Hurricane Resilient Design:

For Multifamily Residential High-rises in Hawaii

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Abstract

The problem motivating this research is the author's belief that residential high-rise building's vulnerability to hurricanes is not being addressed. Therefore, the general idea behind the research is to find out where those vulnerabilities are by looking at hurricanes science, significant historical hurricane events, building failures, building codes, and building guidelines.

From the information gathered the author will propose mitigation strategies that when implemented respond to these vulnerabilities. Then using a theoretical case study location on the south shore of Oahu, Hawaii, to show how the mitigation strategies can be employed to protect those living in the coastal areas.

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Chapter 1. Introduction

"Currently 85% of the world's population lives in coastal cities."[1] One of the major disadvantages in some coastal areas is the threat of tropical cyclones commonly known as hurricanes. Even though this threat is present, we design high-rise residential buildings to withstand only low category hurricanes, which leave occupants at risk during and following a storm.

For those living in Hawaii, this can be especially problematic being isolated by the Pacific Ocean. Following a major hurricane, people have nowhere to go when their homes are destroyed by a hurricane. It can take an estimated two weeks for aid to arrive in the islands.[2] This leaves the people of Hawaii more vulnerable than those in the mainland. Following a hurricane people can no longer stay in emergency shelters forcing them to return to their homes. Often homes have no power, water, or sewage these systems in most cases can be repaired quickly in single family homes. However, this can cause problems for those living in multifamily residential high-rises, because many of these system rooms can become inundated which can require major repairs. This leaves these individuals at a higher risk post-hurricane that those living in single family homes, creating a need to develop design guidelines for how multifamily high-rise buildings.

Creating emergency shelters may appear to be a minor issue. However, it is important to look at the broader context of the effect of a hurricane on Oahu. Consider if a category five hurricane made landfall in Urban Honolulu CDP. According to the 2010 census data, there are approximately 345,610 people[3] that live in Urban Honolulu CDP. Along with the 345,610 there are a large number of tourists that visit the island daily. Waikiki averages 72,000 visitors per day. Including tourists in Waikiki the population increased to roughly 415,000 people

[1] Washburn, *The nature of urban design, 3*
[2] "Central Pacific Hurricane Center - Honolulu, Hawai`i.", accessed May 5, 2014
[3] "2010 Census Interactive Population Search.", accessed April 18, 2014

in this one area of Oahu. With the majority of the population located in the tsunami evacuation zone, which is similar to the coastal floodplain which is the same area that would be affected by hurricane inundation from storm surge.

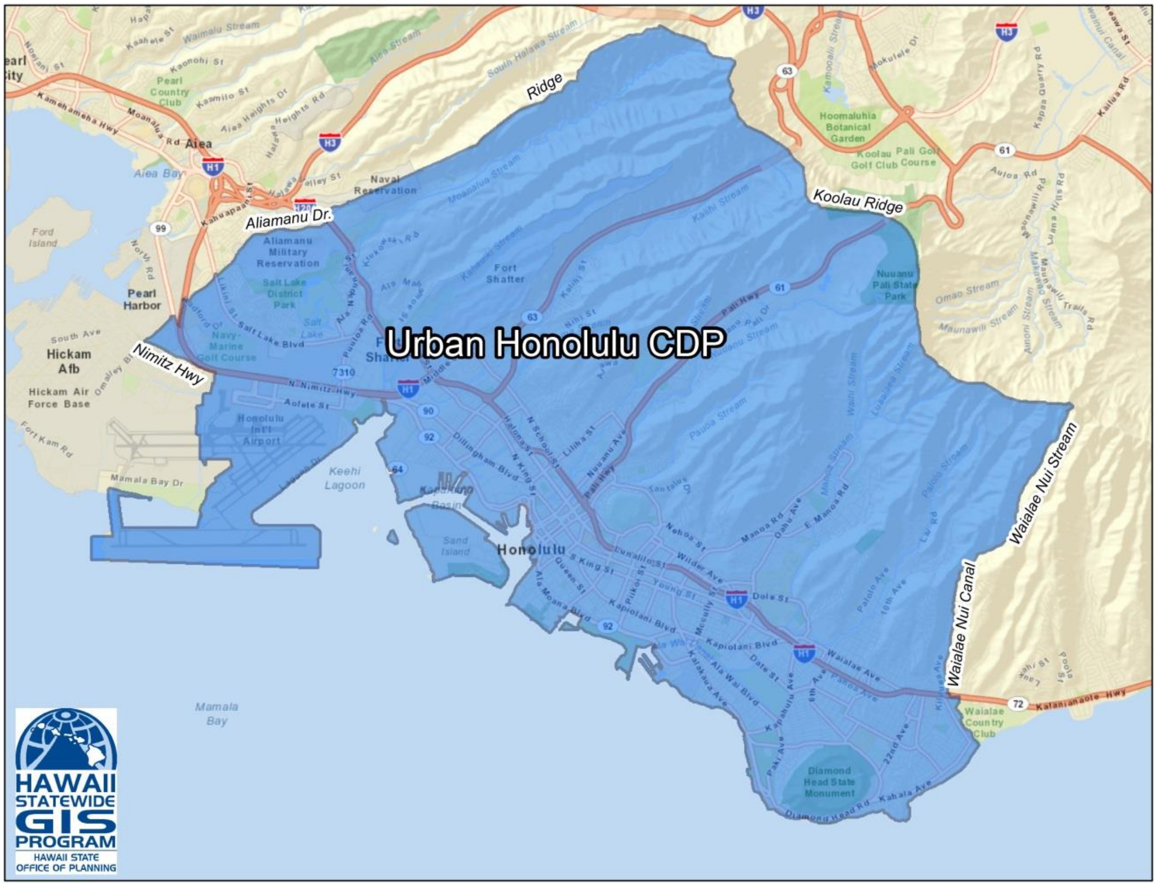

Figure 1 Honolulu CDP Source
http://files.hawaii.gov/dbedt/op/gis/maps/2010_cdp_urban-honolulu.pdf

The wastewater treatment extremely damaged and rendered out of service. The Honolulu Power Plant would also likely be damaged causing a loss of power throughout the region. Then storm drains would probably back flow, causing inflow to sewage collections resulting in sewage to backup and spill into the streets spreading diseases and inundating and contaminating potable water sources. Water and electrical systems in buildings along the coastline (e.g. Waikiki, Ward, Ala Moana, and Kakaako) would experience damage. Windows would be shattered leaving the interior of buildings exposed to rain and high winds. Buildings with water damage begin to mold[4]. These combined effects would render buildings throughout the Urban Honolulu CDP uninhabitable.

Such a storm might displace 50% of the 415,000 occupants, leaving 207,500 without a home. According to FEMA sheltering standards, there should be at least 20 square feet per[5] person in a shelter or 4,150,000 square feet. This is only about 1/3 of the population of Oahu. If the storm were of the same size as Hurricane Sandy (1000 miles wide[6]), it would impact the entire island.

As an alternative to current development, it would mandate that development happen away from the coastline. However, this is not a solution to the problem. The ocean environment brings tourist and is one of the primary economic drivers. People have always and will always desire to live by the ocean despite the potential hazards.

The goal of this research is to discover typical high-rise building failures during a hurricane and, then to develop guidelines to help a building to resist a Category Five hurricane's destructive force. In order to understand the threat of hurricanes residential high-rise buildings, the research will first look at the science of hurricanes, followed by major historical hurricanes, and finally current building practices, codes, and guidelines. The information gathered will then be used to develop mitigation strategies to help a residential high-rise function during and following a hurricane, allowing residents to shelter in place.

By first examining the science of hurricanes we can gain an understanding of how they form, their structure, and the hazards generally associated with them. This information helps give a better understanding of how hurricane forces caused the building failures recorded in the historical hurricanes section.

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[4] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[5] FEMA 361, 3-19
[6] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance ,2013.

In the historical hurricanes section three storms will be studied: Hurricane Iniki (Kauai, HI), the most recent and one of the most deviating hurricanes to strike Hawaii; Hurricane Katrina (Gulf Coast), considered to be one of the United States worst hurricanes. Much of the way we address hurricane preparedness has been based on the devastating effects of Katrina. This will help to create a clearer picture of what is still necessary. Lastly, Hurricane Sandy (New York/ New Jersey) because of the size and one of the only hurricanes to affect areas of extreme density of high-rises. Along with this was the fact that NYC was in the process of preparing New York for climate change and, much of their efforts helped prepare the city for the effects of Sandy. All general information gathered about these storms will come from the FEMA Mitigation Assessment Team Reports. FEMA sends out multidisciplinary teams to investigate failures and success in buildings and infrastructure following the storm. The teams are made up of experts in architecture, engineering, disaster management, planning, and hurricane science and gather based upon all their fields. They can give a broad concise, factual view on the effects of the hurricane on the built environment. The information collected is then used to help shape future planning and building regulations. The information collected will show some current causes of building failures that render them uninhabitable.

The section following the historical hurricane section will research current building codes that address hurricane hazards. Helping to show current gaps between existing building design and hurricane resilience. This information will be used to help to formulate mitigation strategies to respond to this gap.

To supplement the review of current building codes will be a section dedicated to guidelines and best practices. FEMA has released many guidelines for helping the general public design structures to perform better against natural disasters. These guidelines focus on single family homes and emergency shelters. Leaving large groups of people living in high-rise multifamily residential buildings and hotels at risk. The information gathered will be adapted to help develop mitigation strategies for residential high-rises.

This research will then look at potential mitigation techniques for multifamily residential high-rises that respond to the hazards of hurricanes. After giving a brief description of these techniques, a theoretical design will be used to show how these techniques can be implemented in a community to help create resilience.

Chapter 2. Research Methodology:

The nature of this project is twofold. The first is for the pursuit of knowledge about hurricanes and how architecture can be designed to mitigate the hazards and damage caused by hurricanes. The second is to formulate mitigation strategies the help to mitigate the dangers of a hurricane.

For this pursuit of knowledge about hurricanes, information will be collected from various sources. Methods include Interpretive-Historical Research and Experimental Research which will also include Simulation and Model Research.

The initial research seeks to understand the nature of hurricanes, and to document the effects of hurricanes in the United States, paying close attention to major storms on the mainland and Hawaii. Following this data and information will be presented on current building codes and their relation to hurricane response. Finally, a list of potential mitigation strategies and how they can be applied, to help shape the way we design for coastal communities.

The action plan and topic breakdown for this project are as follows:

1. Hurricane science
2. Historical hurricane information
3. Building Codes and Standards
4. Beyond Code and FEMA Guidelines
5. Context

Chapter 3. Hurricane Science

Meteorology can now predict the formation and monitor hurricanes throughout the world. Early warning has sometimes given people a chance to escape the dangerous effects of storms. Hurricane science has progressed since 1900 when a hurricane struck Galveston, TX without warning killing 8,000-12,000 people[7]. However, the disconnect between the progression of hurricane science and the progression of hurricane resilient design remains.

This separation often comes from a lack of understanding of what happens during a storm and the related hazards. Designers have been slow to respond or have only addressed hazard issues after a catastrophic event. Designers should actively seek a greater understanding of hurricane resilient design. Site analysis should extend beyond typical weather patterns.

This issue is becoming increasingly more important as we see the effects of climate change. S.C.B. Raper, states that, as climate change continues we will see an increase in hurricane frequency and increase in magnitude of these storms.[8] We are able to see this as we look at the sheer size of the last two "super storms" we have experienced throughout the world. Hurricane Sandy (New York)[9] and Hurricane Haiyan (Philippines)[10] both stood out because of the broad reach of the storms and the distance from one edge to the other. Both Sandy and Haiyan stretched over 1000 miles in diameter. Oahu is only 44 miles across at the widest point while the entire Hawaiian Island chain is 1500 miles long, if either of these storms made landfall in Hawaii it would cover the whole island chain.

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[7] "Hurricanes in History.", accessed May 5, 2014
[8] Raper, Climate and Sea Level Change, 209
[9] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013
[10] "Building Codes: They're Not Just Hot Air.", accessed May 5, 2014

Definition and Structure of a Hurricane

The word hurricane comes from the Mayan god Hunraken[11] and is used as a regional term to describe an intense tropical cyclone. A tropical cyclone is a non-frontal low-pressure system occurring over tropical waters with a cyclonic surface wind circulation.[12]

A low-pressure system is an area of a relative pressure minimum that has converging winds and rotates in the same direction as the earth. In the Northern Hemisphere, the winds rotate counterclockwise while they rotate clockwise in the Southern Hemisphere.[13] These winds create the cyclonic winds that form the cyclone as they converge.

The United States uses three different terms to describe tropical cyclones. The intensity of the winds within the storm is the basis for the terms they are tropical depression, tropical storm, and hurricane. A tropical depression is a cyclone where the winds are between 0 to 39 MPH and associated with an assigned number for the storm. A tropical storm has winds between 39 to 74 MPH and assigned a name. Lastly, a hurricane has winds greater than 74 MPH and is named then assigned a category based on its wind speed using the Saffir-Simpson Scale.[14]

The Saffir-Simpson Scale gives a hurricane a category 1 to 5 based on the sustained wind speed. The following chart shows the wind speeds based upon category.

[11] "Hurricanes Unleashing Natures Furry.", accessed May 5, 2014
[12] NDPTC, Hurriplan, 85
[13] "weather.com - Glossary - L .", accessed March 3, 2014
[14] NDPTC, Hurriplan, 90

Table 1 Saffir-Simpson Scale Source Michael Hill

SAFFIR-SIMPSON SCALE	
CATEGORY	SUSTAINED WIND SPEED IN MPH
1	74-95
2	96-110
3	111-129
4	130-156
5	157 OR HIGHER

Chart based upon information from NOAA's Hurricane Center.[15]

Hurricane Structure

A hurricane has three separate parts that make up the structure the eye, core, and rain bands. The following images show the three parts of the hurricanes structure:

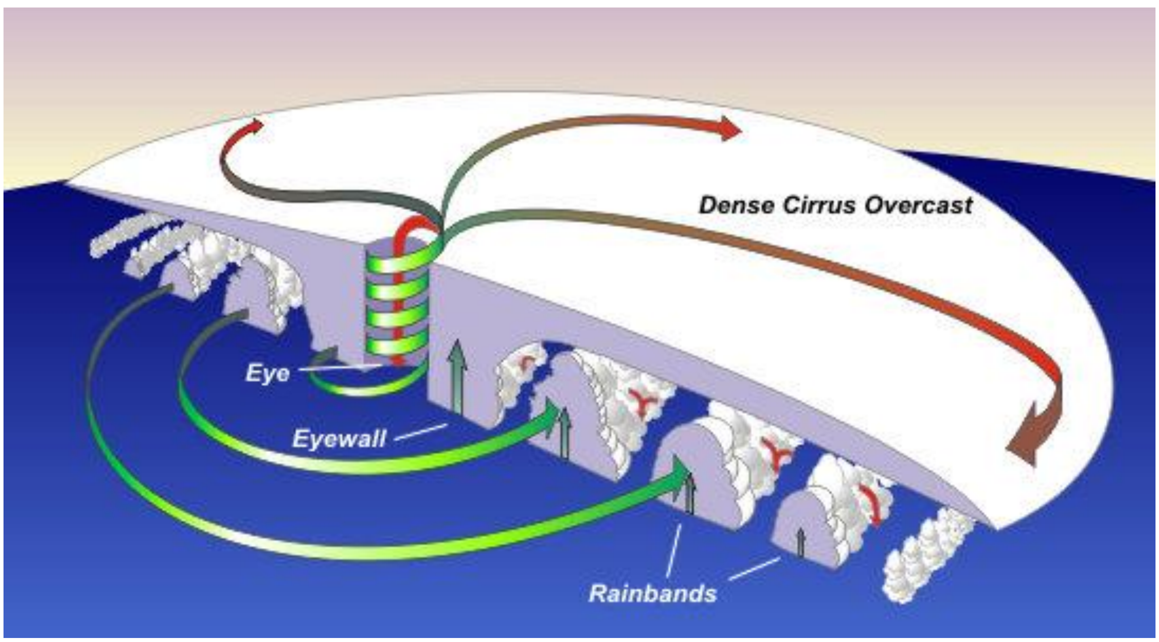

Figure 2 Structure of a Hurricane Source NOAA.gov

[15] "Central Pacific Hurricane Center - Honolulu, Hawai`i.", accessed May 5, 2014

The eye is the center of the cyclone and can be 20 to 40 miles in diameter. When we look at images of a hurricane's, the eye is extremely noticeable. The wind is minimal, and the weather is fair within the eye. The winds increase from the eye outward. [16]

The core (also known as eyewall or cloud wall) of the storm is the clouding area built of cumulonimbus clouds directly circling around the eye of the hurricane. The wall is formed by convection from the cyclone which pulls wind downward creating the eye. Along the eyewall, there is often the formation of tornadoes as the cyclonic forces of the wall act upon each other.[17]

The third and last part of the storms structure is the rain bands. These bands are where the highest winds and heaviest rains are located. The rain bands spiral outward from the center of the storm and gradually diminish in intensity as they move away from the hurricane's eye.[18]

Hurricane Formation

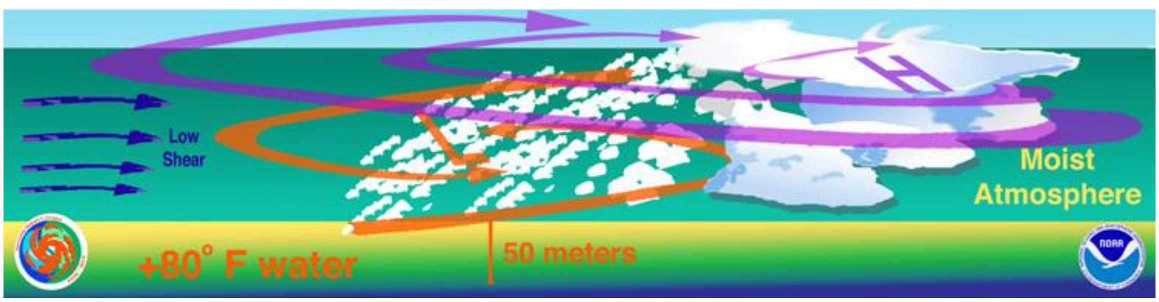

Figure 3 Formation Diagram from NOAA Hurricane Research Division Source NOAA.gov

There are certain conditions required for a tropical cyclone to form:

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[16] "Tropical Cyclone Structure." , accessed March 3, 2014
[17] Central Pacific Hurricane Center - Honolulu, Hawai`i.", accessed May 5, 2014
[18] "NOAA Jetstream"

1. Warm ocean waters (of at least 80°F) throughout a sufficient depth (unknown how deep, but at least on the order of 150 ft). Warm waters are necessary to fuel the heat engine of the tropical cyclone.
2. An atmosphere which cools fast enough with height such that it is potentially unstable to moist convection. It is the thunderstorm activity which allows the heat stored in the ocean waters to be liberated for the tropical cyclone development.
3. Relatively moist layers near the mid-troposphere (3 mi). Dry mid-levels are not conducive for allowing the continuing development of widespread thunderstorm activity.
4. A minimum distance of at least 300 mi from the equator. For tropical cyclogenesis to occur, there is a requirement for non-negligible amounts of the Coriolis force to provide for near gradient wind balance to occur. Without the Coriolis force, the low pressure of the disturbance cannot be maintained.
5. A pre-existing near-surface disturbance with sufficient vorticity and convergence. Tropical cyclones cannot be generated spontaneously. To develop, they require a weakly organized system with sizable spin and low-level inflow.
6. Low values (less than about 20 kts 23 mph) of vertical wind shear between the surface and the upper troposphere. Vertical wind shear is the magnitude of wind change with height. Large values of vertical wind shear disrupt the incipient tropical cyclone and can prevent genesis, or, if a tropical cyclone has already formed, large vertical shear can weaken or destroy the tropical cyclone by interfering with the organization of deep convection around the cyclone center.

Even though, all of the conditions may are met this does not mean, a storm will form.[19] These necessary conditions happen each year annually during what has

[19] Central Pacific Hurricane Center - Honolulu, Hawai`i.", accessed May 5, 2014

commonly become referred to as hurricane season. In Hawaii, the season occurs from June to November. However, according to the experts at the US Global Change Research Program the hurricane season is increasing due to the effects of climate change.[20]

It is an important issue to understand because if this season is increasing we may even come to a time where a hurricane could strike at any time. That means hurricanes could even become a common occurrence as we see a frequency of storms increase.

Hurricane Prone Regions

Because a tropical cyclone needs such specific conditions to form there are only seven regions around the world that meet the requirement. The image below shows where the regions are located.[21]

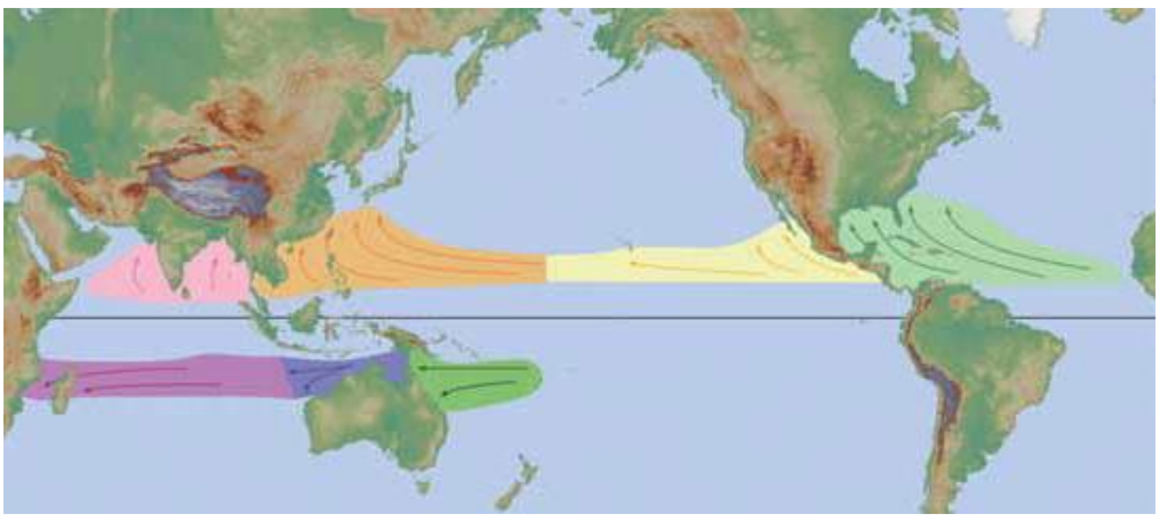

Figure 4 Hurricane Region Source NOAA.gov

[20] “"HurricanesA compendium of hurricane information.", accessed May 5, 2014
[21] Central Pacific Hurricane Center - Honolulu, Hawai`i.", accessed May 5, 2014

The arrows also indicated the direction that the tropical cyclones move in these areas. In the northern hemisphere, all tropical cyclones move in a northerly direction while spinning in a counter-clockwise direction. While those in the southern hemisphere move southerly spinning in a clockwise direction.[22]

Hawaii is located within region two, which is indicated on the image above in yellow. Its location makes for an ideal place for hurricane development. However, only two major hurricanes shave struck Hawaii in the last 50 years; Hurricane Iwa and Hurricane Iniki. The lack of frequency tends to make Hawaii residents apathetic about hurricane preparedness, thus leaving them vulnerable. Similarly, building developers, contractors, and designs overlook the importance of hurricane preparedness.

