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Improving Hurricane Survivability of Heritage Structures

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Abstract Worldwide, hurricanes or tropical cyclones cause immense damage and loss of life, yet we do not have a clear set of guidelines for improving the survivability of heritage structures. This paper synthesizes lessons learned in practice regarding appropriate assessment with discussion of vulnerability indicators, wind and storm surge forces and retrofit approaches

Keywords: Hurricane, tropical cyclone, cyclonic storm, vulnerability, retrofit, mitigation, heritage structure

Introduction

Traditional structures often constitute a large part of the existing building stock in the areas most vulnerable to hurricanes. These structures, their damage, and their survival present a body of knowledge to inform current understanding of hurricane performance and to find ways to improve survivability while respecting the historic fabric.

This paper attempts a synthesis of the author's experiences in disaster recovery and rebuilding following major hurricanes Ivan, Katrina, and Ike in the U.S., including the systematic triage of hundreds of traditional buildings on the Mississippi Gulf Coast. The opinions in this paper are based on visual observations and engineering judgment, rather than quantitative analysis. Nevertheless, it is possible to suggest broadly applicable conclusions regarding heritage building behavior and improvements to survivability during major hurricanes.

Destructive Energy and Risk Analysis

Hurricanes, also called tropical cyclones or typhoons are large scale cyclonic storms that form over warm oceans. They are capable of producing massive destruction in low lying coastal areas. To improve survivability, an accurate assessment of local risk is needed, and this depends on historical records as well as good models for prediction.

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 orders of magnitude more destructive than a Category 1. 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.

Officially-defined flood (storm surge) elevations in North America are set at 1% recurrence, which is usually significantly lower than the historical maximum. For example, Hurricane Camille produced a 7.0m 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 9.2m surge in the same location. Even after the devastation of Katrina, official flood elevations were typically set at only 6.0m. Moreover, hurricane risk analysis has in the past neglected the most severe historical storms as 'outliers' (Seed, et al. 2006). To address this problem, Barton and Nishenko (1997) have identified a self-similar scaling property based on fractals that more accurately estimates the rate of occurrence and damage-consequence of extreme hurricanes, which is essential for developing rational intervention strategies.

Post-Storm Stabilization

One important aspect of structural survivability is the critical period immediately following the storm when it is essential to evaluate damaged buildings and to make recommendations regarding how to move forward with stabilization. After a major hurricane, temporary shoring is essential. Buildings that are stabilized immediately will have a much greater chance of long-term survival. Unfortunately, the resources needed to accomplish stabilization may not be available except on a small scale, and may not become available for more than a year or two. Damage assessment and stabilization after Hurricane Katrina are discussed in Sparks (2007).

Observed Behavior

Heritage buildings perform as well as many modern constructions subjected to the same conditions. Some of the author's key observations of behavior from the field are presented here.

Concentration of Mass over theFootprint: The vertical massing of a structure is perhaps the single strongest predictor of its survivability. Tall, heavy buildings survive more readily than short, light structures. Even heavy pre-cast bridge spans were displaced because of their broad, flat shape. In hydrodynamic loading this is precisely the behavior we would expect. Chimneys also served to anchor many structures 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.

Continuity: Balloon framing performed better than platform framing due to the continuity of vertical members across the floor line in two and three story buildings. Similarly, timber-frame buildings performed well due to continuous members with few splices.

Connectivity: Of course, basic connectivity is essential for survival in any extreme event.

Traditional timber frame construction uses joinery techniques that provide good resistance to wind forces. Even in storm surge, timber-framed buildings performed 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.

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

Decay: The climate in hurricane 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 (inabilitiy to make repairs) and micro climate (e.g. prevailing breeze, tree cover, etc.) Obvioulsy, decay and corrosion dramatically reduce resistance, in particular connection strength.

Foundations: Generally, most traditional buildings have shallow foundations. If the local soils have good bearing and are not expansive, then pre-storm foundation damage will be minimal. Unfortunately, stable soils lead to shallower foundations, which are susceptible to erosion. Typical of coastal construction, structures may have post-in-ground, pier-and-beam, or masonry foundations.

