Mangrove Housing: Ecosystem as a Housing Typology for Culebra, PR

Jose Manuel Marti

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MANGROVE HOUSING: ECOSYSTEM AS A HOUSING TYPOLOGY FOR CULEBRA, PR

JOSE MANUEL MARTI
THESIS
SYRACUSE UNIVERSITY
SCHOOL OF ARCHITECTURE

ADVISOR: VASILENA VASSILEV
SECONDARY ADVISOR: BRUCE ABBEY
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This thesis is inspired by the conditions of housing in Culebra, Puerto Rico and asserts that architecture is able to respond and perform effectively to an ecosystem which includes natural factors such as hurricanes. As an ecosystem, it aims to create a network within a community that arranges into a complex system and several levels of bigger systems in order to sustain every life supporting function, including water filtration.
This thesis will address ways in which design can provide safe shelter for the local residents of Culebra. It promotes an architecture that provides safe shelter during hurricanes, which creates an awareness of the danger and effects this natural force has.

While hurricanes are not perceived as an aspect in the housing design, these natural disasters put people in great danger. The construction of a housing complex will provide an opportunity to design keeping in mind the tropical climate and the threat of hurricanes. Hurricanes are natural forces that have been increasing with intensity and frequency as a result of climate changes. These forces bring high winds, heavy rain, rise of sea level, and storm surge that threatens and damages many homes and peoples lives.

Year round, locals of the island of Culebra find themselves and their housing threatened by these forces. The conditions of Culebra provide an opportunity to design a type of housing that takes into consideration the threats that hurricanes bring. Culebra is a municipality of Puerto Rico, located off the east coast of Puerto Rico. Recent history has witnessed struggle for adequate shelter in this island, since 60% of Culebra’s residents are under the poverty levels, and their homes are not able to withstand the consequences of hurricanes.

The island’s geographic location, the high poverty rates, the lack of educational achievement in the population, houses located in high risk zones, and lack of disaster mitigation initiatives, contribute to the island’s vulnerability to disasters. In consequence, this island becomes at risk for high levels of destruction as well as the loss of property and life. Designing housing that attends more effectively the specific needs of Culebra will provide the residents with safe housing which will reduce the disaster related deaths, injuries and damage to property in the island.
**Ecosystem:** a system formed by the interaction of a community of organisms with their environment. (Dictionary.com)

**FEMA:** Federal Emergency Management Agency

**Flying debris:** scattered remains of something broken or destroyed that given the force of the wind fly damaging properties.

**Hurricane:** A severe tropical cyclone having winds greater than 64 knots (74 miles per hour; 119 kilometers per hour), originating in the equatorial regions of the Atlantic Ocean or Caribbean Sea or eastern regions of the Pacific Ocean, traveling north, northwest, or northeast from its point of origin, and usually involving heavy rains.

**Prevailing winds:** A wind that blows predominantly from a single general direction. (The Free Dictionary)

**Shelter:** something beneath, behind, or within which a person, animal, or thing is protected from storms, missiles, adverse conditions, etc.; refuge. (Dictionary.com)

**Storm surge:** (oceanography) A rise above normal water level on the open coast due only to the action of wind stress on the water surface; includes the rise in level due to atmospheric pressure reduction as well as that due to wind stress. Also known as storm wave; surge.

**Sustainability:** to meet present needs without compromising the ability of future generations to meet their needs. (WEC, 1987)

**Sustainable development:** is about maintaining and enhancing the quality of human life-social, economic and environmental – while living within the carrying capacity of supporting ecosystems and the resource base. (Barton, 2010)
Puerto Rico Winds in relation to the Caribbean
Sources:
image-Wikipedia Commons
winds-NOAA

Culebra in relation to Puerto Rico & Wind direction
Sources:
image-Puerto Rico Office of Planification
winds-NOAA

Culebra
Sources:
image-Puerto Rico Office of Planification
winds-NOAA
Culebra’s geographic location has a high propensity to hurricanes. The lack of educational achievement within its residents makes them unaware of the effects and consequences of the hurricanes. Even if people are aware of the force a hurricane might bring, they are unable to act upon it, since 60% of the population is under poverty levels (2000 Census). In consequence, this prevents the majority from constructing appropriate shelter that withstand hurricane forces. This fact is contrary to the poor people in the main island of Puerto Rico, whom are provided with appropriate housing by the government.