Hazards of a Hurricane

There is a broad array of hazards associated with hurricanes. Not all hazards a hurricane create (e.g. strong winds, flooding, debris damage) will become a major destructive force during a storm. This is a perceived notion that has been developed because of the way we categorize hurricanes.

Clearing up this perception helps to give a better view of what hurricanes are and can do. For example, before Hurricane Katrina was a category 5 made landfall. When it made landfall, it was a category three because the winds decreased, but the destructive force was in the surge[23]. The storm surge was created by a category five hurricane. Even though the winds dissipated, the storms real force came through as storm surge.

Wind

The first major hazard associated with hurricanes result from high wind speed, which can cause significant damage. However, the gusts are often more dangerous. Gusts can be 20% greater than sustained winds. Winds speeds

[22] TCFAQ A15) How do tropical cyclones form ?.", accessed March 3, 2014
[23] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

increase with elevation above ground. This means high rise buildings and buildings set at higher elevations will have heavy winds loads placed upon them which can cause major destruction. Winds on the right side of the hurricane are often stronger in storms found in the northern hemisphere. However, there is no single preferred direction of threat in the storm as winds can vary in direction.[24]

Thomas A. Schroeder describes another a wind effect that occurs in Oahu caused when extreme winds are driven down the Koolau Mountains down the mountainside toward the valley below[25]. In wind general models for hurricanes, this information is not looked into because it is site specific. Therefore, those living at the base of these mountains might experience more extreme wind speeds during a hurricane.

Wind Borne Debris

Along with the high winds comes wind-borne debris. Often a majority of damage is due to debris. Unsecured objects, building materials, or gravel can be lifted and thrown through the air damaging anything in its path. This threat is overlooked because it is not thought that heavy elements, such as rooftop mechanical unit could be lifted off and hurled into adjacent structures. Because wind-borne debris is such a hazard building materials are tested for their resistance to wind-borne debris. This is done by using missile testing whereby 2x4's are shot out of an air cannon into materials at different speeds.

Current building codes address the issues of roof top mechanical units and loose roof gravel. Much of Oahu was developed during the period 1959 through the late 1970's. Thus, many buildings in Oahu may not have been updated to current codes, leaving surrounding buildings vulnerable to the hazards of windborne debris.

[24] NDPTC, Hurriplan, 90
[25] Schroeder, Localized Wind Conditions

Storm Surge

"Along the coast, storm surge is often the greatest threat to life and property from a hurricane. In the past, large death tolls have resulted from the rise of the ocean associated with many of the major hurricanes that have made landfall."[26] Storm surge is a rise in water level above the astronomical tide caused by a tropical storm. This rise allows for waves to break further inland causing significant damage. Storm surge creates inland flooding and major inundation. The surge often has the same inland reach and force as a tsunami.

Storm surge inundation is influenced by bathymetry, the "topography" of the ocean floor.[27] The majority of Oahu is surrounded by reef which creates a barrier that protect the coastline from large swell. However, storm surge is a persistent force. Even though, a wave may break far from shore, the water will still build up and then cause flooding. This build up in some cases is caused by still water build up during a low pressure system, which allows the surge levels to move further inland before breaking.

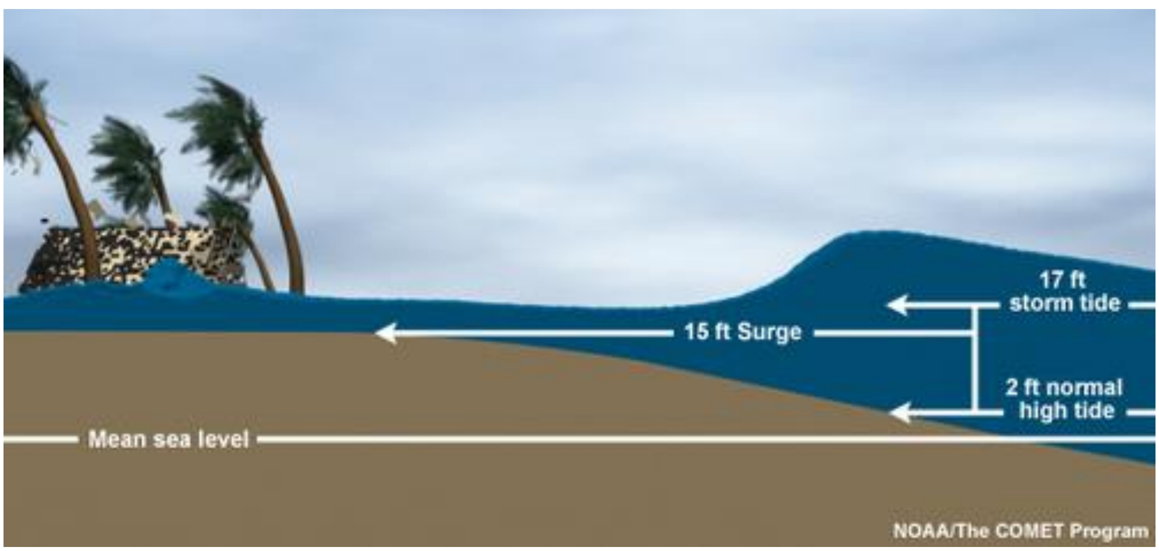

Figure 5 Storm Surge Image Source NOAA.gov

[26] "Storm Surge Overview.", accessed March 12, 2014
[27] Weaver, Influence of bathymetric fluctuations on coastal storm surge, 63

Flood

Flooding can also result from heavy rainfall. Tropical cyclones suck up large amounts of sea water that are stored it in its rain bands. As the tropical cyclone moves inland, it deposits that water through heavy rainfall, overpowering storm drains and streams causing them to overflow creating widespread flooding. As these floods waters rush toward the ocean, they are often met by the incoming storm surge doubling the effects of this hazard.

The hazards of flooding are a regular occurrence in many areas of Hawaii each year during the rainy season; Waikiki, Kakaako, and Ala Moana are some of these areas. The threat of flooding comes from the fact that there are areas created on former swamp and reef from dredging beginning in the 1920's.[28] This makes these areas even more susceptible to flooding when the extreme rain events happen during a hurricane.

Flood Borne Debris

Flooding and storm surge can carry materials and objects causing damage. Flood borne debris is sometimes one of the biggest hazards. As people are caught in the flood waters, debris can be hidden deep in the water being hurled with great force and speed. This same danger exists for buildings as materials can be slammed into buildings penetrating the envelope as well as damaging main structuring elements.

Tornadoes

Tornadoes can form within the eye walls and rainbands of a tropical cyclone. These tornadoes can cause vast amounts of damage. These tornadoes are often low to medium in intensity and cause isolated damage most often from the center of the storm.[29]

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[28] "HONOLULU IN 1902.", accessed May 6, 2014
[29] NDPTC, Hurriplan, 109

Chapter 4. Historical Hurricane Information

Hurricanes are one of the most destructive forces on earth and cause extensive damage wherever they make landfall. We often overlook them when we design buildings in areas that can experience hurricanes. According to the director of National Center Hurricane, “massive loss of life is possible unless significant mitigation activities area undertaken.”[30]

One of the largest problems we face is the way we frame our response in the U.S. to hurricanes. Our goal is to “minimize loss of life and property”[31]..

“Society’s efforts to respond to hurricanes will be enhanced with a systematic understanding of the issues associated with hurricane impacts. Often, people neglect to identify the problem that they face, leading to misdirected solutions with unintended consequences. If the hurricane problem encountered by the United States is to be dealt with effectively then an important first step is to understand the nature of that problem”[32]. In order to understand the nature of the problem, we must first look at the effects of hurricanes on society.

The Federal Emergency Management Agency (FEMA) is the United States branch that deal with and respond to disasters throughout the country. One of the ways they deal and respond is sending out teams of experts to survey areas following disasters to monitor failures in the built environment. By looking for the way buildings fail and what causes their failures we then gain a better understanding of the nature of the problem. This section looks at the reports prepared by FEMA’s Mitigation Assessment Team (MAT) for Hurricane Iniki, Hurricane Katrina, and Hurricane Sandy.

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[30] Piekle, Hurricanes Their Nature and Impacts on Society, 35
[31] Piekle, Hurricanes Their Nature and Impacts on Society, 35
[32] Piekle, Hurricanes Their Nature and Impacts on Society, 32

FEMA MAT Reports

What is an FEMA MAT Report

The Mitigation Assessment Team (MAT) Program was created to evaluate buildings and infrastructures following a disaster. Subject experts are assembled to form the team often from federal, state, and local governments along with other private practice partnerships. These individuals enter the area following the disaster, investigate and report on the resistance of buildings and infrastructure to storm hazards. This information is then used to develop mitigation tactics by using the data to develop building codes and guidelines.

Figure 6 MAT Team in New Orleans September 2005 Source FEMA.GOV

The teams have been deployed to disasters since 1990. “Using the information and observations collected in the field, MATs work closely with local and state officials to develop recommendations for improvements in building design and construction, code development and enforcement, and mitigation activities that will lead to greater resistance to hazard events"[33]. In addition, this information has helped in the post-disaster cleanup process.[34]

Iniki MAT Report

Hurricanes in Hawaii do not make landfall annually. Before Iniki struck in 92' the last hurricane of record was Hurricane Iwa ten years prior.[35] When people are not directly affected by hurricanes on a regular basis; they tend to lack diligence in hurricane preparation.[36] People develop a "this will not happen to me" mentality, which affects design and development standards.

"Prior to Iniki, the County of Kauai adopted the Uniform Building Code 1985 edition in 1988. The UBC defines an 80 mph design wind speed for the Island of Kauai."[37] 80 mph wind speed is a mid-category one hurricane well below what Iniki ending up being. This decision was made even though Hurricane Iwa 6 years prior caused $250 million in damage as a high category 1 with wind speeds of 92 mph.[38] The denial of hurricane potential became even more apparent when Iniki struck a few years after the adoption of UBC 1985.

Context

On September 11, 1992 Hurricane Iniki made landfall on the island of Kauai. With wind speeds of 143mph at some locations, Iniki was the strongest and most destructive recorded hurricane to hit Hawaii.[39]

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[33] Dolhon, FEMA Mitigation Assessment Team Program, 428
[34] "What is the Mitigation Assessment Team Program? | FEMA.gov.", accessed March 13, 2014
[35] "NOAA Hurricane History"
[36] Stein, How risk perceptions influence evacuations from hurricanes,
[37] Hawaii Structural Engineer Association, A Survey of Structural Damage Caused By Hurricane Iniki, I-2
[38] "NOAA Central Pacific Hurricane Center"
[39] "FEMA FIA-23 Online"

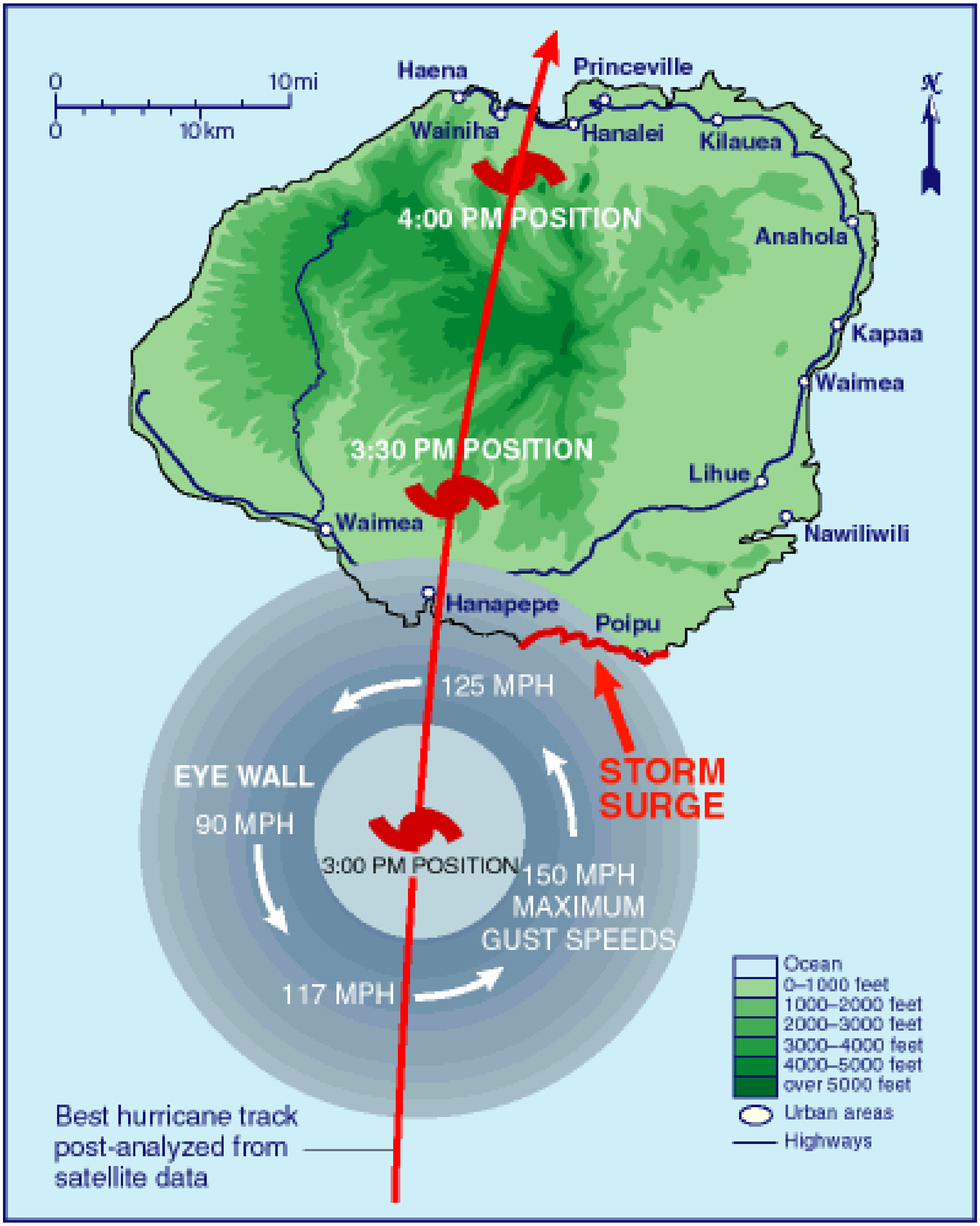

Figure 7 Iniki Path Image Source SOEST Hawaii

On September 22 a team was assembled comprised of FEMA staff, State Civil Defense staff, local leadership, and professional architects and engineers from

Kauai and Oahu. The team explored the damage from the winds and flooding to buildings.[40]

Overview of Damage and Hazards

As the storm moved through the island of Kauai, it left a wake of damage of approximately 1.8 billion dollars and damaging 14,350 homes. Of that number, 1,421 homes were destroyed, and 5,152 suffered major damage.[41]

There were extreme amounts of coastal flooding on the island. Still flood water levels ranged from 10.5 to 12.5 feet in Kekaha and 12.5 to 20 feet at Poipu Beach.

Figure 8 Map of Kauai Source Google Maps

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[40] FEMA, *Building performance: Hurricane Iniki in Hawaii: observations, recommendations, and technical guidance*

[41] FEMA, *Building performance: Hurricane Iniki in Hawaii: observations, recommendations, and technical guidance*

Typical damage sustained was due to buildings set near grade. The team found that these buildings received most damage from flood borne debris. Most homes in this area were set far enough back from the shoreline (100+ ft) that wave action was minimal.

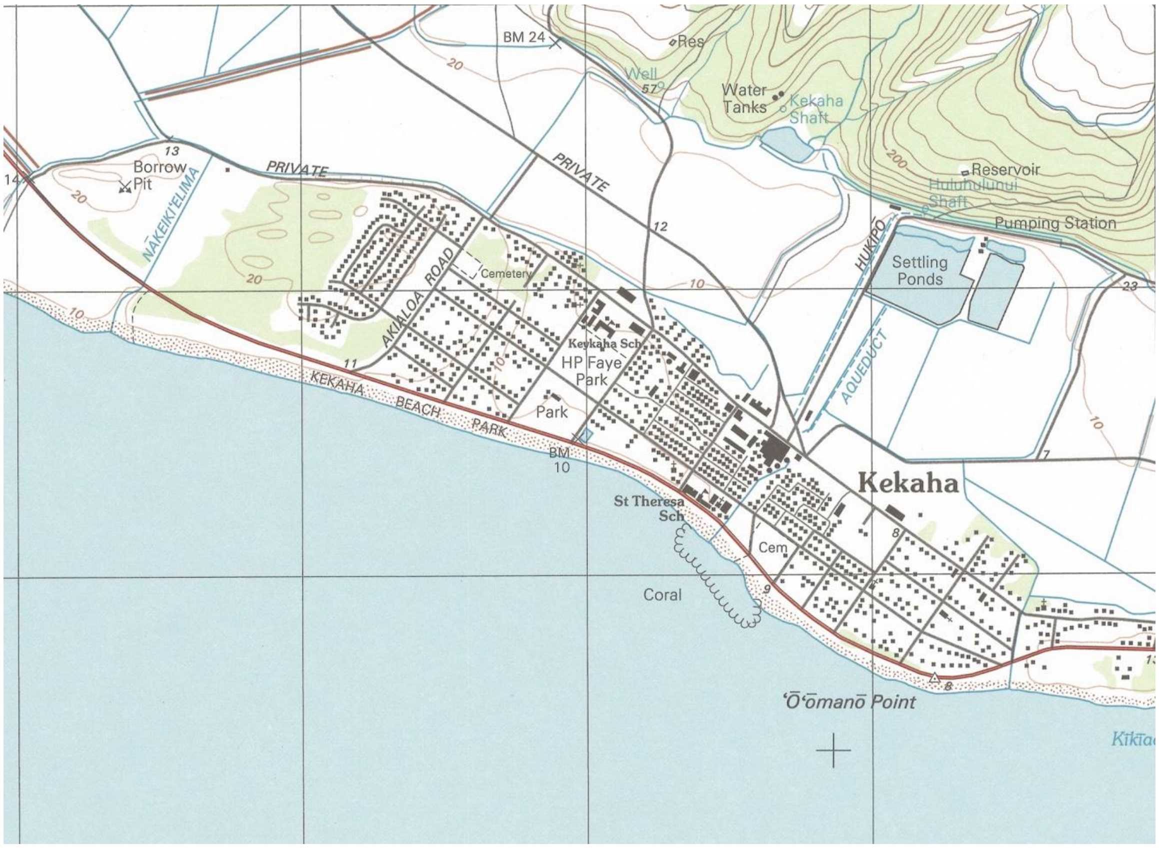

Figure 9 Kekaha Topographic Map Source USGS 1991

The flood damage in the Poipu Beach area was extensive. The team observed that there were three types of failure modes due to flooding in this area. Buildings set close to grade level were completely exposed to the impending wave action and debris, and often were damaged beyond repair.

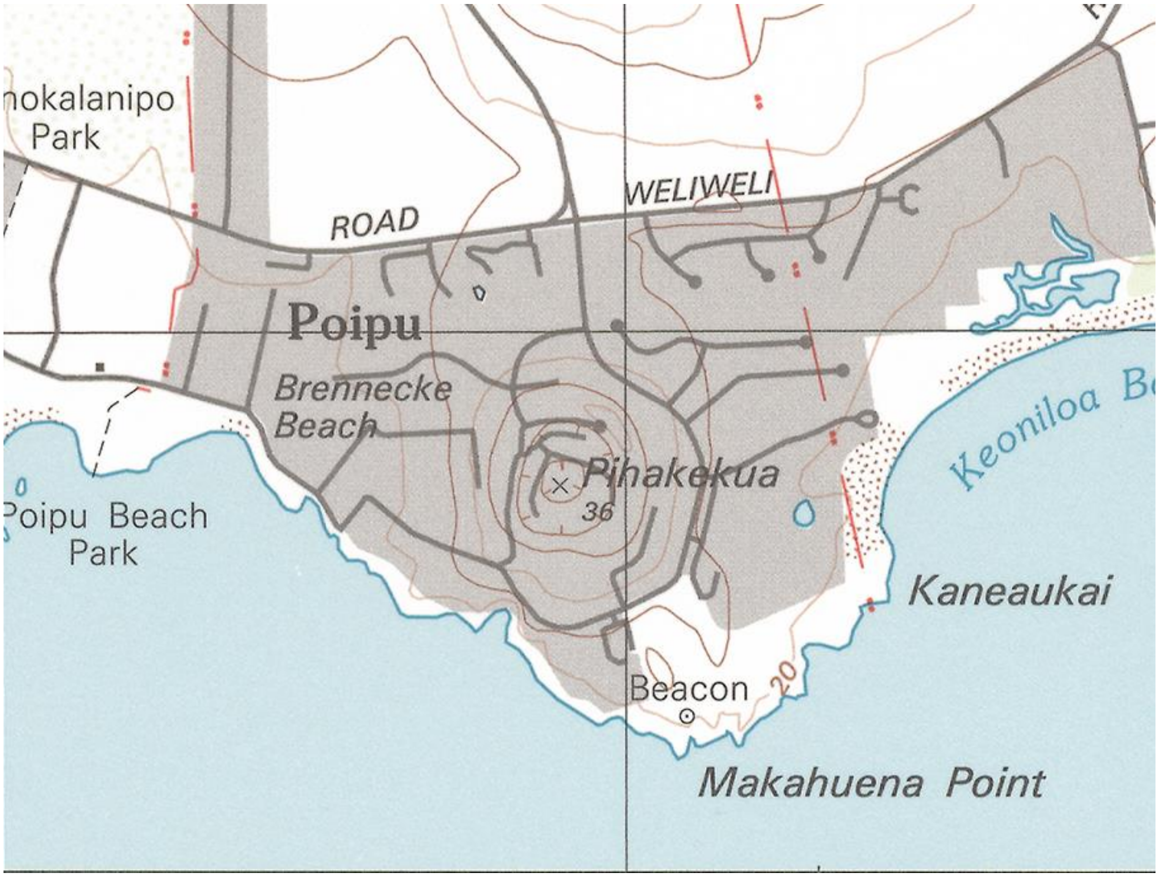

Figure 10 Poipu Beach Topographic Map Source USGS 1996

The second type of flood failure observed in this area was improperly embedded or constructed foundations. Foundations, piles, and piers were undermined due to erosion and scour. This caused the structural integrity of the building to be compromised.