In the US, FEMA prohibits continuous or enclosed foundation walls. This is because of the higher load transfer to the structure, and because continuous foundation walls are vulnerable to undermining by erosion where storm surge velocities are high. However, many heritage buildings have continuous or enclosed-wall foundation 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.

Diaphragms: Lowest-floor diaphragms are often not considered especially important stucturally; 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, supporting the interior cross walls. Where floor diaphragms floated up, the walls moved either inward or outward, and with the loss of the floor diaphragm, the buildings warped or were destroyed. Where the floors remained intact, the buildings had a higher survival rate.

Interior Cross Walls: The presence of interior cross walls is always correlated with improved performance in hurricanes, even if they are oriented perpendicular to the direction of the wind and surge. There are several reasons for this. They provide shear capacity when oriented in-line with the flow, and resist secondary buckling of the main walls when oriented perpendicular.

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. So, if the seaward buildings remain intact, then the shielding effect is positive. If however, some of the buildings are destroyed and become floating debris, then the effect is worse than direct exposure to storm surge.

Vulnerability Indicators

These 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. 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. The following relative scoring system is suggested as a qualitative measure of vulnerabililty. 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 1: Relative Vulnerability Indicators

	More Vulnerable	→	*Less Vulnerable*
Stories	1 story	2 story	3 or more
Cross-walls	None	Some	Many
Wall thickness	300mm	400mm	500mm +
Wall Framing	Platform	Balloon	Timber-frame
Sheathing	Lap siding only	Horizontal boards	Diagonal boards
Vertical ties	None	Foundation	Foundation & Roof
Wall-to-floor ties	None	Some	All levels
Elevation	< 4m	4m – 7m	> 7m
Enclosed foundation	Slenderness >3.0	2.5<Slenderness<3.0	Slenderness<2.5
Seaward structures	Weak	None	Large & Strong

Structural Actions

A hurricane 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, foundation movement, etc.

Wind: Wind is the most often accounted for and well-studied of the hurricane actions. The structural analysis for severe winds is established by standards of practice and building codes. These storms become structurally damaging to buildings when their winds are above about 180 km/h (100 mph). Many traditional structures can survive the code-prescribed wind forces 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 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 hurricanes, with winds reaching 500 km/h. These are not accounted for in ordinary wind load calculations.

Storm Surge: Despite its role as the most damaging action in hurricanes, there is a lack of comprehensive procedures to address analysis and design for storm surge, even for new structures (Kallaby 2007). In the US, FEMA publishes guidance for storm surge resistance (FEMA 55). 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 is the a simple surge 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.

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 accomodated by small floor or wall vents.

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:

$$V = d_s / t \text{ (lower bound)} \quad \text{or} \quad V = (g d_s)^{1/2} \text{ (upper bound)}$$

where d_s is the design still-water flood depth, t is time (1 second), and g is the gravitational constant (9.8 m/s^2). 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. The behavior of coastal storm surge (wind driven) is fundamentally distinct from riverine flooding (gravity driven). For example riverine flood theory holds that obstacles such as buildings and embankments increase flood velocities. It is clear, however, from field observations that in coastal flooding, flow velocities decrease around obstacles due to attenuation of momentum, and that the flows do not reaccelerate (see *Shielding* below). Fine-scale modeling in the future may allow studies of surge-structure interaction.

Debris: 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 as impact. Potential debris includes other buildings, harbor structures, vessels, shipping containers, trees. Understanding the sources of debris is important in assessing survivability.

Methods of Intervention

It is possible for a traditional structure to be strengthened to survive the actions of a major hurricane. The goal of any intervention should be to improve survivability without harming the historic character. The engineer should prioritize interventions based on relative vulnerability in the context of extrinsic risk. Three types of intervention are: *Raising*, *Strengthening*, and *Shielding*.

Raising: Raising (lifting or elevating) a building to a higher elevation definitively improves survivability, but only if the substructure is adequately designed and constructed to resist storm surge. Structural moving contractors are readily able to lift structures that have been displaced from their foundations, and raise buildings to higher elevation onto new foundations. For example, the response to the Galveston Storm of 1900 was to raise thousands of the surviving buildings, even very large masonry buildings, onto new foundations. After Katrina, some houses were raised onto new foundations at higher elevations, typically one to three meters higher than before the storm.