Many of the houses in Culebra, given to its coastal conditions, are located on high-risk zones. This makes them have even more propensity to damages. Another important aspect is the lack of disaster improvement initiatives and the unimportance given to the island from the central government. All these factors contribute to the island’s vulnerability to disaster related damages and destruction, including the loss of property and life.
Besides the issues mentioned before that make Culebra the ideal site for hurricane housing construction, there are other problems to take into consideration. The hurricane and its effect is the main issue. With the problem of hurricane propensity to this island, the housing construction and materials becomes critical as well as the connections to prevent uplift forces from strong winds. With the strong wind forces another problem that arises are the flying debris.
PROBLEMS
HURRICANES

Hurricanes are “the most powerful weather disturbances on the earth.” Hurricanes are natural forces that are of such magnitude that can “affect thousands of square miles of area and extend above 50,000 feet into the lower stratosphere, plus several hundred feet into the ocean depths.” These are powered by heat from the sea and sun. Because of this, the hurricane season is during the hottest months of the year: from June to November. Hurricanes have been increasing in intensity and frequency as a result of climate changes. They bring strong winds, heavy rain, rise of sea level, and storm surge. All these outcomes cause threats and damages to many homes and families. One of the biggest destruction impacts on coastal communities is the storm surge (FEMA). Storm surge is the rise of water level based on the wind pushing the water surface and creating waves that can be greater than 19 feet in a category 5 hurricane. Another factor that harms housing and people are the flying debris. Hurricane winds can carry many fragments and waste, such as metal from rooftops that can act as missiles.

Hurricanes are divided in 5 categories of intensity based on the Saffir-Simpson Hurricane Scale. The 5 categories are measured based on a criteria of wind speed, storm surge, air pressure, and potential damage and are divided as follow: Category 1: wind speeds ranges from 74 to 95 mph, with storm surges of 4 to 5 feet; Category 2: wind speeds ranges from 96 to 110 mph, with storm surges of 6 to 8 feet; Category 3: wind speeds from 111 to 130 mph, with storm surges of 9 to 12 feet; Category 4: wind speeds from 131 to 155 mph, with storm surges of 13 to 18 feet; Category 5: winds speeds of 156 mph or higher with storm surges greater than 19 feet.

FEMA has divided the United States and its territories in 4 different wind zones. Puerto Rico is in zone 3 (US map Far right).
Hurricanes and tropical storms that have affected Culebra, Puerto Rico from 1999-1989

Source: Weather Underground
Housing in Culebra is highly threatened by hurricanes every year. The conditions of construction in which these houses are found is poor. Most of the housing in Culebra are single detached houses. There is also a small amount of duplex and small apartments. Based on the 2000 Census, Culebra has a total of 1,024 housing units, of which 36% were vacant. Of the 36%, the majority are weekend homes of residents of Puerto Rico or foreigners. The houses tend to be small, containing normally 2 to 3 bedrooms. The 2000 Census estimates 2.62 persons per household, but it is being estimated that in the 2010 Census the average will be 4.

A major issue in Culebra’s housing design is the lack of consideration of the island’s climate when designing. Many local housing gets damaged or destroyed by the hurricane and natural forces, threatening people’s lives, since its design and construction are not suitable for hurricanes.

In an interview with a local resident, who was a former Director of the Civil Defense, he mentioned that during hurricanes depending on the intensity of it, around 50%-60% of the population seek for shelter at houses made out of concrete or local shelter provided by the government and church. In 1989, with the pass of Hurricane Hugo, 80% of the wooden houses in Culebra were destroyed (Puerto Rico Hurricane Center). Hurricanes have many effects on the island’s housing, driven mainly by the wind forces, rain, and sea rise level due to the storm surge. In addition, wind forces affect the stability of the houses and the roofs. The wind born flying debris is another aspect that threatens the houses, as well as the storm surge, which brings high waves and rise of sea level to flood the coastal areas and destroy structures.
Typical concrete house

Typical house plan
PROBLEMS
HOUSING IN CULEBRA

COASTAL CONSTRUCTION

One of the issues of housing construction in Culebra is its proximity to the coast. Although flooding is not a big issue in this island because of its topographical conditions, there is an amount of housing that suffers because of it. The sea rise level places a risk to coastal housing construction. During hurricanes these houses are the ones that get affected the most by the storm surge.

Raised construction for rise of sea level

Coastal housing
Hurricanes has many effects on the island’s housing, driven mainly by the wind forces, rain, and sea rise level due to the storm surge. Taking in consideration the effects these forces have, it must be looked at the way the houses are attached to the ground. The foundations of the houses is a really important aspect in how these are attached to the ground.

There are three basic way that the houses are attached to the ground. The first one is at ground level, mostly found in the urban area of the town of Culebra were flatter lands make this possible(Fig. 1). The second way is elevated a couple of feet, mostly built in coastal areas to prevent damage from the water level rise(Fig. 2). The third is raised from the floor, mainly given to the topography and terrain inclination (Fig. 3). Wind forces affect the stability of the houses and the roofs. The wind born flying debris is another aspect that threatens to the houses. Another factor that threatens the housing is the storm surge, which brings high waves and rise of sea level to flood the coastal areas and destroy structures that find its path.