Figure 11 Poipu Beach Improper Foundation Source FIA-23 p40

The third failure resulted from flood borne debris from low-lying (2ft – 4ft tall) lava rock walls. Many of these walls were destroyed, and the debris was hurled into the surrounding buildings causing significant damage.

Figure 12 Flood Borne Debris Source FIA-23 p34

The team observed that buildings close to the shoreline where most vulnerable. Buildings that were not elevated and the first level of many of the condominiums and hotels in these areas were destroyed or rendered useless following the storm.

Along with flooding, there were excessive winds, however due to power failures during the storm the peak winds we unable to be recorded. The report indicated that wind speeds at Makahuena Point were recorded at 143 mph, and winds in low-lying areas were in excess of 80 mph specified in the building code.

The team observed most building failures occurred in standard light wood construction buildings and pre-engineered buildings. They found that many buildings were not designed and built to withstand the wind loads.

Figure 13 Home Floated into Neighboring Home Source FIA-23 p35

These failures included uplift which caused roof cladding, sheathing, and structural members to be lifted off the structure.

Internal pressure in the buildings caused by the winds caused building cladding and glazing to fail, thus exposing the interior of the structure and causing further damage and uplift to occur.

While looking at pre-engineered metal buildings, the team found that excessive weathering and aging caused the steel to fail in many cases. They also found that the metal sheathing and connections were insufficient to withstand the forces and often were completely removed from the structure.

These structural failures resulted in extreme amounts of windborne debris. Which then caused extensive damage to the surrounding buildings.

Figure 14 Home Floated Away Poipu Beach Source FIA-23 p35

Lessons Learned

The recommendations from the observation team for flooding included elevating buildings, and designing foundations to withstand flooding impacts. They gave examples of how to develop better foundation systems. A recommended cited was to drill deep enough attach to bedrock especially in coastal areas. This foundation will help to secure the structure and to prevent scouring to keep the building in place. The team also recommended setting floor levels above the potential flood height.

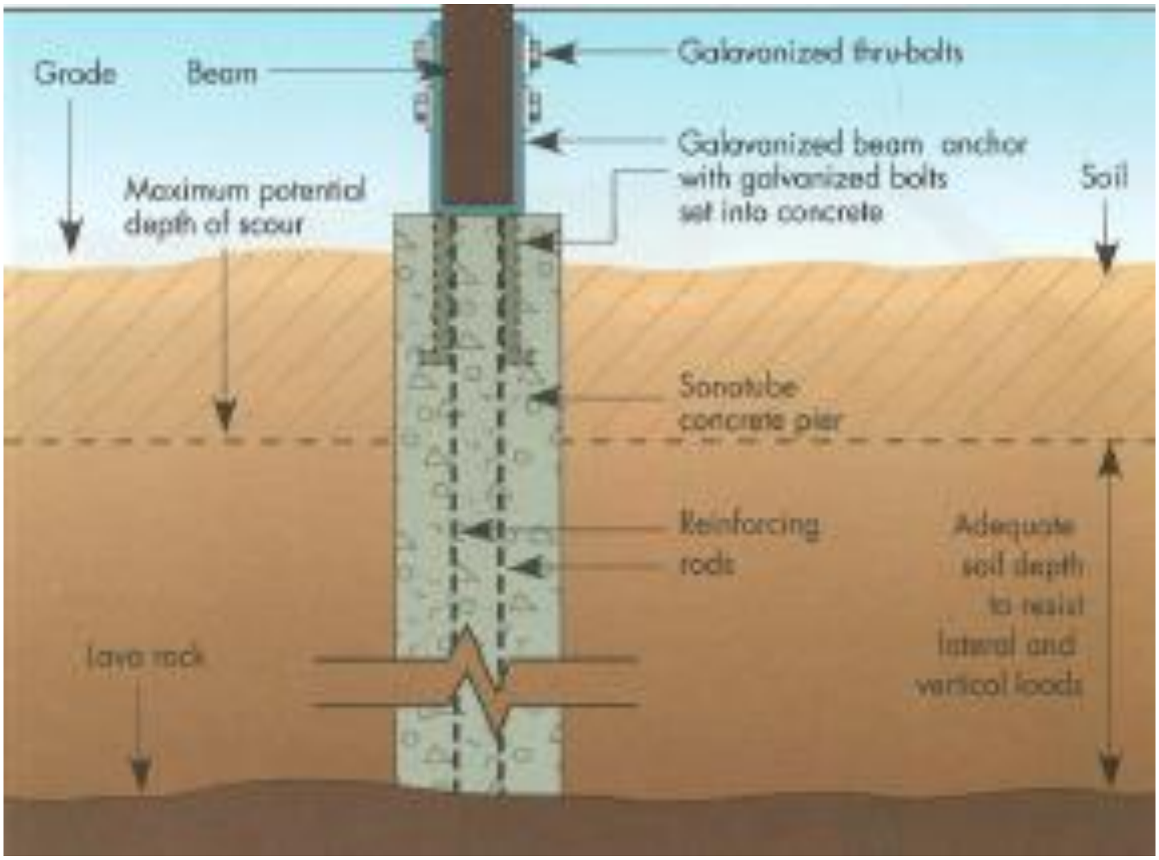

Figure 15 Proper Foundation Connection Source FIA-23 p85

The team stressed the need for continuous load paths in structural connections from roof to the foundation. They also recommended building a fortified envelope and indicated many buildings that withstood the storm had a protected envelope.

Katrina MAT Report

In 2005 when Katrina made landfall no one expect how much damage this storm would do. Hurricanes are a regular occurrence throughout the Gulf. Every year the news is filled with hurricanes and tropical storms coming through this area. One would think that due to this constant barrage of storms they would be prepared for anything to happen. Perhaps this may have even been a sort of false security that they deal with hurricane so often if one comes they will be okay.[42]

This security may come from the fact that they did have preventative hurricane systems in place.[43] Levees, dikes, controlled flood areas, flood mapping, and other hurricane preparedness activities set up. What seemed to be a problem is that no one ever addressed the idea that what if these systems failed? What would happen then, and what measures can be taken in case they do fail. Because this question perhaps was never explicitly addressed when the levees failed the storm's destructive force was compounded.

“The inability of the local, state, and federal governments to respond to a major disaster was clearly displayed time and time again during and after the hurricane (Katrina). From inadequate planning and resources for evacuation of poor residents before the storm to the delay in the federal response for those left behind. The combination of Hurricane Katrina, the levee breach, and subsequent flooding revealed a city, state, and nation ill-prepared to protect its citizens.” [44]

Context

Hurricane Katrina was the most devastating storm to strike U.S. shores up to that date. The storm first made landfall in Florida as a Category I on August 25, 2005. After crossing Florida, the storm moved to the Gulf of Mexico where it increased in power becoming a Category 5. It then made landfall again on August 29, 2005 as a Category 3 in South East Louisiana.[45]

[42] Stein, How risk perceptions influence evacuations from hurricanes,
[43] National Academy of Engineering, The New Orleans Hurricane Protection, 8
[44] Levitt and Walker, Hurricane Katrina, 147
[45] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Figure 16 Katrina's Path Source FEMA-549 p30

In September of 2005 a Mitigation Assessment Team of 26 individuals was sent to the Gulf Coast to develop this report. They were charged with analyzing failures to buildings and infrastructure, as well as looking at buildings and infrastructure that sustained the storm. This information was then used to help guide and create more stringent standards of designing for storms.[46]

Overview of Damage and Hazards

Hurricane Katrina caused $125 Billion in damage spread across Florida, Mississippi, Louisiana, and Alabama. A total of 170,000 individuals died in the storm.[47]

In total 310,353 single family homes were destroyed, 102,297 received major damage and 135,879 minor damage. A total 40,762 apartments destroyed, 33,691 sustained major damage, and 27,881 received minor damage. When a home receives major damage, it's typically uninhabitable. Storm damage caused 450,000 people to be displaced from their homes.[48]

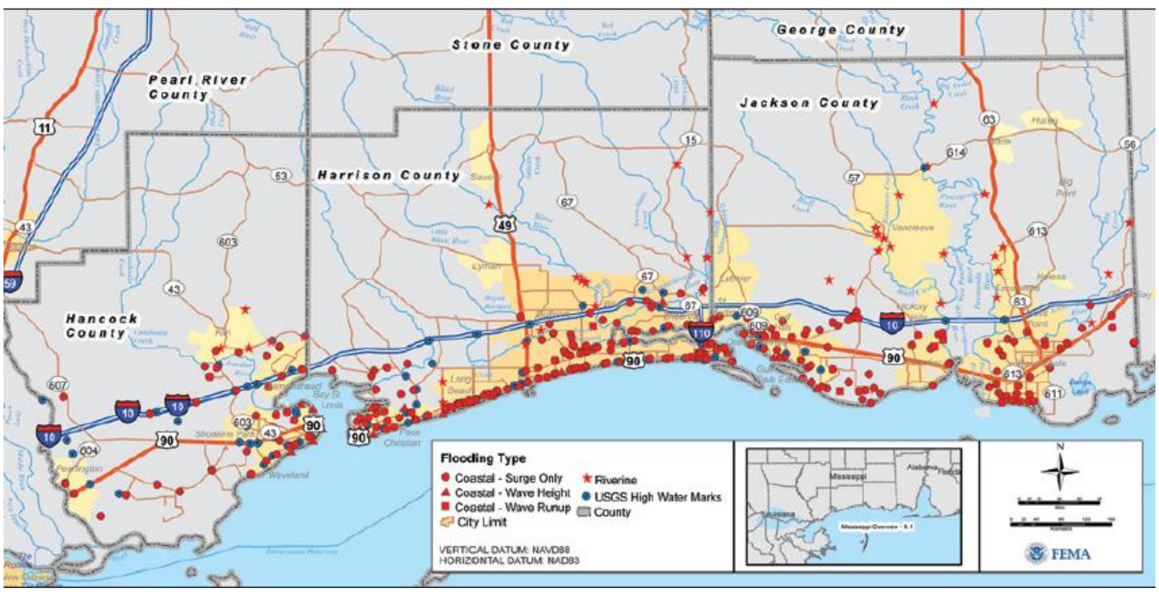

Figure 17 Places Marked Showing Storm Surge and Excessive Flooding Source FEMA-549 p37

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[46] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[47] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[48] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Heavy winds, rains, and storm surge were the causes of all this destruction. While still a category 5 in the Gulf, Katrina created the devastating storm surge that caused the levees to fail flooding much of the region. With surge wave heights upward of 34 feet, the amount of water was too much for the levees to handle causing failure and mass destruction. The waves inundated the coastline causing flooding in areas outside the levees. Building equipment located at the ground level was often destroyed or displaced.[49]

Figure 18 Mold Damage After Flood Waters Receded Source FEMA-549 p95

[49] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Figure 19 Flooding in Mississippi Following Levee Failure Source FEMA-549 p75

Wave impact caused many buildings to fail. Along with wave action, there was excessive damage following the storm. Most homes in these areas that were able to escape with minor damage had extensive mold damage following the receding waters. Leaving the homes uninhabitable and contributed to the significant number of those displaced.[50]

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[50] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Figure 20 First Level Destroyed from Wave Action Source FEMA-549 p101

Along with the wave action and flooding was a large amount of flood-borne debris. Material, barges, and complete homes were thrown about in the flood waters. In Biloxi, Mississippi a casino barge was washed ashore into a hotel. While in other areas buildings were lifted off their foundations, floated into other buildings, setting off a chain reaction of further destruction.[51]

[51] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Figure 21 Casino Barge Run Aground Biloxi Source FEMA-549 p92

There was also wind damage in many areas. Building failures from high winds were generally seen in the building envelope, and often in glazed areas. Once the glazing failed the winds entered the buildings causing the interiors to pressurize, and in some cases causing complete destruction. The team noted that a large number of buildings had sheathing materials ripped off, exposing the interior to wind and rain. Also observed was cantilevered lightweight concrete decks lifted off their structures. There were many cases of pre-engineered that buildings failed much in the same way as those on Kauai.[52]

In many instances, roof top equipment was blown over and off buildings. This created perforations in the building envelope which allowed rain and wind to

52 FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

enter the building causing further damage and making them uninhabitable following the storm.[53]

The team observed that in dense urban areas, high-rise buildings suffered extensive damage as debris destroyed much of the glass facade. Many of the soffits and light framed canopies on these buildings were also destroyed.

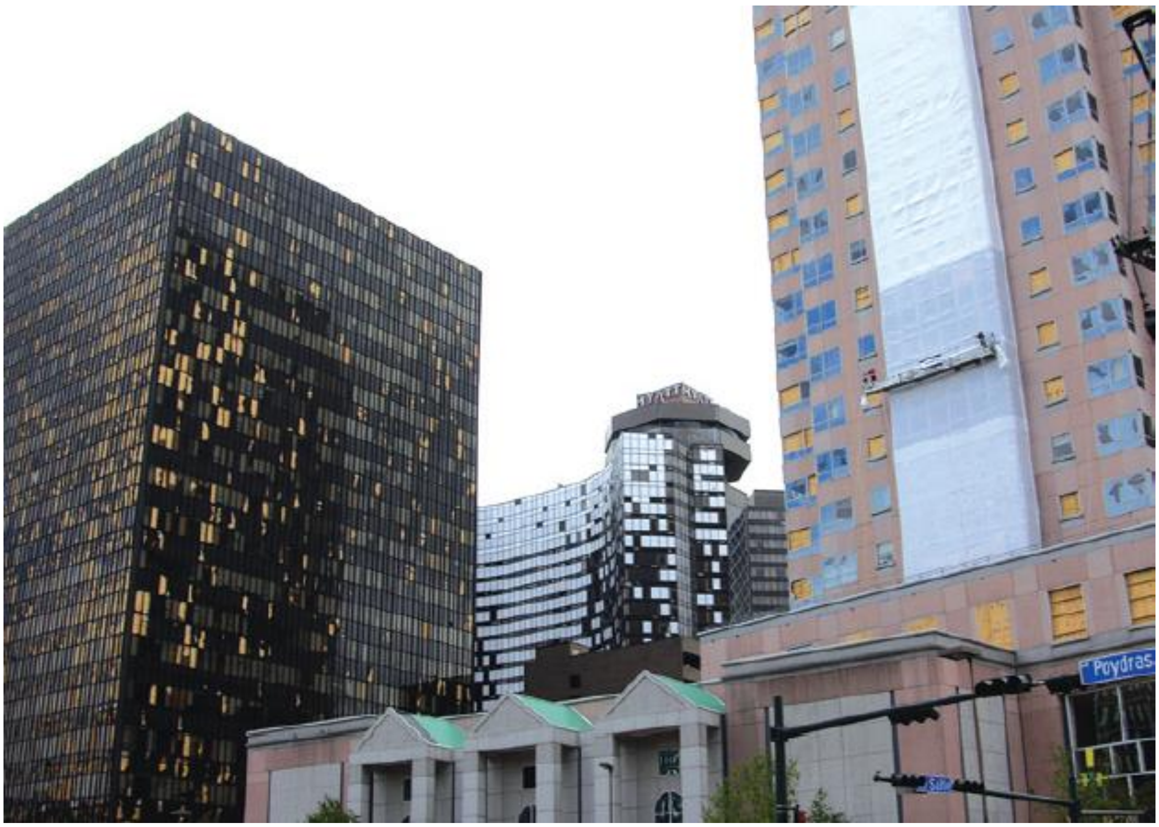

Figure 22 Windborne Debris from Roof Top Aggregate Damaged Glazing Source FEMA-549 p107

High winds cause wind-borne debris. Unsecured objects are lifted and thrown into surrounding buildings creating a ripple effect. Where loose rock aggregate

[53] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

was used as ballast for membrane roofs, the material was lifted into the air impacting surrounding buildings.[54]

Lessons Learned

The team also observed buildings that were able to withstand the impact of the storm. This information gives insight into what can be done to resist storm hazards.[55]

The team observed that buildings using properly attached storm shutters protected glazing from damage. This allows the building envelope to remain intact and prevented internal pressurization. [56]

Figure 23 Storm Shutters Protected Glazing Source FEMA-549 p381

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[54] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[55] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[56] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Buildings that were properly elevated were able to withstand flood waters and flood borne debris. The key to this was proper connections and piles that were embedded correctly. [57]

Figure 24 Properly Elevated and Anchored Building Source FEMA-549 p379

Another observation from the team was buildings that properly elevated and secured their service equipment. They were no longer hazards and able to function once power was restored and for those buildings with backup generators they could operate immediately. [58]

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[57] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[58] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006

Figure 25 Elevated HVAC and Power Systems Protected from Flood Waters Source FEMA-549 p384

One of the greatest lessons learned from Hurricane Katrina is the shear force and destructive power a hurricane can bring and the need for preparation. [59]

Sandy MAT Report

When Hurricane Sandy made landfall to the dense shores of New York and New Jersey in the fall of 2012. It became the most devastating recorded natural disaster to strike the shores New York[60]. In 2007, Mayor Bloomberg recognized

[59] FEMA, Hurricane Katrina in the Gulf Coast building performance observations,2006
[60] PlaNYC, Stronger Resilient New York, 1

the effects of sea level rise in New York and started an initiative to make New York more resilient.[61]

In 2012 "progress on PlaNYC's resiliency efforts had advanced substantially. Greenhouse gas emissions in New York were down 16%. The City was updating its Building Code to make new buildings more flood-resistant."[62]

New York's effort to invest in protection methods for extreme weather was the right choice. They noticed that recently restored wetlands were able to soak up floodwaters. New elevated buildings emerged with less damage than their counterparts.[63] Proving preparation and planning for these events can significantly change the outcomes.

However, despite these measures there was still extensive damage throughout the region. New York City, the Rockaways, and many other areas suffered severe flood damage causing power outages, sewer inundations, building damage and destruction, and displaced citizens. These issues are exacerbated in a city like New York that is home to 8,336,697[64].

Context

October 29, 2012 Hurricane Sandy made landfall to the eastern United States. The storm was 1000 miles wide with winds of 80mph (category 1) with the pressure of a category three hurricane. On the same day was the spring high tide and that night would be a full moon which made the tides higher than normal. Because all these things aligned, there was extreme coastal inundation due to storm surge. Sandy stretched across 24 states from Florida all the way up to Maine. Of those 24 states, New York and New Jersey were the hardest hit.[65]

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[61] PlaNYC, Stronger Resilient New York, 1
[62] PlaNYC, Stronger Resilient New York, 1
[63] PlaNYC, Stronger Resilient New York, 1
[64] "Census"
[65] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

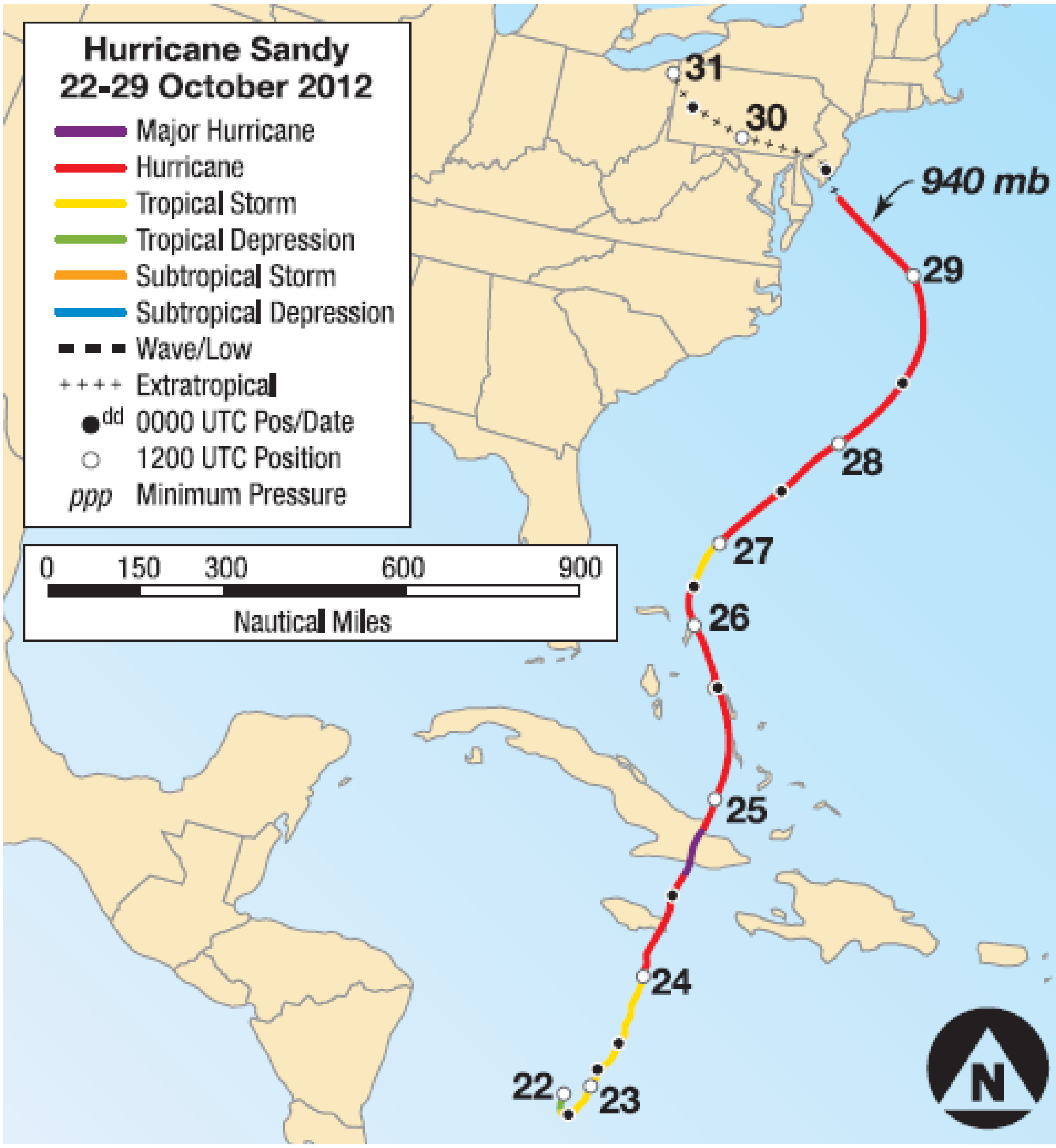

Figure 26 Hurricane Sandy's Path and Development Source FEMA P-942 p1-4

In December of 2012 the Mitigation Assessment Team was deployed finishing up in February of 2013. This team was comprised of interdisciplinary experts from the fields of planning, disaster management, architecture, engineering, and government. The team was charged with looking at the effects of a hurricane in urban environments including underground inter-building connections, flooding, and saltwater intrusion into electrical systems and other infrastructure.[66]

Overview of Damage and Hazards

Sandy caused 147 deaths and $50 billion in damage. [67]

The majority of damage sustained from hurricane was due to the storm surge and inundation. In some areas the surge wave heights reached 12 feet. Though these surge heights are not the same as seen in Katrina and Iniki, the size of the storm played the largest factor This was because the surge lasted so long the inundation levels were extreme and entered deep inland in some areas. The inundation levels in some areas reached levels of 9 feet.