Strengthening: Strengthening is by far the most reasonable choice for many structures. Structures with even basic connectivity and continuity survive better than those without, so hurricane strengthening often consists primarily of establishing a comprehensive system of connections throughout the building.

Vertical Tying: Assure connectivity from the footings to the roof. Threaded steel rods can be used inside wood-framed walls. In masonry buidings, roof hold downs must engage sufficient mass of masonry for ballast against uplift.

Lateral Tying: Assure connectivity at walls-to-floors and walls-to-roof. Tying floors to walls can be accomlished satisfactorily in masonry buildings with with simple bolting and exposed end plates.

Foundations: Foundations perform a range of functions in hurricane resistance: base shear resistance, anchorage and ballast against overturning and flotation, confinement against lateral forces, and attenuation of moving water. The judicious use of concrete can create tying between piers, provide ballast, and prevent erosion.

Timber post foundations are subject to decay at ground level, the most critical location. Laterally bracing is generally recommend between posts.

Erosion barriers: Erosion barriers may be needed for buildings that are close to the shore, on sandy soil, or on steeper slopes. Such barriers can be constructed by excavating a trench along the vulnerable sides of the building and casting a lightly-reinforced concrete wall below ground.

Masonry walls: Slender masonry walls may require direct strenghtening for flexural resistance. Modest interior framing can sometimes be added without adversely affecting the historic character.

Wood framed walls: Shear resistance of wood-clad exterior walls can be improved by re-fastening the cladding properly. Interior cross walls may lack positive connection to the exterior walls and to floor framing; establishing these connections is usally straightford. Damaged historic plaster can be reconstituted easily.

Durability: Design practice must consider the effects of future decay and corrosion on survival. To achieve long-term performance, new materials used in strengthening must have long-term durability. In warm marine climates, the ambient conditions can cause corrosion and decay, even at interior details, so lumber must be durable and fasteners must be corrosion resistant. The use of hot dip galvanized and stainless steel fittings and fasteners is preferred. Fasteners in wood connections should be kept as far away from the ends of members as possible.

In most concrete for footings, erosion barriers, etc. the reinforcement requirements for strength are often minimal. Use the minimum reinforcement necessary due to the life-limiting nature of steel reinforcement. Galvanized wire is a good choice for convenience and durability, and for important work, stainless steel wire should be considered. Plain steel and ordinary zinc-coatings are not durable enough for heritage buildings. Stainless steel should be used for nails and screws in exposed conditions, galvanized in interior conditions. Bolts and lag screws should be hot-dip galvanized if used in accessible connections, stainless if inaccessible. Embedded anchors into masonry should be stainless; hot-dip galvanized if removable. Unfortunately, these durable materials are expensive and they may not available in developing countries. Furthermore, after a disaster they may be even harder to obtain. It is important to consider what materials are available before designing the repairs.

Bolted connections are more robust, more durable, and more easily replaced than nailed connections. So where possible, detailing should emphasize the use of bolts, then screws, and lastly nails, especially if the available fasteners are not durable.

Shielding: Finally, it is worth discussing briefly the important but overlooked concept of shielding. Sea walls have traditionally been built on coastlines to protect from surge. But strong buildings can offer much the same benefit. There is often resistance to the construction of modern buildings on coastlines in heritage areas because they are not aesthetically compatible, obstruct the view of the ocean, and may affect the socio-economic makeup of the community. However, new seaward structures can be designed to fully resist storm surge, thereby providing a protective shadow to more vulnerable heritage structures. This idea leads to a globalized design philosophy where individual structures are seen as part of a system, and their design is intended to limit damage to the system, not just themselves. New constructions of reinforced concrete with as little as three stories in height can resist storm surge.

Summary

We must be serious in our approach to evaluating and retrofitting historic structures to survive hurricanes. 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 hurricanes 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.

Storm surge is the least understood but most damaging action of hurricanes. More robust and fine-scale modeling methods are needed, as well as simple estimations for assessment purposes.

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.

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