</tr>
<tr>
<td>Enclosed foundation</td>
<td>Slenderness &gt;3.0</td>
<td>2.5&lt;Slenderness&lt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~</td>
</tr>
<tr>
<td>Seaward structures</td>
<td>Weak</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 1. Vulnerability Indicators (Sparks 2010)
5 CONCLUSIONS

We must be serious in our approach to evaluating and retrofitting historic structures to survive tropical cyclones. Accurate assessment of risk depends on historical records as well as good models for prediction of recurrence and estimation of destructive power.

Despite their lack of conformance with modern standards, traditional constructions have survived tropical cyclones at least as well as newer buildings. Features of traditional construction that increase survival have been identified, and a set of relative vulnerability indicators is suggested.

The findings of extensive field surveys and rehabilitation designs suggests the following structural survival model:

1. Assure connectivity from the footings to the roof
2. Assure lateral connectivity
3. Engage as much mass as possible
4. Keep the structure from becoming debris
5. Make seaward structures strong
6. Attenuate the energy of the moving water.

Raising the foundation and strengthening buildings can be appropriate responses, and interventions must be sensitive to historic fabric and character defining features. Shielding of heritage structures with new appropriately designed seaward constructions should also be considered.

REFERENCES