[66] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[67] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

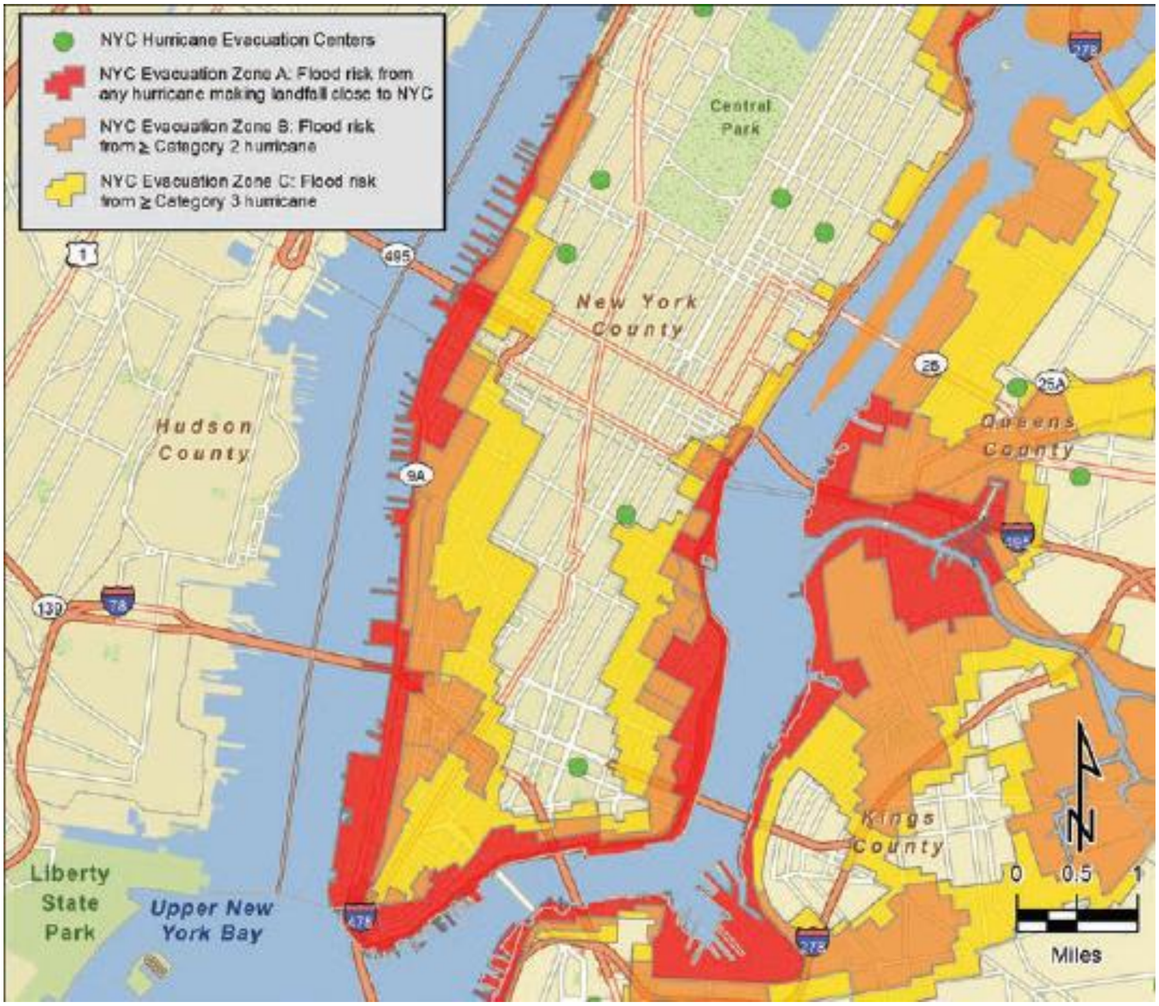

Figure 27 Areas of Evacuation During Sandy Source FEMA P-942 p1-7

There were many places that received excessive damage. Red Hook, Lower Manhattan, and the Rockaways received much of the attention for damage sustained from the storm.[68]

The team found many system failures. It was apparent that the conventional form of placing building systems in basements left the buildings crippled. The systems damage ranged from boilers to electrical panels.

[68] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

Figure 28 Boiler in Basement Damaged Due to Flooding Source FEMA P-942 p4-22

In the Rockaways, the team observed many buildings failed due to improper foundation anchoring. They also noted a large number of improperly secured and constructed piers that allowed buildings to shift. Because a large portion of the Rockaways is covered with sand dunes, there was excessive scour and coastal erosion that caused building foundations to fail.[69]

Red Hook offered some significant insights into the effects of hurricanes in densely populated areas. Much of Red Hook is comprised of multi-story multifamily buildings. The area experienced standing water at 3ft above grade

[69] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

which inundated basements which housed boilers, electrical panels, pumps, and control stations. Without these essential services, these buildings were rendered useless because buildings could not be heated. Unlike other areas of flooding the water in many of these basements had to be pumped out manually.[70]

Figure 29 Solid Brick Wall Destroyed from Storm Surge Source FEMA P-942 p7-14

High rise buildings seemed to withstand the storm without any structural damage. The flood waters entered the first floor damaging interior finishes and filling up the basement and lower level parking garages. In one case, uneven flood loads

[70] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

caused a parking garage column on at a lower level to crack and spall, which compromised the structural integrity of the entire building.[71]

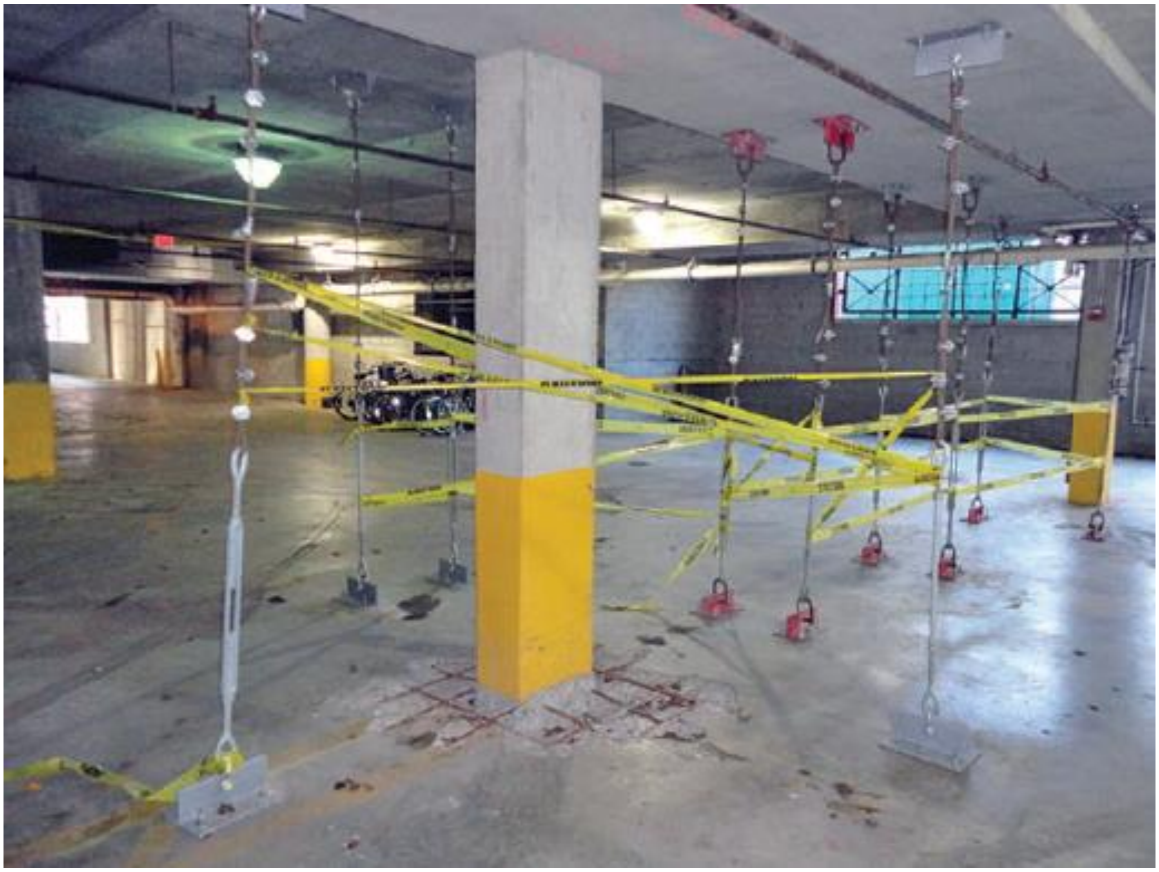

Figure 30 Parking Garage Column Below Residential Tower Cracked and Spalling at Base Due to Uneven Flood Loads Source FEMA P-942 p5-7

The damage to Lower Manhattan was extreme. All spaces below grade and subway tunnels where flooded. Mechanical and infrastructure systems were rendered out of service. Because most of this area is impervious surfaces the water had to be pumped out.[72]

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[71] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[72] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

Lessons Learned

Hurricane Sandy demonstrated what could happen in dense urban areas during a storm event. It shows dangers and complication, but also points toward what needs to be done to ensure the resilience of a building to make it useable following the storm.[73]

One of the first major lessons learned was to locate systems out of a floods reach. This was one of the greatest problems following the storm. People were unable to return to their residences, even though, there wasn't structural damage causing pressure on temporary housing. Because of systems failures other operable mechanics were rendered useless, such as elevators. So protecting these systems can help ensure a building is functional.[74]

Another lesson is the use of flood resistant materials. Buildings that used these types of materials in the lower levels were able to function again with minimal clean up. This same idea goes for the use of emergency flood systems, such as sump pumps. Buildings fitted with sumps were able to remove water faster.[75]

One of the greatest lessons taken from the hurricane was regarding foundation connection. Buildings that were properly anchored and attached to their foundations survived the storm.[76]

The last lesson learned was building siting, soils, and topography. There was a large amount of damage in the Rockaways from sand driven into the streets and buildings and from erosion and scour. [77]

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[73] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[74] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[75] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[76] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[77] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

A Critical Look at Post Hurricane Disasters

These three storms offer a broad look at what can indeed happen during a hurricane. They show the need for storm preparedness. These failures come from low building standards and poor disaster prevention and preparedness. With this societal goal of “minimizing the loss of life and property”[78] it seems we still have a long way to go.

The preparations that New York took in response to climate change and sea level rise shows how we can effectively “minimize the loss of life and property”. It became apparent from each MAT report that there are a collective of buildings that were designed with the thought of the effects of hurricanes. This thinking caused these buildings to perform to a higher standard and in many cases even completely functioning following the storm.

Designing to this higher standard is often perceived as a luxury and during post-disaster recovery buildings are often rebuilt to their previous state. Leaving the same buildings vulnerable to hurricanes in the future, instead of solving the issue we are perpetuating the same problem.[79]

This is in contrast to properly designed, storm resistant buildings which allow occupants to return to their homes following the storm while the main recovery effort is left to restoring urban infrastructure.

In one extremely useful recovery event documented the Congress of New Urbanism (CNU) was brought to Mississippi to aid in community design charrettes.[80] These charrettes helped to offer better more resilient development and recovery plans. These plans help with building design and reconstruction efforts as a preventative measure for future hurricanes.

[78] Piekle, Hurricanes Their Nature and Impacts on Society, 35
[79] Piekle, Hurricanes Their Nature and Impacts on Society, 145
[80] Liu, Resilience and Opportunity, 152

What this Means for Hawaii

Though two of these storms happened outside of Hawaii the information, the teams gathered in all three give clear basic failure examples. Going over the reports it was clear that many of the strategies and failures are similar to those used in Hawaii. One of the first examples is buildings not properly secured to their foundation. As many of the single family homes in Hawaii are slightly elevated, they are placed on "tofu" blocks which aren't usually secured.[81] This is because a timber post set up a precast block which sits atop another precast block (see figure 23). Leaving these homes vulnerable to being lifted off their foundations thus becoming flood borne debris to other areas. Many of the buildings were built and designed before a more stringent code was put into place.

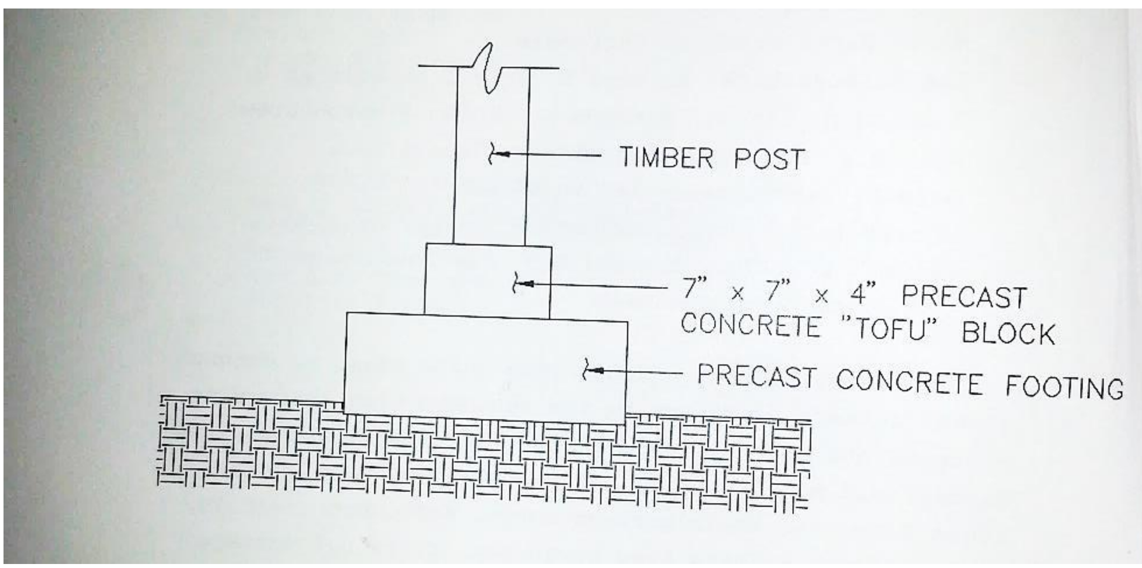

Figure 31 Tofu Block Construction Diagram Sources A Survey of Structural Damage Caused By Hurricane Iniki p I-2

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[81] Hawaii Structural Engineer Association, A Survey of Structural Damage Caused By Hurricane Iniki, I-2

This lack of structural integrity is the result of the fact that much of Oahu was developed directly following statehood in 1959 before building codes were applied. Alternatively, if building codes were used they had minimum load standards and none of which addressed hurricanes. These buildings, in particular, tend to be the most vulnerable to debris impact failures. These failures are due to building material choices. The use of hollow concrete blocks and tiles were used extensively during this time in multifamily low and midrise buildings. These materials are not rated for impact resistance and have failed in the impact missile testing. During this time, building utilities were often placed at grade or below grade leaving them exposed to flooding. Also roof top equipment they may not have been secured properly.

The topography of Oahu makes it very vulnerable to flooding. If the same conditions seen with Sandy were to occur in Oahu, the flooding would be extensive. Much of the densely developed parts of the island are directly on the shoreline. If Sand Island were to experience the surge from Iniki, the wastewater treatment plant would be inundated spilling raw sewage into the ocean and then pushed inland with surge. The Honolulu Power Plant is sited on the edge of the harbor. Storm surge and debris would likely compromise the power plant.

Figure 32 Topography around Sand Island Wastewater Treatment Facility Generated Source gis.hicentral.gov

Another interesting site-specific problem that could arise is similar to the roof gravel ballast. Throughout the beaches in Hawaii are large deposits of dead coral. If a hurricane were to pick up chunks of coral, they could become dangerous projectiles, likely causing extensive glazing damage to the many waterfront buildings.

Oahu is currently incapable of sheltering its population, causing many people to be displaced following a major storm. In addition, this would also displace the large tourist population. Unlike Sandy and Katrina, if people are displaced, Oahu has very few places to go that may not have been affected by the storms deadly force.

In many coastal industrial areas engineered metal buildings are used. These buildings are preformed and are placed on a site and bolted down. Often the buildings are clad with standing metal seam sheets (see figure 25). Like those mentioned in the MAT reports they too may experience extreme weathering and in some cases even more so with the persistent sun exposure. In Kakaako, in particular, many of these buildings with a wind event would most likely fail. These failures do nothing but add to all aspects of the problem.

Figure 33 Image Source Google Images http://dartdesigninc.com/blog/wp-content/uploads/2012/07/Pre-engineered-Building2.jpg: Engineered Metal Building

Chapter 5. Building Codes

Adopted by local governments building codes are used to regulate the way buildings are constructed. In most cases, they offer minimum standards to protect the Health Safety and Welfare of the public. The standards are not necessarily effective when it comes to extreme events such as hurricanes.[82] This lack of stringent codes allows people to design buildings knowing that if a hurricane were to come their building would be destroyed.

A perfect example of a more stringent code is that of Miami-Dade County Florida. There minimum wind speed loads are for 120 mph at a height of 30 feet.[83] Compare this to the UBC standard used in Kauai Prior to Iniki at 80 mph.[84] These two examples serve to show the gap in design standards. This is not to say that building codes do not help, but that we must design to a higher standard in vulnerable areas.

There is an extremely common misunderstanding on where building codes originate. Also, what codes affect the way we design for hurricanes and extreme weather events. This understanding helps to show gaps in our current system, and where better design can better prepare society for when a hurricane strikes.

International Code Council, ASCE, and ASTM

In the United States many (but not all) states use the International Building Code. The International Building Code is developed by the International Code Council, and then adopted by the local jurisdiction as a standard to be used for design and construction. Currently, Hawaii has adopted the IBC-2006 as their governing code. A companion to the IBC (International Building Code) is the ICC 500-2008: ICC/NSSA Standard for the Design and Construction of Storm Shelters with local

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[82] Piekle, Hurricanes Their Nature and Impacts on Society, 143
[83] Piekle, Hurricanes Their Nature and Impacts on Society, 143
[84] Hawaii Structural Engineer Association, A Survey of Structural Damage Caused By Hurricane Iniki, I-2

amendments. Being a standard for storm shelters, the ICC-500 can give guidance on what it takes to withstand a storm event.

According to the International Code Council website they are a “member-focused association”. It is dedicated to developing model codes and standards used in the design, build and compliance process to construct safe, sustainable, affordable and resilient structures. Most U.S. communities and many global markets choose the International Codes.[85]

The International Codes or I-Codes, published by ICC, provide minimum safeguards for people at home, at school and in the workplace. The I-Codes are a complete set of comprehensive, coordinated building safety and fire prevention codes. Building codes benefit public safety and support the industry’s need for one set of codes without regional limitations.[86]

Fifty states and the District of Columbia have adopted the I-Codes at the state or jurisdictional level. Federal agencies including the Architect of the Capitol, General Services Administration, National Park Service, Department of State, U.S. Forest Service and the Veterans Administration also enforce the I-Codes. The Department of Defense references the International Building Code for constructing military facilities, including those that house U.S. troops around the world and at home. Amtrak uses the International Green Construction Code for new and extensively renovated sites and structures. Puerto Rico and the U.S. Virgin Islands enforce one or more of the Codes.”[87]

These codes typically reference the ASCE. The ASCE is the American Society of Civil Engineers. This organization is made up of civil engineers throughout the world with the goal to promote safety to the general public. As part of that objective, they have developed 60 different standards that affect all aspects of a

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[85] “International Code Council About”
[86] “International Code Council About”
[87] “International Code Council About”

building and construction.[88] The IBC (International Building Code) references these standards in its codes. The two standards that directly affect hurricanes are the ASCE 7-10: Minimum Design Loads for Buildings and Other Structures and ASCE 24-05: Flood Resistant Design and Construction.[89]

Another standard that is referenced comes from the ASTM (Americans Standard for Testing Materials). This organization tests all materials for construction. This testing includes 2x4 missile testing for impact resistance. Materials are set up in a controlled area, and 2x4's are shot out of a controlled air cannon into the material to ensure they can withstand the impact of debris during a storm.[90]

The IBC and ICC-500's give standards for almost all aspects of a building's design. The next two sections will look at those standards related to wind and flooding. Evaluating if these standards are sufficient to the meet the needs of a hurricane.

IBC and ICC-500 for Wind

Wind is the first thing thought of when a hurricane is discussed. The following are the codes in the IBC and ICC-500 directly related to wind loads.

IBC 2006 1609.5: The roof deck shall be designed to withstand the wind pressure determined in accordance with ASCE 7. Roof coverings shall comply with Section 1609.5.1.[91]

The concept of this code is heavy winds can create pressure and uplift, which can cause roofing materials to fail exposing the interior of the building. These types of winds happen extensively during a hurricane which then lets rain and

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[88] "ASCE About"
[89] "ASCE About"
[90] "ASTM"
[91] ICC, IBC 2006, 2005

debris into the structure. Currently, the wind load for Hawaii stated by ASCE 7-10 is 105 mph which is equivalent to low category two hurricane.[92]

IBC 2006 1504.8: Aggregate, gravel, or stone shall not be used on the roof of a building located in a hurricane -prone region.[93]

As mentioned before aggregate, gravel, and stone can be lifted off the roof during a storm. It then becomes wind-borne debris causing damage to building facades and glazing.

IBC 2006 1609.1: Protection of glazed openings shall be impact resistant or protected with an impact-resistant covering. Glazed openings located within 30 feet of grade shall meet the requirements of the Large Missile Test. Glazed openings located more than 30 feet above grade shall meet the provision of the Small Missile Test.[94]

This code is fairly explanatory. It is to ensure that all glazed openings can withstand impacts to protect the building envelope.

IBC 2006 1609.1.2.1: Louvers to protect intake and exhaust ventilation ducts within 30 feet from the grade (Large Missile Test of ASTM 1996).[95]

This code is to protect vent and exhausts from taking on debris. If intake and exhaust vents were compromised, the interior air quality of the building could be compromised.

ICC 500 303.2: Roof live load ASCE 7 or 50 lb./ft squared - whichever is more conservative.[96]

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[92] ASCE, 7-10, 33
[93] ICC, IBC 2006, 2005
[94] ICC, IBC 2006, 2005
[95] ICC, IBC 2006, 2005
[96] ICC, IBC 2006, 2005

This is to ensure not spread across to large of a distance. By spreading the loads too far, the buildings structural integrity is compromised leaving it vulnerable.

ICC 500 304.5: Wind pressures shall be based on exposure category C. Except for hurricane shelters, where exposure category B exists for all wind directions. MWFRS wind pressures shall be permitted to rely upon exposure category B.

Wind exposure categories are related to location. This information is found in the ASCE-7. These exposure categories give the wind speed and load to which a building must be designed. This code in particular looks at the MWFRS (Main Wind Force Resisting Structure) so that the building's primary structure will withstand the pressure. For example, Hawaii's wind speed is 105 mph, where Southern Florida's is 150 mph.[97]

ICC 500 305.1.2: Debris impact- 9lb 2x4 lumber testing speeds= 0.4 x design speed for vertical surfaces, and 0.1x design speed for horizontal surfaces.[98]

As with the IBC codes, impact resistance is critical especially for a building that will shelter people during a storm. For this reason, the standard is more stringent making all vertical surfaces impact resistant along with a lower standard for horizontal surfaces.

IBC and ICC-500 Codes for Flood

IBC 2006 G701.1: Underground tanks in flood hazard areas shall be anchored to prevented flotation, collapse, or lateral movement.[99]

IBC 2006 G701.2: Above-ground tanks in flood hazard areas shall be elevated to or above the design flood elevation[i] or shall be anchored or otherwise designed and constructed to prevent flotation, collapse, or lateral movement.[100]

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[97] ASCE, 7-10, 33
[98] ICC, ICC-500, 2005
[99] ICC, ICC-500, 2005
[100] ICC, ICC-500, 2005

This is to ensure that tanks (such as gas tanks, settling tanks, or water tanks) that are located under or above ground are sufficiently secured and protected. There have been cases where tanks were lifted out of the ground of their anchors and become flood borne debris.

IBC 2006 1612.3: To establish flood hazard areas, the governing body shall adopt a flood hazard map and supporting data.[101]

The standard map that is most often selected is the FEMA Flood Zones map. This map categorizes flood zones and their risk of a flood event. The zones are based on previous flood events and modeling of potential flood conditions for an individual area.

IBC 2006 ASCE 24 Chapter 8: All new or replaced sanitary sewer facilities, private sewage treatment plants, on-site waste disposal systems, and water facilities shall be designed to minimize or eliminate infiltration of floodwater into the system.[102]

When flooding occurs, the water can infiltrate sewage treatment and then cause the sewage to spill out. This can put people at risk of disease and potentially contaminate potable drinking water.

ICC 500 Section 401.1.1: The lowest floor elevation shall be higher: 500 year flood map; OR 2 feet above 100 year flood map; OR 2 feet above highest recorded flood elevation where flood map is not available; OR above the maximum inundation elevation associated with Category 5 storm.[103]

This code directly addresses the elevation of buildings so that they are out of potential floodplain. The level discussed is the Design Flood Elevation (DFE)

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[101] ICC, IBC 2006, 2005
[102] ICC, IBC 2006, 2005
[103] ICC, ICC-500, 2005

where the first floor will begin and which is higher relative to the Base Flood Elevation (BFE) where the potential standing flood water elevation will exist.

ICC 500 Section 703.5: Standby electrical power system required for shelter having more than 50 occupants. Standby lighting system required for shelter having more than 50 occupants.[104]

Due to the nature of storm shelters they must be able to function during and after a storm even if the loss of power occurs elsewhere. By providing generators and backup power supplies, these buildings can continue functioning during and following a storm event.

A Critical Look at Current Building Codes

Currently, these building codes are in place throughout the United States. Current codes provide for basic life safety but are insufficient to address category five hurricanes. According to ASCE 7, all coastal areas throughout the country that can be affected by hurricanes have wind speeds of at least a category four hurricane while Hawaii is only a category 2. [105]

Looking at the extensive damage caused by hurricanes in areas where of higher wind speed is listed should show that current standards are insufficient. The main focus of these codes for hurricane response is for winds. These wind codes do not address factors other than windborne debris. However, storm surge and flooding is the greatest danger associated with the storm.[106] Codes related to flooding for general building construction are not linked to the building envelope, but only to the sewer and tanks outside of the building.

Flooding is addressed in the ICC-500, but these codes are only applied to buildings used as emergency shelters[107]. Even then, its only suggestion is to

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[104] ICC, ICC-500, 2005
[105] ASCE, 7-10, 33
[106] “NOAA Storm Surge”
[107] ICC, ICC-500, 2005

elevate above the base flood elevation and gives no further guidance. We, therefore, need to address flooding in the way we design.

Each of the MAT reports touched on wind failures, but focused mainly on hazard of flooding. If these reports are used in the development of codes, there seems to be an obvious gap that needs to be addressed. Local jurisdiction's do somewhat address flooding through zoning ordinances by setting base flood elevations and creating flood zones/ tsunami evacuation zones. However, these measures are not sufficient; stipulations are needed for proper connections between elevated structures and foundations. As was repeatedly recorded improperly anchored buildings were destroyed, destroying other structures in the process.

Current building codes take into consideration what can happen during a hurricane. A further problem is the way codes are enforced. In an article by J. Mulady in the Natural Hazards Observer in 1994, Dr. Mulady explains that after further investigation of buildings that adhere to the codes strictly withstand heavier forces exerted on them.[108] These structures were in areas where strict code enforcement took place this ensured that all buildings in the area were designed to withstand the forces. This is important to understand because post-disaster observations showed most often building failures caused by further failures through an exponential chain reaction.

What this Means for Hawaii

These standards from IBC 2006 are the current building codes used in Hawaii today, adopted in 2012 and six years out of date. However, before adopting the IBC 2006 the Unified Building Code 96 (UBC 96) was the standard. This, in essence, means that all buildings up until 2012 were being designed to a standard that never took hurricane loads into account.

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[108] Mulady, Building Codes They're Not Just Hot Air, 4

The standards in IBC 2006 are minimum standards and in the event of a major hurricane are incapable of withstanding the force exerted. Even though Hawaii is no longer completely out of date, they are still behind the curve. This leaves the community at risk and the ones who will suffer. It is imperative that a higher standard must be looked into for Oahu, especially for those in low-lying coastal areas.

Under both standards (UBC 96 or IBC 2006) if any of the three extreme events Iniki, Katrina, and Sandy were to happen on Oahu the damage would be extensive. Buildings would be rendered incapacitated and unable to be occupied. This problem is further complicated by the fact the according to the state civil defense; the State of Hawaii should be prepared for no aid for at least two weeks.[109]

[109] "Hawaii State Civil Defense"

Chapter 6. Going Beyond Code

The Federal Emergency Management Agency has released a series of guidelines to help protect the public against the hazards of disasters. The following section will look at five of these documents which relate to coastal development, flooding, and wind.

It is important to understand that these documents are strictly guidelines and do not have to be adhered to unless adopted by a local jurisdiction. However, they do offer a greater insight into what techniques can be used to mitigate hazards and further protect the lives within the built environment.

Many of these guidelines have been developed from lessons learned during disaster recovery efforts.

FEMA 361 Design and Construction Guidance for Community Safe Rooms

"FEMA 361 was first published in 2000 and was updated in 2010. When first developed, the standards and guidelines were more stringent than existing codes. However, FEMA 361 is a set of guidelines, so it is considered "Beyond Code" and is unenforceable unless adopted a governing document.

The International Code Council then took the 2000 version of FEMA 361 and amended the guideline to produce the ICC 500 which has been adopted by local jurisdictions. FEMA then updated the document in 2010, once again going beyond existing codes. When a topic is not explicitly covered for safe room facilities, FEMA 361 defers to ICC 500 standards for design.[110]

There were four recommendation related to the codes discussed in the previous section that extend beyond the standard enforced. These recommendations are

[110] NDPTC, HURRIPLAN, 493

from MAT Reports and help to show some of the gaps in design and construction for hurricanes.

Conventional construction builds for wind loads of design speeds ranging from 140- 150mph for a 3-second gust. In contrast, FEMA 361 2.1.1 recommends 200-225mph for a 3-second gust. At first glance, you would think that conventional is designing to a category five However this is only gust speeds that are discussed above. A category five hurricane has continuous winds of 157mph plus and gust speeds that surpass that base speed.[111]

For debris protection, FEMA 361 3.4.2 suggests having all cladding be impact resistant, not only windows. This includes wall and roof coverings, doors, vents, and windows. The impact resistance is higher than ICC-500 for near-absolute protection. [112]

For the issue of flooding FEMA 361 3.6.1 states that community safe rooms should be located outside of all high-risk flood hazard areas. This helps to minimize the risk of inundation.

While FEMA 361 3.6.1 suggests guidance for the "Design Flood Elevation (DFE): 2ft above the BFE*. Stillwater flood elevation for 500-year flood. Lowest floor elevation within a community's ordinance. 2ft above highest recorded flood elevation in the area. If the community safe room is an area subject to coastal storm surge inundation: Maximum still water inundation elevation associated with a Cat 5 Hurricane. The wave crest elevation has a 0.2% annual chance of being equaled or exceeded in any given year.[113]

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[111] FEMA, Design and construction guidance for community safe rooms FEMA 361, 2008
[112] FEMA, Design and construction guidance for community safe rooms FEMA 361, 2008
[113] FEMA, Design and construction guidance for community safe rooms FEMA 361, 2008

Protecting Building Utilities from Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems

This reference "provides guidance for incorporating flood damage resistant techniques in the design and construction of building utilities. This guidance is applicable for both new construction and substantially improved buildings. The material is covered in terms of performance characteristics rather than specific construction techniques or approaches."[114] This helps to allow for further modification and personal adaptation to each differing situation.

"The primary protection methods that apply to residential and non-residential building utilities and meet the minimum requirements of the NFIP (National Flood Insurance Program) include: the elevation of equipment and system components above the Design Flood Elevation (DFE) on pedestals, platforms, or fill, suspending them from structural elements, or moving them to upper floors or attics; and the protection of system components that exist below the DFE by utilizing water tight enclosures, protective utility shafts, and anchoring systems."[115]

The document discusses techniques for all of the following:

- Heating, Ventilating, and Air Conditioning (HVAC) Systems
- Fuel Systems
- Electrical Systems
- Sewage Management Systems
- Potable Water Systems

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[114] FEMA, Protecting Building Utilities from Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems, 3.0-2

[115] FEMA, Protecting Building Utilities from Flood Damage: Principles and Practices for the Design and Construction of Flood Resistant Building Utility Systems, 3.0-2

This shows a complete set of suggestions to prepare a building better for a storm. As was recorded in the Sandy MAT report, system failures caused some of the greatest problems following the storm. By better designing to address the issue of flood damage to utilities we are capable of making building better able to function after.

Flood Damage Resistant Materials

""Flood [damage]-resistant material" is defined by the NFIP (National Flood Insurance Program) as "any building product [material, component or system] capable of withstanding direct and prolonged contact with floodwaters without sustaining significant damage." The term "prolonged contact" means at least 72 hours, and the term "significant damage" means any damage requiring more than cosmetic repair. "Cosmetic repair" includes cleaning, sanitizing, and resurfacing (e.g., sanding, repair of joints, repainting) of the material. The cost of cosmetic repair should also be less than the cost of replacement of affected materials and systems. In addition to these requirements, individual materials that are considered flood damage-resistant must not cause degradation of adjacent materials or the systems of which the material is a part."[116]

These materials help aid in the recovery process by preventing molding and are easily cleaned. Using these types of materials, a building will be better prepared if inundated.

The following list shows materials their use and whether or not they can be used for flood proofing:

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[116] FEMA, Flood Damage Resistant Materials, 2

Table 2 FEMA Flood Resistant Materials Source Technical Bullet

Table 2. Types, Uses, and Classifications of Materials (continued)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls/ Ceilings	5	4	3	2	1
Structural Materials (floor slabs, beams, subfloors, framing, and interior/exterior sheathing)							
Preservative-treated, Borate[2]	■	■	■				
Exterior grade/Exposure1 (WBP – weather and boil proof)	■	■		■			
All other types	■	■					■
Recycled plastic lumber (RPL)							
Commingled, with 80-90% polyethylene (PE)	■		■				
Fiber-reinforced, with glass fiber strands	■		■				
High-density polyethylene (HDPE), up to 95%	■		■				
Wood-filled, with 50% sawdust or wood fiber	■				■		
Stone							
Natural or artificial non-absorbent solid or veneer, waterproof grout	■	■	■				
All other applications		■				■	
Structural Building Components							
Floor trusses, wood, solid (2x4s), decay-resistant or preservative-treated	■	■		■			
Floor trusses, steel[3]	■		■				
Headers and beams, solid (2x4s) or plywood, exterior grade or preservative-treated		■		■			
Headers and beams, OSB, exterior grade or edge-swell resistant		■				■	
Headers and beams, steel[3]		■	■				
I-joists	■					■	
Wall panels, plywood, exterior grade or preservative-treated		■		■			
Wall panels, OSB, exterior grade or edge-swell resistant		■				■	
Wall panels, steel[3]		■		■			

Table 3 (Continued) FEMA Flood Resistant Materials Source Technical Bullet

Table 2. Types, Uses, and Classifications of Materials (continued)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls/ Ceilings	5	4	3	2	1
Structural Materials (floor slabs, beams, subfloors, framing, and interior/exterior sheathing)							
Wood							
Solid, standard, structural (2x4s)		■		■			
Solid, standard, finish/trim		■			■		
Solid, decay-resistant[4]	■	■	■				
Solid, preservative-treated, ACQ or C-A		■		■			
Solid, preservative-treated, Borate[2]		■		■			
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Asphalt tile[5]							
With asphaltic adhesives	■				■		
All other types	■						■
Cabinets, built-in							
Wood		■				■	
Particle board		■					■
Metal[3]		■		■			
Carpeting	■						■
Ceramic and porcelain tile							
With mortar set	■	■		■			
With organic adhesives	■	■				■	
Concrete tile, with mortar set	■		■				
Corkboard		■				■	
Doors							
Wood, hollow		■				■	
Wood, lightweight panel construction		■				■	
Wood, solid		■				■	
Metal, hollow[3]		■		■			
Metal, wood core[3]		■		■			
Metal, foam-filled core[3]		■		■			
Fiberglass, wood core		■		■			
Epoxy, formed-in-place	■		■				

Table 4 (Continued) FEMA Flood Resistant Materials Source Technical Bullet

Table 2. Types, Uses, and Classifications of Materials (continued)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls/ Ceilings	5	4	3	2	1
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Glass (sheets, colored tiles, panels)		■		■			
Glass blocks		■	■				
Insulation							
Sprayed polyurethane foam (SPUF) or closed-cell plastic foams	■	■	■				
Inorganic – fiberglass, mineral wool: batts, blankets, or blown	■	■			■		
All other types (cellulose, cotton, open-cell plastic foams, etc.)	■	■				■	
Linoleum	■						■
Magnesite (magnesium oxychloride)	■						■
Mastic felt-base floor covering	■						■
Mastic flooring, formed-in-place	■		■				
Metals, non-ferrous (aluminum, copper, or zinc tiles)		■			■		
Metals							
Non-ferrous (aluminum, copper, or zinc tiles)		■			■		
Metals, ferrous[3]		■		■			
Paint							
Polyester-epoxy and other oil-based waterproof types		■		■			
Latex		■		■			
Partitions, folding							
Wood		■				■	
Metal[3]		■		■			
Fabric-covered		■					■
Partitions, stationary (free-standing)							
Wood frame		■		■			
Metal[3]		■		■			
Glass, unreinforced		■		■			
Glass, reinforced		■		■			
Gypsum, solid or block		■					■

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Table 5 (Continued) FEMA Flood Resistant Materials Source Technical Bullet

Table 2. Types, Uses, and Classifications of Materials (continued)

Types of Building Materials	Uses of Building Materials		Classes of Building Materials				
			Acceptable		Unacceptable		
	Floors	Walls/ Ceilings	5	4	3	2	1
Finish Materials (floor coverings, wall and ceiling finishes, insulation, cabinets, doors, partitions, and windows)							
Polyurethane, formed-in-place	■		■				
Polyvinyl acetate (PVA) emulsion cement	■						■
Rubber							
Moldings and trim with epoxy polyamide adhesive or latex-hydraulic cement		■		■			
All other applications		■					■
Rubber sheets or tiles[5]							
With chemical-set adhesives[6]	■		■				
All other applications	■						■
Silicone floor, formed-in-place	■		■				
Steel (panels, trim, tile)							
With waterproof adhesives[3]		■	■				
With non-waterproof adhesives		■				■	
Terrazo	■			■			
Vinyl asbestos tile (semi-flexible vinyl)[5]							
With asphaltic adhesives	■		■				
All other applications	■						■
Vinyl sheets or tiles (coated on cork or wood product backings)	■						■
Vinyl sheets or tiles (homogeneous)[5]							
With chemical-set adhesives[6]	■			■			
All other applications	■						■
Wall coverings							
Paper, burlap, cloth types		■					■
Vinyl, plastic, wall paper		■					■
Wood floor coverings							
Wood (solid)	■						■
Engineered wood flooring	■					■	
Plastic laminate flooring	■					■	
Wood composition blocks, laid in cement mortar	■					■	
Wood composition blocks, dipped and laid in hot pitch or bitumen	■					■	

Along with using flood resistant materials is the use of wet flood proofing. “Wet floodproofing is a method to reduce damage that typically involves three elements: allowing floodwaters to enter and exit to minimize structural damage, using flood damage-resistant materials, and elevating utility service and equipment. When a building is retrofitted to be wet floodproofed, non-flood damage-resistant materials that are below the BFE should be removed and replaced with flood damage-resistant materials. This will reduce the costs of repair and facilitate faster recovery.”[117]

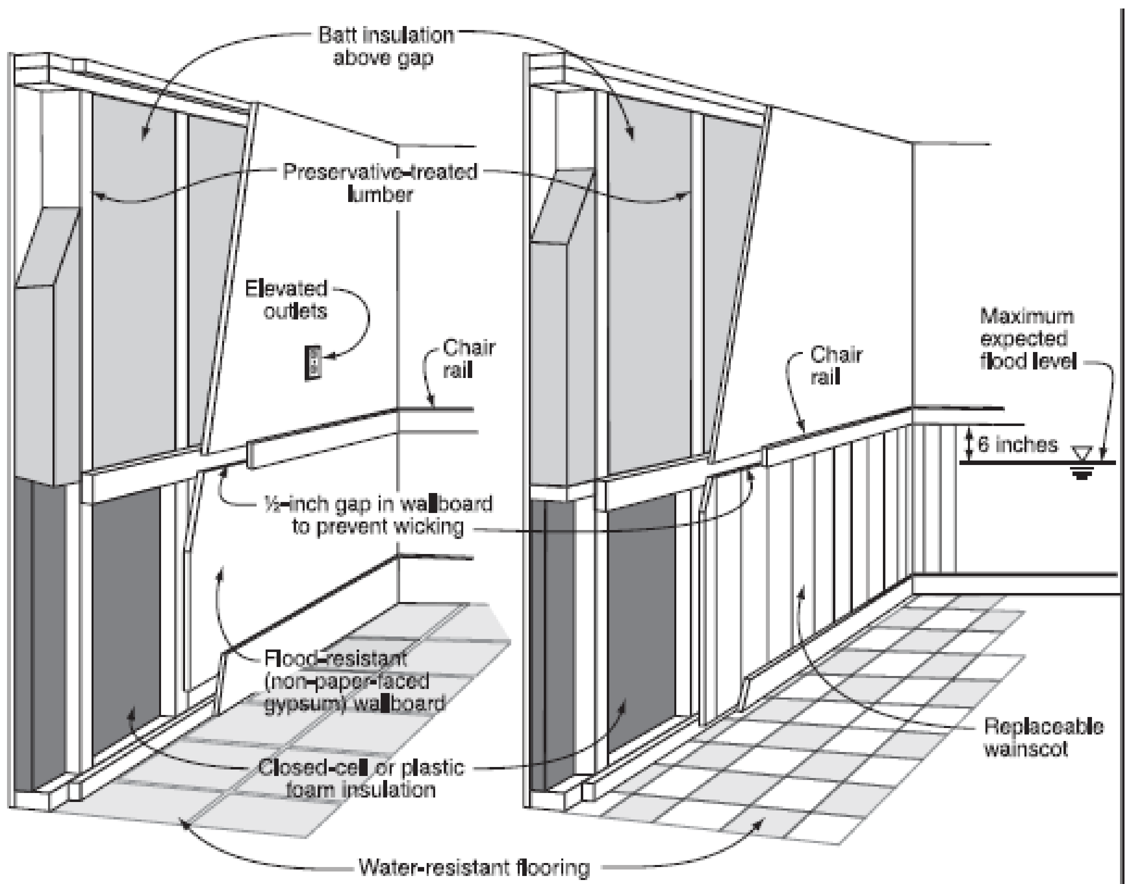

Figure 34 Wet Floodproofing Source Flood Damage Resistant Materials, p18

[117] FEMA, Flood Damage Resistant Materials, 15

Design and Construction Guidance for Breakaway Walls

"Coastal waves and flooding can exert strong hydrodynamic forces on any building element that is exposed to the waves or flow of water. The NFIP (National Flood Insurance Program) requires that all new buildings, substantially damaged buildings, and substantially improved buildings in Coastal High Hazard Areas (Zones V, VE, and V1030)[ii] be elevated to or above the base flood elevation (BFE)[iii] on open foundations consisting of piles, posts, piers, or columns. These open foundations must be designed to allow waves and water moving at high velocity to flow beneath buildings.

NFIP (National Flood Insurance Program) regulations require that the area below the lowest floor of elevated buildings either be free of obstructions or have any enclosed areas be constructed with non-supporting breakaway walls, open lattice-work or insect screening. The walls, lattice, or screening are intended to collapse under wave loads without causing collapse, displacement, or other structural damage to the elevated building or the supporting foundation system. Obstructions below an elevated building can significantly increase the potential for flood damage by increasing the surface area subject to wave impact and velocity flow."[118]

Sacrificial walls help to provide secured space at the ground level of an elevated building. However, when a storm comes they are not rigid and will not compromise the structural integrity of the overall building.

"MAT reports prepared after significant coastal storms have consistently concluded that breakaway wall systems perform as intended when they are designed and constructed to break away without damaging the elevated home and without becoming debris that can be trapped under buildings."[119]

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[118] FEMA, Design and Construction for Breakaway Walls, 1
[119] FEMA, Design and Construction for Breakaway Walls, 5

Beyond Code

These guidelines provided by FEMA show the gaps in current building codes. This need to protect buildings from flood waters is a pressing issue. Especially as we see sea levels rising with climate change.[120]

However, there is still a gap between dense areas/large buildings and these guidelines. While FEMA 361 discussed storm shelters, the other documents addressed single family homes. The information provided, however, is still valid. It offers insight into techniques and materials in preparation for flooding events. This is especially helpful for an area like Kakaako that is low lying and within the tsunami evacuation zone.

[120] Fletcher, Living on the Shores of Hawaii,

Chapter 7. Mitigation Strategies

There are two critical factors when designing for a hurricane resilience, material selection, and design techniques. The selection of materials help to ensure that the building will perform under the harsh conditions a current can present. While the design techniques contribute to mitigate these hazards or adapt to meet them. When used together a building is capable of functioning following a storm event. This ensures that those who occupy the space are safe during and following a hurricane.

The following section will first look at a selection of building materials that can be used in hurricane-prone areas. These materials are ideal for severe flooding areas and can withstand impact from debris. They also are cleaned simply up and won't degrade when exposed to water.

It will then look at a list of techniques that have been identified as key factors to ensure a building is habitable following a hurricane. These consist of protecting interior spaces from hazards, preserving building systems, and ensuring the building can function properly following a storm.

Material Selection

When designing for hurricane resilience, material selection can play a crucial role. In order for the material to hold up to the forces of a storm, it must be easily repairable, easily cleanable, impact resistant, and not degrade when exposed to water. The following list of building materials are some of the wide variety available that posses these qualities.

Large Thin Tile: This tile is used in wall, floor, and ceiling finishes and comes in a large variety of sizes and finishes. These ceramic tiles have a fiberglass backing to give them extra strength and come in nominal sizes of 3'x9' rough and about 1/8". Being a tile if one is broken you can remove the single tile alone and replace it easily. They also can be cleaned easily and won't mold or degrade with water. This makes it an ideal candidate for areas that could flood but are occupied the rest of the time.

Modern Vinyl Flooring: Vinyl flooring has come a large way since being developed. There are a large number of companies that sell modern vinyl flooring today. The tiles themselves come in a wide variety of colors and patterns. Being adhered directly to the floor they will not mold and will last through the storm. Being modular they can be repaired easily if damaged while not damaging the rest of the tiles. In addition vinyl flooring is extremely cost effectived compaired to other flooring materials available.

Metal Wall Panels: The metal wall system comes in a large variety of size color and shapes. It is a system of metal tiles that can be custom made to color and pattern you desire. These systems work on both the exterior and interior of a building. As an exterior finish, these systems are installed as rain screen system and are impact resistant to create a protective layer around the building. As an interior finish it the system is offset to create an air cavity that allows interior spaces to dry out following a storm.

Solid Surface: This material is anti-microbial easily repairable and offers a streamlined finish. Solid surface can be thermally formed, and heat welded. This allows the material to cover large area. It also enables the material to be cut and repaired on the spot without any sign of patching or filling. The material is also anti-microbial, this means that it can be clean easily and will not mold or degrade from water exposure. This is one of the most versatile of materials; it can be used to create furniture, all interior finishes, as well as serve as an exterior wall cladding.

Acrylic Panels: There is a large variety of acrylic panels that can be used to separate spaces or as wall finishes. These panel solutions are off the shelf type systems, which makes them cheaper and easy to apply. They are great to accent plain walls or add feature ceiling pieces. The company itself has a large number of solutions that help designers create beautiful interior spaces with minimal cost. The simple constructability offers the chance to remove the systems and store them before the storm comes. Then to clean the space and replace them as if nothing ever happened, offering a different solution to the problem.

Precast/Cast in Place Concrete: Traditional solution to dealing with water is using exposed concrete. There are a large number of elegant ways to use concrete, as an either a standalone finish or a base for another material. This offers two layers of protection or provides a strong base if the top layer is removed as in the case of acrylic panels. When precast concrete panels are used, they provide a similar strength but the cost is lower because casting molds can be used multiple times.

Modular Wall Systems: Architectural modular folding walls/doors provide a solution in letting flood waters directly enter the building and remove the hydrostatic pressure from the front of the building. This significantly helps in the controlling flood waters and contributes to eliminate damage to the exterior of the building. These doors/walls come in a variety of material finishes and styles. There is a wide range of styles from vertical folding, pivoting, to collapsing.

Hurricane Shutters: Impact resistant hurricane screens help to ensure that glazing and openings to be protected from debris. They also can create a buffer zone between the interior and exterior of the building. Often perforated they allow rain waters to pass through and leave. This eliminates hydrostatic pressure on the surface to ensure that they will withstand whatever the storm brings.

Building Organization

One major failure during hurricanes to high-rises and dense built areas is failures in mechanical systems. These failures resulted from the way the building spaces were organized and. When mechanical equipment is placed on rooftops, the hazards from winds either caused damage from impact or uplift. While when placed in basements and first levels it was flooded and destroyed. By first rethinking the way we organize buildings we can better prepare for hurricanes. Like the Unité d'Habitation by Le Corbusier, we need these buildings to function as vertical neighborhoods.[121] By developing vertical neighborhoods, we can separate spaces in vertical zoning.

Figure 35 Building Organization Diagram Source Michael Hill

Figure 35 depicts one example of how to organize the space in a building to respond to the hazards of a hurricane. The first two floors are commercial spaces. These spaces can aren't mandatory for a building to function but aid in creating a better-designed community. The next floors are designated to being equipment spaces. These spaces are the internal workings of the building and crucial to it function following the storm. The next spaces are public spaces. These spaces give additional refuge space if needed but operate as function

[121] "Unité D'habitation (Cité Radieuse) Marseille by Le Corbusier.", accessed February 3, 2015

rooms, fitness area, laundry, and spaces like this. They also serve as a buffer zone between mechanical systems and the residential areas. Finally, the last top floors of the building are housing units. The two critical areas for this concept to work are the sacrificial floor and the centralized mechanical and equipment floors.

Sacrificial Lower Floors: The first two floors are what usually are flooded during a hurricane. By designing these floors to allow flood waters to enter the space, we can protect the rest of the building. This technique removes potential mold problems and hydrostatic pressure caused by flooding on the structure.

This is done by using modular exterior wall systems that can be opened or removed to let flood water enter the structure. These walls can either be panelized, pivoting, or folding; there is currently a large variety of these types of products available off the shelf.

In addition to the walls, the interior material choice helps to allow this space to be flood resistant. By using materials that can be cleaned easily and won't degrade after being exposed to water you can ensure the space can be restored quickly after a storm. The material list provided in the previous section offer some of these materials that are ideal for this purpose. By planning and designing with materials that can withstand impact or are easily repairable when damaged. Designers can create a space independent from the rest of the building. It also allows operators of these spaces to return to their areas quickly, helping to restore areas faster during post disaster cleanup.

Centralized Mechanical and Equipment Floors: Hurricane Sandy was able to show us how high-rise buildings failed when their mechanical systems failed[122] while their structure stayed intact. By designating the third and fourth floors of a

[122] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

building to be the mechanical system space, we can create another level of protection.

This location allows the space to be easily accessed during and following a storm which is important to monitor systems and repair equipment as needed. Elevating keeps equipment out of the potential flood threat to keep failures from happening similar to those in New York.[123] These floors are usually the first set atop a buildings podium which allows the spaces to be hidden from view from the street. While hurricane screens can be integrated into the space to offer another level of protection and allow mechanical systems the proper ventilation, they require.

Defensible Perimeter

The integrity of the envelope is the key to the performance of the building and the amount of loss it may suffer during a hurricane. Likewise, the performance of exterior equipment will strongly affect whether the building is habitable after the hurricane.[124] By not having impact resistant glazing and envelopes, buildings envelopes can be penetrated which results in damage to the interior spaces.

[123] FEMA, Hurricane Sandy in New Jersey and New York: building performance observations, recommendations, and technical guidance, 2013

[124] NDPTC, Hurriplan, 90

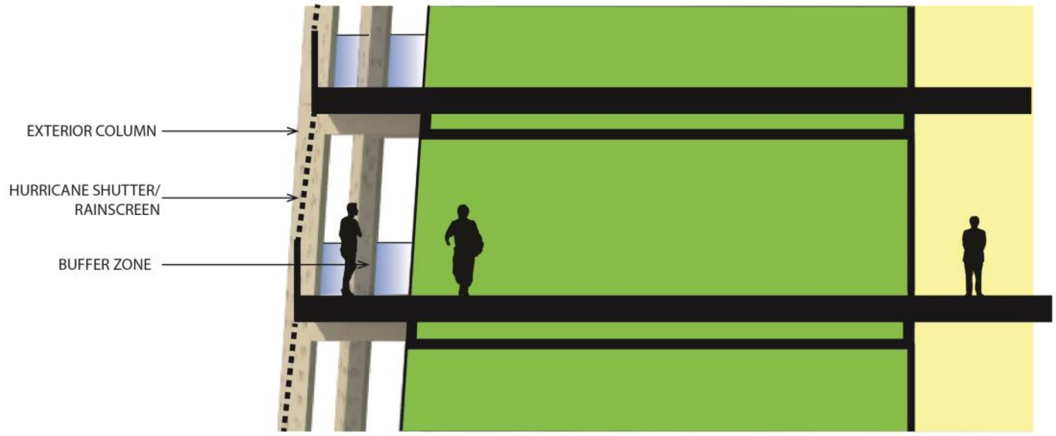

Figure 36 Defensible Perimeter Diagram Source Michael Hill

In order to mitigate this hazard, a defensible perimeter is required. This can be done by moving structural members to the exterior of the building and suspending the floor plates between them. The structure is then able to create the frame of a protective shell. In order to complete this shell impact resist hurricane screens can be placed between these columns. Creating a buffer zone between the interior the defensible perimeter and the interior space. This allows standard materials to be used within the interior residential and offices space to eliminate the additional cost of flood resistant materials.

Bioswales and Permeability

During Hurricane Sandy, there was extensive flooding throughout Lower Manhattan due to the lack of permeability and storm drains back flowing. Permeable surfaces allow water to soak into the earth and can help dissipate flood waters. However, cities often lack the permeability due to the extensive amount of paving and lack of green spaces. By introducing materials and spaces that allow water to percolate into the ground. This serves two purposes, it helps to reduce storm water runoff and to remove flood waters faster following the event. There are many techniques to allow waters to return to the earth's surface. Two of these techniques are permeable paving and bioswales.

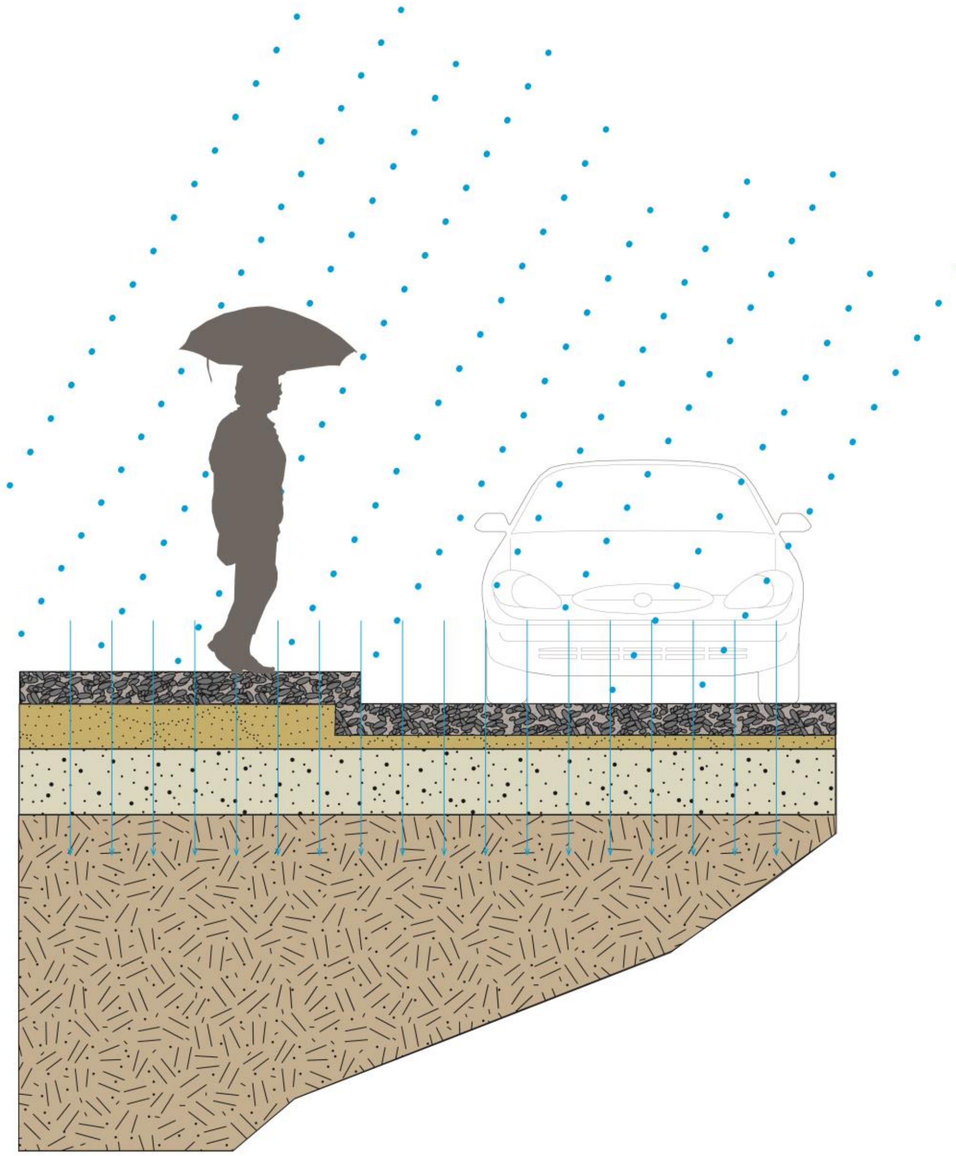

Figure 37 Permeable Paving Diagram Source Michael Hill

Permeable paving is created the same way as a normal paving except that it does not add the finer materials in the mix. This creates gaps in to allow water to pass through underneath into a holding area comprised of gravel. Giving the water a place to stay until it can percolate into the soil. There are both permeable concretes and asphalts, which mean that all pathways and roadways at the ground level can be built with these permeable surfaces.

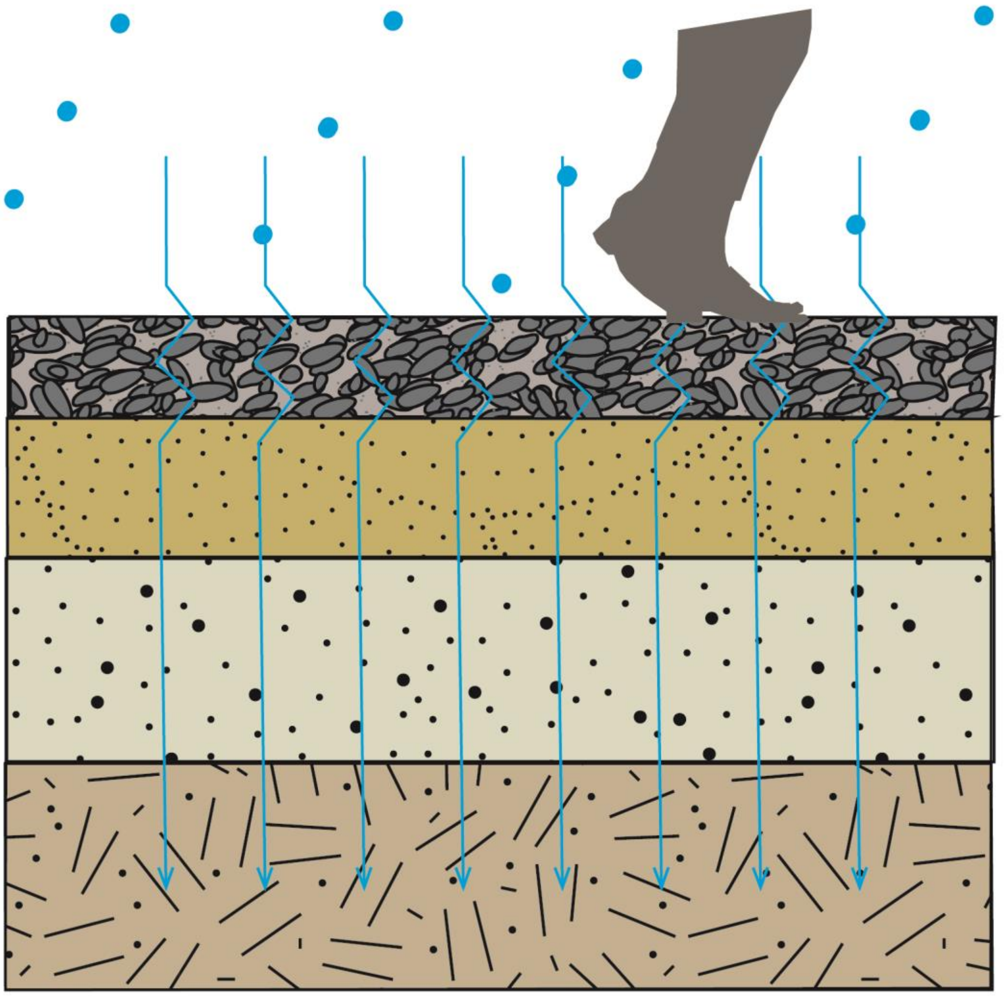

Figure 38 Enlarged Permeable Paving Diagram Source Michael Hill

Bioswales offer a similar solution by containing water in a green space until it can normally dissipate. Bioswales are designed as water catchments with a gravel holding area and overflow drain. This maximizes the amount of water these areas can hold. Locating the bioswales as island in the center of roads or as along sidewalks allows them to act as planting strips until they are needed for storm water mitigation. This helps to beautify the community while helping protect it.

Figure 39 Bioswale Diagram Source Michael Hill

Wind Tolerant Form

A buildings form can help to remove pressures caused by the severe wind loads during a hurricane. When buildings have flat surfaces, wind is forced down word creating stronger winds and pressure. By rounding the form, the winds are diverted around the shape. This removes the downward force and internal pressure. Which helps to distribute the load more equally across the form rather than one centralized location. Figure 40 shows how the concept works, the darker the color, the more pressure that is being exerted on the form.

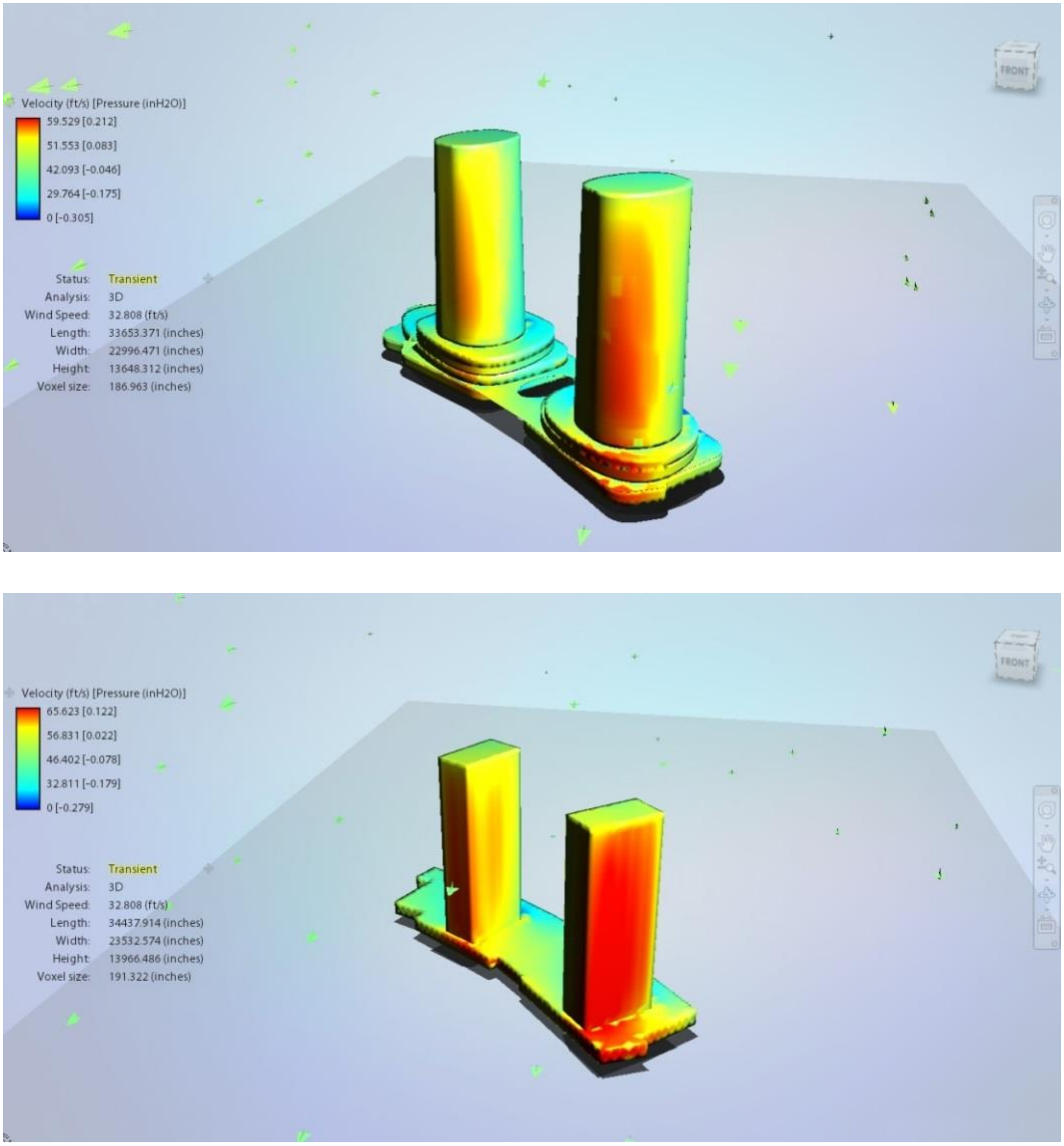

Figure 40 Wind Load Model Source Michael Hill

Building Systems Hazard Mitigation

In order for a building to function during and following a storm the buildings systems must operate. Hurricane hazards will cripple a community's water and power supplies, or render a buildings equipment nonoperational.

To respond to this issue systems need to work even if power stations and water treatment plants fail. There is currently a large variety of different systems available that either functions completely or partially off the grid allowing them to function without a city's infrastructure. Many of these systems can be easily installed and can help a building to have water and power following a storm. However integrating these features types of systems can better prepare a building to be more resilient and resistant.

By elevating and running all forms of services lines through a system of elevated piers/walkways that connect the building, we can protect and keep services functioning during a major hurricane event. We are also able to integrate some features into these elevated public spaces, such as parks, fountains, and solar walkways that aid in the protection of the community.

Water

Water is the key to life, and it is important that people have potable water available during and following a hurricane. It also requires the removal and treatment of wastewater. The average person uses 80 to 100 gallons of water daily.[125] In order to extend that water, we need to rethink the way we look at water. This means that the water we use needs to be lengthened. Water from sinks, bathing, and washing should be used to flush toilets and irrigate as needed. This in its self will cut the amount of water we use. Then we need to create closed loop systems of water so that we no longer are overly dependent on water supply lines. This can be done by treating water onsite. There are a

[125] "Water Questions & AnswersHow Much Water Does the Average Person Use at Home per Day?", accessed 30 Mar. 2015.

large number of onsite wastewater treatment systems being researched and studied an ideal solution for Hawaii is an algae-based system (see figure 53).

Rainwater Harvesting: Rainwater harvesting has been throughout history. It is a creative alternative approach to water supply. By capturing, diverting, and storing rainwater for later use it can reduce demands on existing water supply, and reduces run-off, erosion, and contamination of surface water. This helps to create reservoirs of water available for use following a storm as long as storage tanks are not compromised or contaminated.

Gray Water Reuse: Greywater is water that has been used for washing dishes, laundering clothes, or bathing, essentially, any water, other than toilet wastes. Reusing greywater serves two purposes: it reduces the amount of freshwater needed to supply a household and reduces the amount of wastewater entering sewer or septic systems. By extending the use of water, we can limit the quantity of water required for each person on a daily basis. This can help ensure that following the storm, water supplies can last longer.

Water Reclamation: Water reclamation removes solid waste and treats the water so that it is safe to return to the environment. The most common type of water reclamation is done by using bioremediation. Where plants are used to clean and treat the water so that it can be used as greywater for irrigation, flush toilets, or any use other than for drinking or ingesting. These systems offer a chance to extend the life of the water we use and to place it back into the environment.

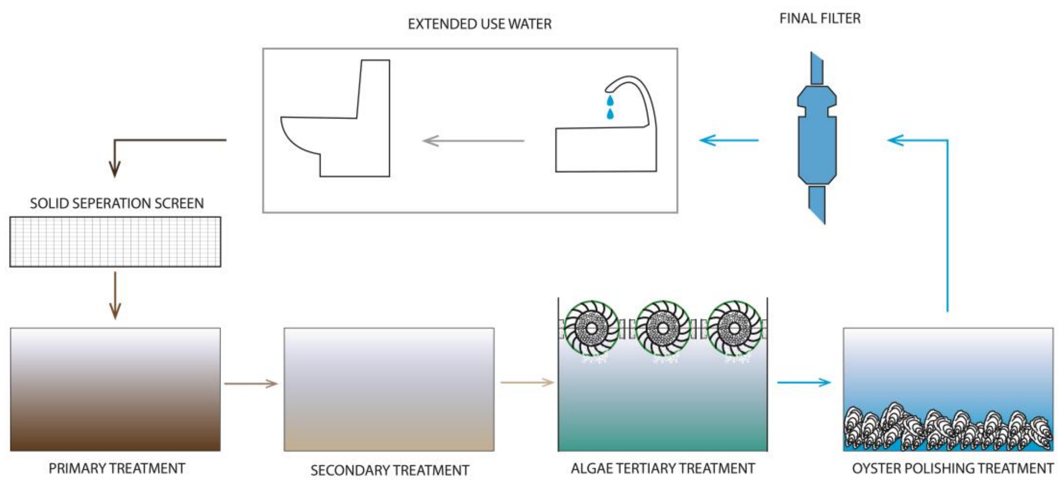

Figure 41 Algae Wastewater Treatment Process Diagram Source Michael Hill

The algae cleans both the water and air during its processing. A bacterium converts the waste into a food source for the algae and through photosynthesis the waste is removed from the water.

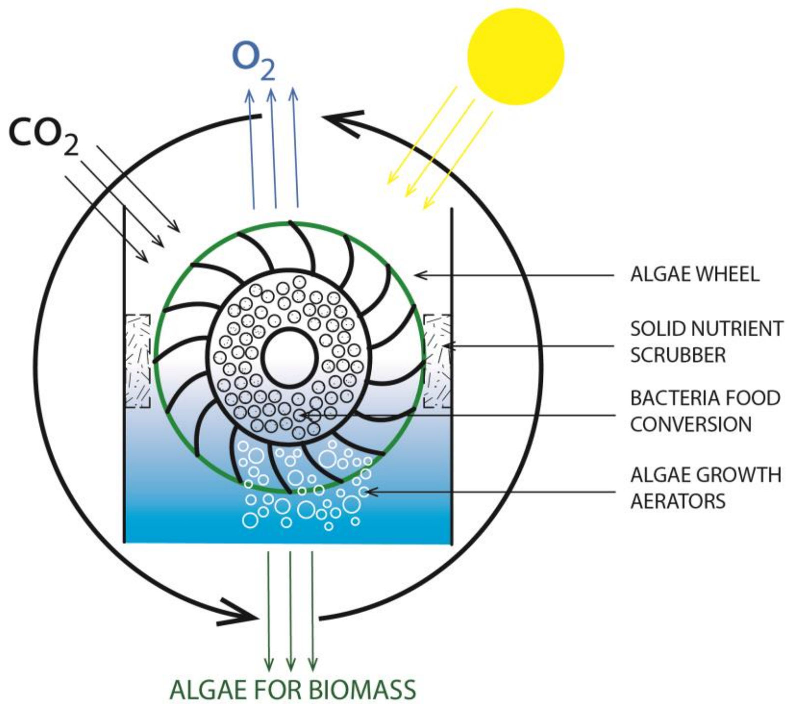

Figure 42 Algae Wheel Process and Benefits Diagram Source Michael Hill

Following this algae cleaning process a final polish is completed by Pacific Oysters. One oyster is capable of cleaning 50 gallons of water in 24 hours.[126] Following this polishing process the water is then filters at each unit per potable use or is used to irrigate.

Electrical

Photovoltaic Panels: A fairly standard use today photovoltaic cells are placed in large panels; these cells convert sunlight into electrical energy. This energy is then stored in banks of batteries for later use.[127] These panels can often fail during a hurricane by uplift. This leaves this type of system less reliable in hurricane-prone areas.

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126 "Oyster Reefs - Oysters - Chesapeakebay.noaa.gov.", accessed March 30, 2015.
127 "How Do Photovoltaics Work?", accessed February 18, 2015.

Integrated Photovoltaic: These photovoltaic systems integrate the photovoltaic cells into building components such as roof tiles, glazing, and sunshade devices are just a few examples. These components offer greater resilience to uplift during a storm. Working the same way as a standard photovoltaics if able withstand the impact of debris and uplift; this type of system should be able to function following a storm in not damaged. [128]

Wind turbines: Onsite wind turbines offer the chance to use wind to generate electricity through a turbine generator.[129] Wind turbines come in a variety of scales. Similar to photovoltaics the energy created is stored in a system of batteries. These turbines need a minimal and maximum amount of winds they can operate in. If left to operate in excessive winds turbines can fail and cause irreparable damage.

Geothermal: Geothermal energy is the heat from the Earth. Resources of geothermal energy range from the shallow ground to hot water, and hot rock found a few miles beneath the Earth's surface. Wells can be drilled into underground reservoirs for the generation of electricity. Some geothermal power plants use the steam from a reservoir to power a turbine/ generator while others use the hot water to boil a working fluid that vaporizes and then turns a turbine.[130]

Photovoltaic Road/ Pathways: Another form of integrated photovoltaic are photovoltaic roadways and pathways. These systems have a top coating that enables vehicles and people traffic on top of them. This lets public areas such as bike paths and parks take advantage of sun's energy. This type of system is being further developed. The Netherlands have installed a photovoltaic pathway

[128] "Building Integrated PV for Commercial and Institutional Structures", accessed 30 Mar. 2015 United States. Dept. of Energy ;, 2000. Print.
[129] "Energy.gov.", accessed February 18, 2015.
[130] "Geothermal Energy.", accessed 30 Mar. 2015.

with outstanding success.[131] This system can withstand the rain and flood waters because the system is sealed within the coating material. Which makes a system like this optimal for hurricane prone areas, as long as battery banks are in a secured location.

Biomass: Biomass is the use of plant life to create a fuel. This fuel is burned to create power from a system of boilers that produces steam and runs a turbine generator. In order for this type of system to work you must have a viable fuel source.[132] There are a few different types of plants that are used to create fuel; the two most common are corn and algae. There are current developments in creating small-scale generators that can be integrated into a building. This allows a building to work off the grid. Currently, these systems are being further developed with cost for a single family home for one unit to cost $12,000.[133]

An algae biomass system works in harmony with the wastewater treatment system. As algae dies and falls off the filtering wheels, it is then collected and turned into a biomass fuel. This fuel is then burned in generators to create steam and energy which is then saved in a bank of batteries. Ensuring that power is available during and following a storm. [134]

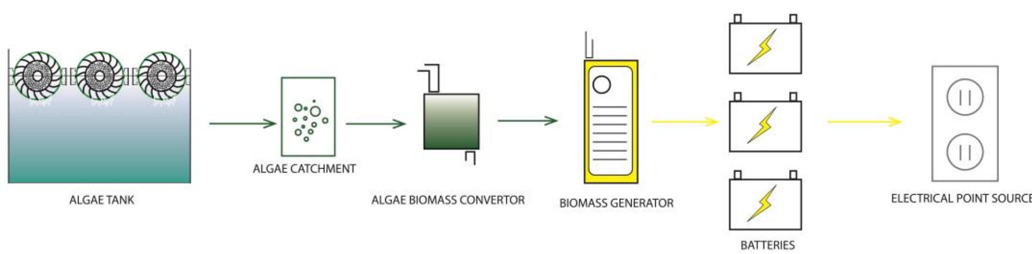

Figure 43 Algae Biomass Generators Process Diagram Source Michael Hill

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[131] "Introducing The World's First Solar Sidewalk.", accessed 30 Mar. 2015.
[132] "How Biomass Energy Works.", accessed February 18, 2015.
[133] Wallis, David. "When Algae on the Exterior Is a Good Thing.", accessed February 18, 2015.
[134] IBID

Solar pathways are a new type of technology emerging. Photovoltaics are integrated into pathways, with a protective and slip resistant top coating. These pathways can connect buildings through public spaces adding additional power supply as needed. This helps to bolster the community, and better prepare it for the hurricane. It also eliminated the load on power stations and can create nodal power supplies for communities. [135]

Elevated Pathways

As mentioned before system failures can often cause building failures. These failures can occur when service lines become inundated. It is common for water and sewer mains to become inundated with flood water. This can taint and cause sewers to back up into streets. While power and communication lines can be rendered unusable by flood waters or in cases of elevated power lines can be destroyed by debris and severe winds. In any case protection of these systems help protect the building's they service.

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[135] "Introducing The World's First Solar Sidewalk.", accessed 30 Mar. 2015.

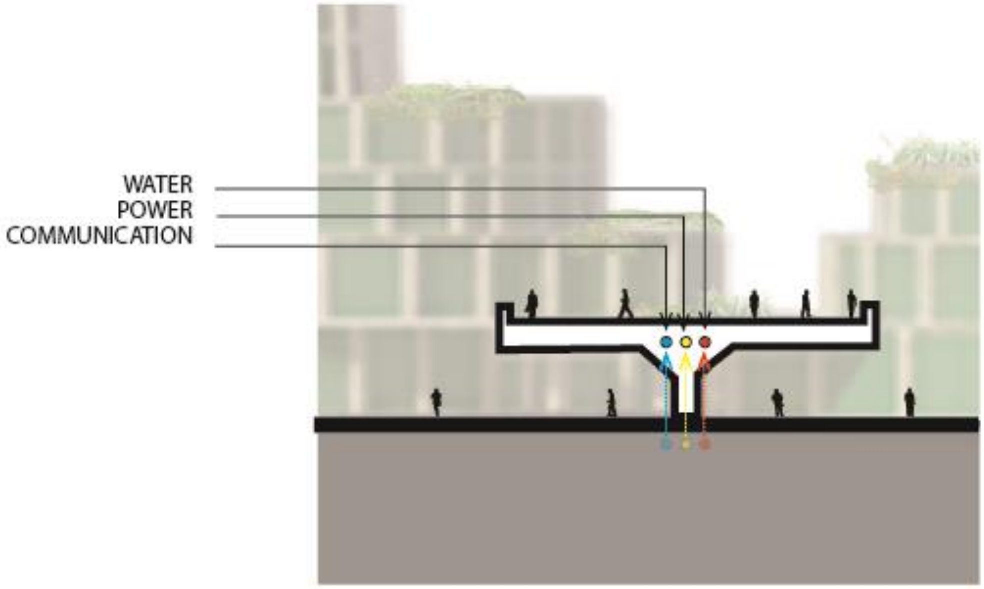

Figure 44 Elevated Walkway Diagrams Source Michael Hill

By running these systems through a series of elevated walkways you can protect them from both wind and flooding hazards. In addition, these pathways offer an alternate means of travel between spaces in case flood waters do not recede quickly as in the case of Katrina. In order to maximize these spaces, potential integration of solar pathways helps to bolster the available energy resources for the community.

Chapter 8. Designing for a Hurricane

Current construction and design practices most often do not sufficiently address hurricanes. In Hawaii, people are apathetic to the threat of a severe hurricane because it has been 20 years since Iniki leaving people vulnerable.

Oahu is the most densely populated island in Hawaii and holds a majority of the population. According to the Census 2010 the population of Oahu is 953,207, with the majority of the development within coastal areas. [136]

Oahu is still growing and with a new rail proposal there has been increasing in new development around Honolulu County Planning Department's TOD (Transit Oriented Development) Plan.[137] Kakaako, a former industrial area on Oahu's South Shore, has seen a boom of development around these locations, which gives an ideal location for developing a hurricane resilient community.

The first section will look at Kakaako and the section of the community being considered for a potential site for this development. Looking at zoning and regulations, flood zone information, sea level rise projection, and base flood elevation (BFE) will help to create a comprehensive response to the hazards associated with a hurricane. Along with the previous information this section will also look at infrastructure and how/what systems may be affected by a storm at both the regional and local scales that will affect occupancies of the buildings in this area.

It will then go over a conceptual master plan of the area with phases to achieve hurricane resilience through building and infrastructure mitigation strategies. To show how simple steps can better prepare not only a building but an entire community to respond to the hazards a hurricane can present.

[136] "2010 Census Interactive Population Search.", accessed April 18, 2014.
[137] "TOD Honolulu Transit-Oriented Development.", accessed April 18, 2014.

History of Kakaako

"Kakaako's history is rooted in industry, entrepreneurship, and cultural diversity. In ancient times, Kakaako was an area comprised of fishing villages, fishponds, and salt ponds. To Native Hawaiians, salt was valued like gold and Kakaako's salt ponds were of significant importance to the area.

In the 1800's residential construction began and diverse immigrant "camps" grew. Kakaako's industrial roots began here with the establishment of the Honolulu Iron Works, a metal foundry and machine shop. Small stores, churches, schools, and parks were built including Pohukaina School, which sat next to Mother Waldron Park. Kakaako grew and became a community built on a blue-collar work ethic, social activism and a strong sense of family.

In the mid-1900's zoning for Kakaako changed from residential to commercial. Small businesses and entrepreneurship grew as wholesaling, warehousing and other industrial businesses displaced residents leading to the urban Kakaako you see today."[138]

Two major developers have proposed major changes to Kakaako. Kamehameha Schools and Howard Hughes have proposed large residential and mixed use developments. Howard Hughes is developing a large section of Kakaako including a commercial space and a series of residential towers called Ward Village. This new development is situated next to one of the new proposed rail stations and, has increased density and a mixed of uses district to encourage healthier communities. However, this area is directly next to the coastline and located with tsunami evacuation and FEMA flood zones. Making it a prime location for destruction from a hurricane. However, measures are not being taken beyond codes.

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[138] "Our kaka'ako.", accessed April 18, 2014.

This means buildings will only be designed to a minimum standard such as large missile impact glazing from 30ft above grade and below and small missile impact glazing above 30ft. While all structures and cladding components will only be designed to withstand a category two hurricane.

Then with the addition of these new residential towers the population of this area is going to increase substantially; leaving the population of the area to shelter within two school facilities. With these schools not capable to withstand a hurricane event. This can be seen from a wind storm that happened in February of 2015 on the windward side of the island of Oahu. An elementary school designated as a shelter’s roof collapsed due to minimal wind loads. Even though, these were “strong” winds, they still didn’t measure on the Saffir-Simpson Scale.

Site Analysis

Zoning: Falling under the Kakaako Development District and the TOD (Transit Oriented Development) this area is a mixed use zoning with height limits of 400 feet with the first two levels as a podium and set back towers.[139]

Soil Condition: Being predominantly man-made this area consists of compacted coral. This material is ideal for implementing permeable surface and natural water mitigation features. Because of its porous nature the compact coral allows water to pass through quickly. This offers an extensive area that can hold a large amount of water until it can dissipate naturally.

Flood Zones: Areas which have been given by FIRM (Flood Insurance Rate Maps) and FEMA as areas of potential flooding during storms. This does not correspond directly with tsunami evacuation zones, however. They give areas and the potential they have to flood from data collected over an extended period. Each flood zones are broken down by elevation and flood potential they are:

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[139] "Ward Neighborhood Master Plan.", accessed January 10, 2015.

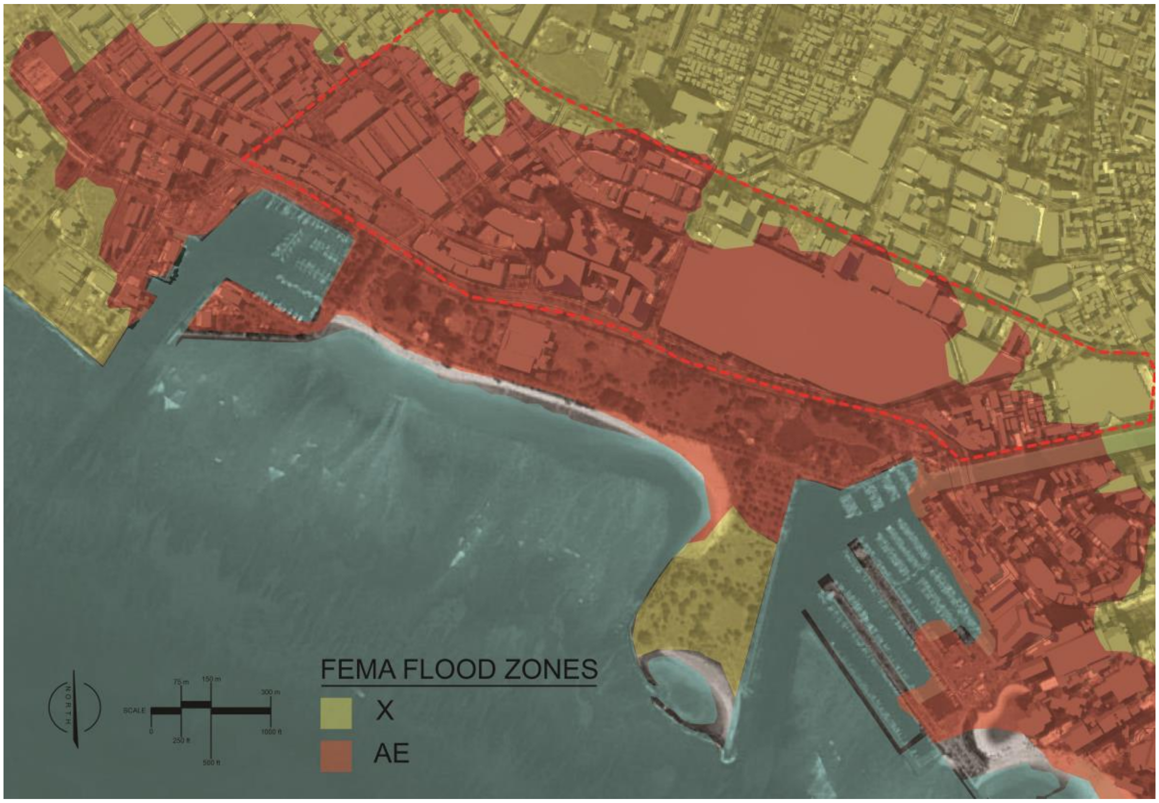

Figure 45 FEMA Flood Zone Map Source Michael Hill

Zone AE and A1-30: Areas subject to inundation by the 1-percent-annual-chance flood event determined by detailed methods. Base Flood Elevations (BFEs) are shown. Mandatory flood insurance purchase requirements and floodplain management standards apply.[140]

Zone X: Areas of minimal flood hazard, which are the areas outside the Special Flood Hazard Areas (SFHA) and higher than the elevation of the 0.2-percent-annual-chance flood.[141]

Tsunami Evacuation Zones: Is the area below a certain elevation that would potentially be flooded during a tsunami and/or a hurricane because of inundation

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[140] "Flood Zones | FEMA.gov." Flood Zones | FEMA.gov. accessed November 1, 2013.
[141] IBID

(high waves caused by hurricane force winds and pushed onto shore causing flooding) from the storm.

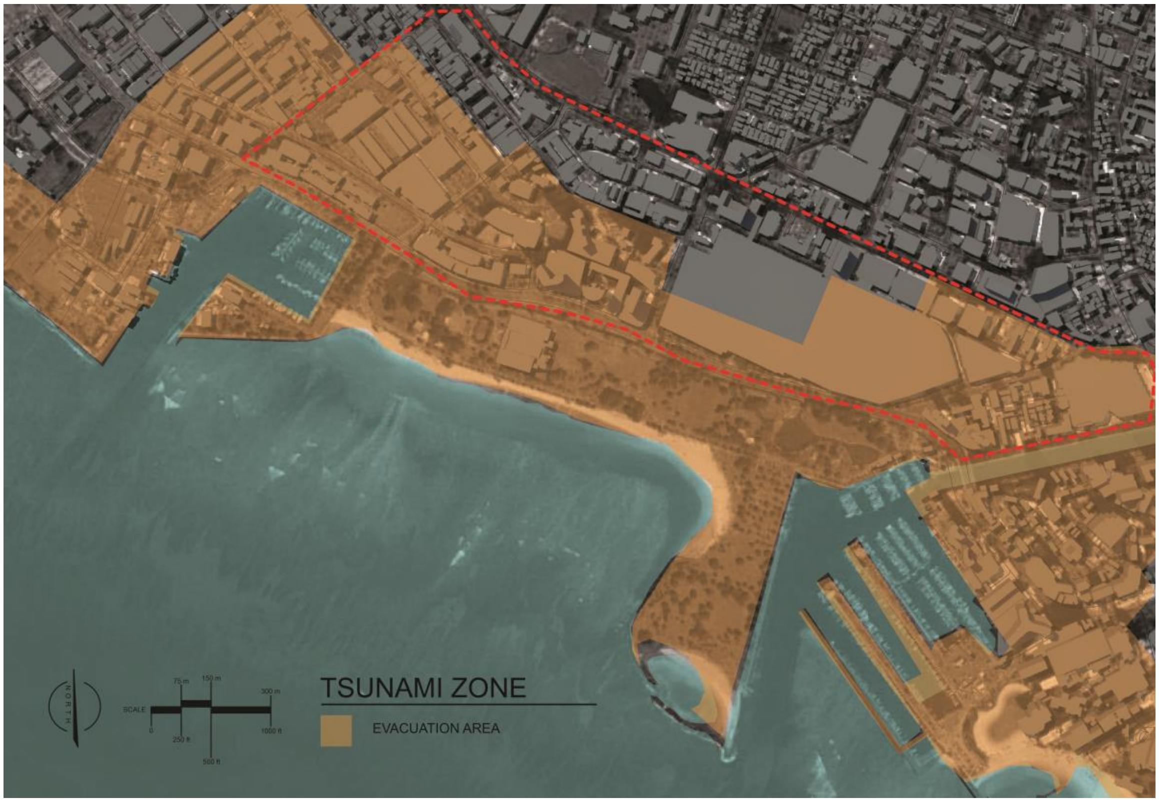

Figure 46 Tsunami Evacuation Zone Map Source Michael Hill

Sea Level Rise: Another issue that affects this area is sea level rise. As we look toward the future and life of this building, there is a high probability that it will be affected. Current projections state that potentially by the year 2100 we may have 3ft plus of sea level rise. The following images show how that will affect this neighborhood block.[142]

Figure 47 shows what this area looks like the only 1-2ft of sea level rise. As can be observed there is very little change in the coastline. However figure 48 shows 2-3ft of change, and now we can see a much more drastic change. The water

[142] “Sea Level Rise Hawaii. (n.d.).” accessed March 30, 2015

has begun to encroach on beaches and low-lying coastal areas. When we reach 3-4ft seen in figure 49 the park area that separates the developed area from the beach has now become a tidal floodplain. This begins to spread into low-lying areas throughout the neighborhood block. Which means basement and ground floor areas could very well be rendered unusable. This becomes a greater concern when combined with storm surge as the water levels can reach extreme heights, see figure 50.

Figure 47 Sea Level Rise Diagram Showing 1-2 FT of Sea Level Rise Source Michael Hill

Figure 48 Sea Level Rise Diagram Showing 2-3 FT of Sea Level Rise Source Michael Hill

Figure 49 Sea Level Rise Diagram Showing 3-4 FT of Sea Level Rise by Michael Hill

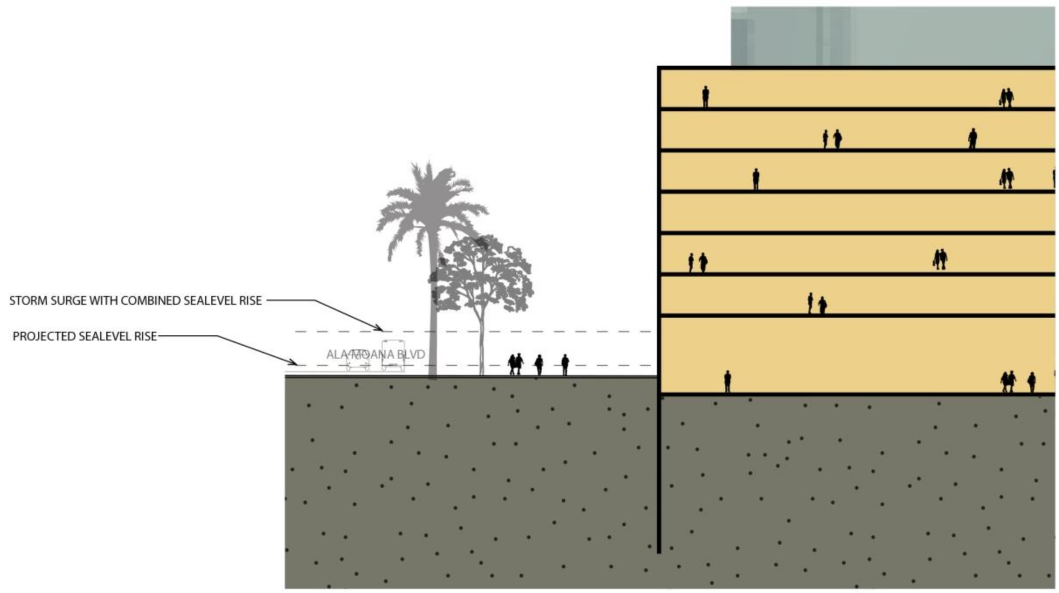

Figure 50 Storm Surge Combined with Sealevel Rise source Michael Hill

Implementation and Phasing

By implementing changes through the development of an area, we can better prepare for the effect of hurricanes. The current plan has a series of towers and public spaces in place. However, these spaces are not being developed with hurricanes in mind. By applying mitigation strategies to this area in phases, we can protect the existing buildings while developing a more robust buildings and features as development continues.

Currently, the Ward Village Master plan consists of three phases of development. The first phase of this development has already begun. The following diagrams illustrate how hurricane resilient design features can be implemented into this phasing resulting in better design community.

Figure 51 Auhi District Map Source Michael Hill

This is the Auahi neighborhood block (figure 50). It has 5579 residents with the plan to add potentially ten additional residential towers to the area.

The first phase of this project area has already begun. Adding office, retail, and residential spaces depicted on white these building help begin the vision of what this space is going to become.

Figure 52 Phase 1 Map. White depicts new buildings. Source Michael Hill

However, not addressing the potential threat from a hurricane this is how the area could look following a major storm event.

Figure 53 Current area before a hurricane Source Michael Hill

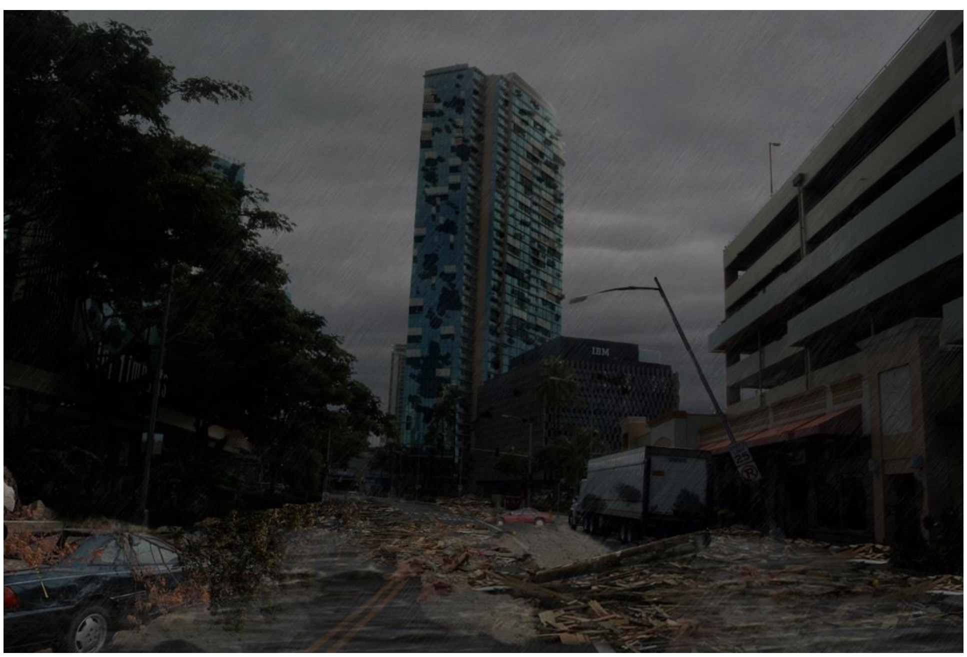

Figure 54 Conceptual rendering of the area following a hurricane Source Michael Hill

We can mitigate this outcome as the area is further developed. The second phase of this project adds additional services including a grocery store another residential tower along with the projected elevated rail line.

Figure 55 Phase 2 Map. White depicts new buildings. Source Michael Hill

The third phase offers the chance to begin implementation of disaster mitigation features. This is because these buildings have yet to be developed it also gives enough time to begin adding features to existing buildings. These strategies could consist of bioswales, rainwater harvesting, permeable surfaces, greywater treatment, integrated photovoltaics, hurricane shutters, or any other strategy that is has been currently developed.

While in the fourth phase implementing hurricane resilient features can be fully integrated into the buildings and area. These could include the previously listed in phase 3 as well as waste water treatment, biomass energy, and other more progressive features. These will create the network that protects not only those within the building they exist in but help to tie the fabric of the community together.

Figure 56 Phase 3 Map. White depicts new buildings. Source Michael Hill

These features can significantly change a buildings capability to withstand the hazards of a hurricane. By joining features together and integrating them into the building design, we able to create residential towers that people can shelter in place. The following images depict how an integrated resilient building design withstands the hazards from a hurricane.

Figure 57 Rendering of Area Before a Hurricane by Michael Hill

These buildings need to function as regular spaces, while the features that have been used should enhance the space. In figure 57, there are a large number of strategies being used. The center island is made up of a bioswale with salt tolerant plants. There are elevated walkways connecting levels above potential flooding. In this case, the first floor is a sacrificial floor with the second floors elevation at 20 ft to help remove it from flood potential. The structure of the building has been moved to the exterior of the building helping to employee a defensible perimeter. There are storm shutters placed between the structural columns helping create a protective shell that can be used during the time of an event. The third and fourth floors are mechanical equipment floors where building systems such as algae wastewater treatment and biomass generators. The elevated walkways second level open space has integrated photovoltaic pathways. This helps to build up the energy the building needs function during a storm event but also functioning every day supporting the livability of the building.

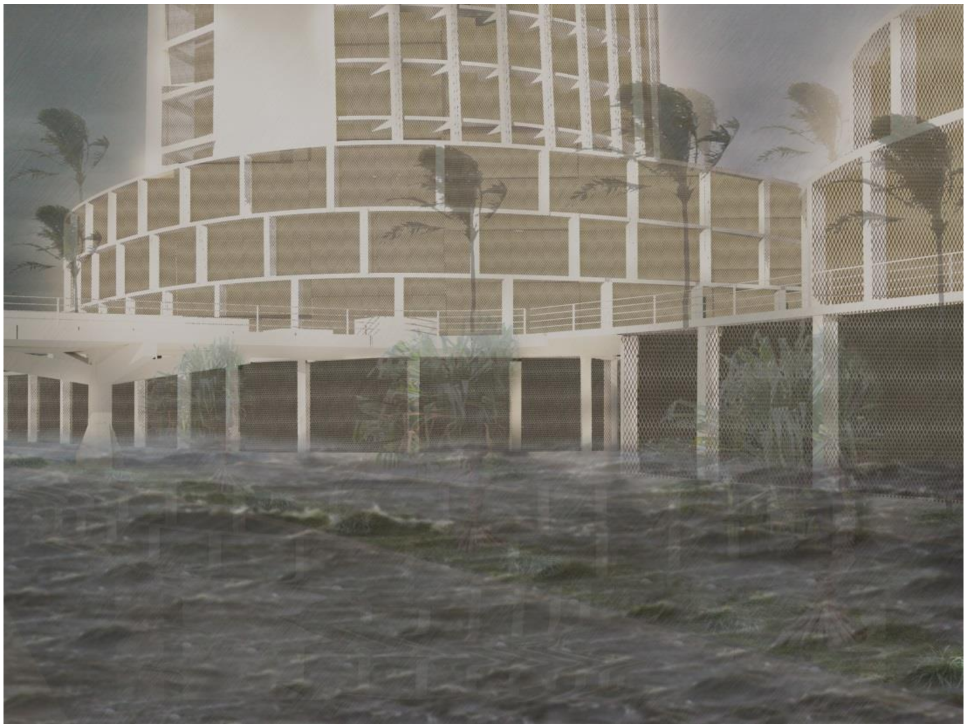

Figure 58 Rendering of Area During a Hurricane by Michael Hill

The when a hurricane happens these features can begin to function in response to the storm. Hurricane shutters are employed creating a buffer between hazardous debris and the interior of the building. The first level uses its movable wall system which enables the building to allow flood waters in the sacrificial floor while the hurricane screens keep large debris out of the space. The biomass generator and solar pathways have stored up the energy required to maintain power on within the building. If something does happen to any of the buildings main systems located within the mechanical equipment room they can be easily accessed during the storm. The public spaces within the buildings envelope can act as potential shelter or as Red Cross and FEMA registration and staging areas to help protect the community.

Figure 59Rendering of Area After a Hurricane by Michael Hill

Once the storm has subsides the occupants of the building can begin repairs as needed. However, second level shopping can open again offering places to purchase and trade goods. Algae ponds are still capable of treating wastewater while the biomass generators can still produce the energy required for the building. This building can support its occupants even following and extreme hurricane event. With a network of these types of buildings in place throughout the area, people can return to normal life more quickly without fear of being displaced from their homes.

Funding

The largest driver for all design and construction is cost. If the suggests don't equal or offer a valid positive they will not be implemented. The key to each of the mitigation strategies being suggested is that they only change the current way we organize and place things.

For example by incorporating impact resistant rain screens we have benefited the design two fold. First we have removed the need for impact resistant glazing. Second we have protected the interior from flood damage. As we look at this from the realm of costs. We can see that the initial cost outweighs the costs that may result from hurricane damage. A storm shutter could cost anywhere from $204.00 to $1000.00.[143] This can seem like and extreme cost increase for a high-rise. However, the average cost per square foot for residential construction in 2011 in Hawaii was $500/sq. ft.[144] If a residence that was damaged was 900 sq. ft. it would cost upwards of $450,000 to repair this space. The current cost offset is now obvious for why a smaller cost increase upfront and be a long term benefit.

The same is true for relocating the mechanical equipment. However, you are simply locating them in a different space. It does offer the chance to use the roof and limit some of roof load which may result in cost savings. You are also protecting the equipment and preventing uplift which can cause structural and envelope damage. A simply solution like this is easy to apply without many major ramifications.

Creating permeable surfaces and adding bioswales is a simple and cost equal solution. As mentioned before permeable paving is simply changing the mix to have larger aggregate, in fact having a larger aggregate often lowers the cost of the mix.[145] Bioswales too are low cost due to the fact you are still landscaping but adding some additional fill material and plants that can help remediate some of the storm water.

Elevating pathways will be a cost, but as a community we need to rethink the way we develop with the impending sea level rise. This will require the entire

[143] "Hurricane Shutters, Storm Shutters, Security Shutters, Rolling Shutter.", accessed 28 March 2015.
[144] "A Design-Build Contractor Who Gets the Picture - Pacific Style Construction | Hawaii Renovation.", accessed Web. 28 Mar. 2015.
[145] "The Role of Aggregate in Concrete." , accessed Web. 28 Mar. 2015.

area and infrastructure to be redeveloped because they will not be able to withstand the fluctuations in sea level. Much of the area as seen in the diagrams will be inundated frequently requiring new infrastructure.

These mitigation strategies are meant to bolster and protect the building from harm without changing the way we currently design buildings. This helps to allow for them to be integrated easily and simply into the process. The following table shows a simple matrix of the relationship between current construction and the hurricane resilient construction strategies suggested in this paper.

Table 3 Current Construction vs Hurricane Resilient Construction source Michael Hill

Current Construction vs. Hurricane Resilient Construction			
		Current Construction	Hurricane Resilient Construction
Mechanical			
	HVAC	X	X
	Electrical	X	X
	Onsite Waste Water		X
	Greywater		X
	Solar	X	X
	Integrated Solar		X
	BioMass Energy		X
Building Construction			
First and Second Floor			
	Gysum Walls	X	
	Cavity Stull Walls	X	X
	Flood Proof Materials		X
	Low Maintance Materials		X
	Mold Resistant		X
Second Floor Up			
	Gysum	X	X
	Stud Wall	X	X
	General Finishes	X	X
Structure			
	Steel	X	x
	Glass	X	x
	Concrete	X	x
	Defensible Rain Screens		x

Chapter 9. Conclusion

Looking toward the future of hurricane resilient design it is clear that there are currently vulnerabilities that exist. By understanding the effects and hazards associated with hurricanes we can plan and design better to withstand these issues. We also need to understand what is happening in terms of climate change and sea level rise because as mentioned these will impact the frequency and intensity of hurricanes.

From what we can see from the major historical hurricanes we have not been prepared to face the results of these storms. Between extreme flooding and major wind-borne debris, buildings failed in a variety of ways leaving people homeless. When it came to high rises, their systems were not capable of withstanding the storm and molding due to rain and flood water exposure left them uninhabitable.

Building codes addressed minimum standards for wind loads. While never fully addressing impact from debris, extreme wind loads, or excessive flooding. This results in buildings that are substandard as only the minimums are met. Leaving large gaps in a buildings performance, or state governing bodies have adopted codes are outdated and thus ill equip for current changing conditions.

While there has been a considerable amount of research on guidelines for hurricane design. There has never been guidance for large-scale buildings, which is becoming more prevalent in Hawaii as we create denser neighborhoods around transit-oriented developments. Which doesn’t allow those who would like to design to a higher standard to learn simple, quick solutions without having to do extensive research.

However designing a building to be hurricane resilient is possible as long as we stop and think about what can happen and what can be done in response, the key being protecting the interior and systems from debris damage and molding. First by addressing the issues of building system failures we must help these buildings to be independent of the rest of the community. By relying on current infrastructure, we are planning on failures. Secondly we must protect residential spaces from molding. In order to do this we must organize our buildings differently, design using onsite building systems, create protective shells around our buildings and design with the intent of having multiple uses within and in proximity to these buildings. By doing these things, we are capable of withstanding whatever a storm can cause.

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[i] Design Flood Elevation (DFE): Is a level set above the Base Flood Elevation for the floor elevation of the first floor relative to the 100 year flood plain.

[ii] FEMA Flood Zones: These zones are created in regard to the National Flood Insurance Program. They break areas into zones based upon probability of flooding.

[iii] Base Flood Elevation (BFE): Is the 100 year flood plain this is used to set a standard of height for buildings to follow if they must be elevated.