The most common material used in the construction of houses in Culebra is wood, mainly because it is more economically accessible to the local residents and it is the cheapest to import from the main island. The wood is also commonly used because of its ability to integrate with the natural environment that surrounds the island. Another material that is also used is concrete, but in a smaller amount, given the high cost of it in Culebra. An important aspect to be mention about construction materials is that all of these have to be imported from the main island; as a result the cost of material is higher than it is in Puerto Rico.

Houses are mostly built by using a wood frame construction raised from floor level due to inclination of the terrain (Fig. 4-5).
Fig. 4 Typical half raised wood frame construction to prevent house from flooding

Fig. 5 Typical completely raised wood frame construction
One of the biggest issues with housing is the high winds that can cause the houses to fail if they are not well designed and constructed. The housing design becomes a critical issue in making them hurricane resistant. Wind passing over a house can apply a lifting force on the house. The combination of push, pull, and lift acts on the entire house and can result in extensive damage. The structure of the house, the foundation, and the joints then become an integral part of the design. Also, issues such as the slope of the roof are critical points as well, since if it is not steep enough it will act as an airplane wing, where the wind that passes under the wing pushes the wing up, and at the same time the air that passes above the wing pulls it up lifting the wing, as shown in the diagram. The perfect inclination for the roof is 30-40 degrees, where the wind will pressure the roof downwards instead of pulling it upwards, keeping it in place. (Source: Hurricane Housing Construction Manual)

Taking the issues mentioned above in consideration, the protection of flying debris becomes a very important issue, since these flying missiles can make opening in the houses and make them fail faster. This is said since a sealed building is much more secure than an open one, given the fact that if there is an opening in the building where wind comes in, it will become easier for the wind to place pressure on the walls and roof, tearing them down and blowing them away.
Inclined roof lifting
30-40 degree Inclined roof down pressure
Sealed Building

Flat roof lifting
30-40 degree pitched roof down pressure
Building with opening
Given the effects wind has on houses, FEMA recommends certain specific connection, which they consider to be ones that hold the most during strong hurricane winds. These connections go from the roof to the wall, and onto the floor assembly, and then to the foundations. Every single connection has an important role in order to prevent a house from failing. If one single connection fails the house has a much bigger probability of being destroyed. The design of houses which construction depends mostly on joints between the different assemblies of the house is not the most functional in places that there is so much threat of hurricanes. Because of the so many parts each house has, it is difficult to certify that a house is ready for hurricanes. Due to this, FEMA suggestion is not the best way to construct since the house could fail if any of these connections are not implemented correctly. The reduction or omission of connections becomes a critical issue in the construction of hurricane safe housing.
The amount of connections the houses has is the same the amount of house parts that can become flying debris. Flying debris are said to be one of the biggest hurricane related damages to the housing structures. This is caused by the high winds that break away parts of other buildings or any laying objects and act like windborne missiles. This wind driven missiles end up damaging houses, penetrating their walls, windows, and roof, making these weaker and more vulnerable for the winds forces to tear them apart. These missiles not only become a threat to the houses, but they also become a threat to the people inside. Depending on the wind speed it can be determined what kind of material is able to penetrate, but even a reinforced masonry wall can be penetrated. Taking this in consideration, people start adding second layers of skin to their houses, in order to protect the house and themselves by using different methods. In some of these cases the second skin layers start creating spaces between the actual skin of the house and the added protective layer. By adding new layers of protection layers to each house, more flying debris threats are placed.
As part of the solutions and proposals it is included the idea of how to provide shelter that can become usable after the hurricane has passed. Utilizing the site conditions, such as the topography and slope of the site can help with the creation of safer shelters. The integration of the community is very important as it can act as a system of support.
Given the effects of flying debris, FEMA Hurricane Housing Handbook recommends that each house has a shelter. This is in order to protect its residents during hurricanes in case outer parts of the house are damage or destroyed. They consider the bathrooms, closets, and storage spaces of the houses as the safest areas, where people should be used and construct them as shelters. They have specific construction details, materials, and size specifications for these shelters.
By looking at the threat that flying debris places on people’s lives and FEMA reactions by suggesting specific parts of the house for hurricane shelters, makes one think how this shelters could be more integrated into the design of each house. These shelters can be designed to meet the necessity of an area that is secure and become useful after the storm has passed. The idea of having different layers or skins of protection becomes useful, by taking in consideration: inside shelters, the creation of layers and how the second and third layers can start creating usable space while providing protection. Houses could be safer if they have different layers of protection built into their design, so the shelter that is within the outer shelter is standing after a hurricane has passed even if the outer layer is destroyed. A simple example of creating layers of spaces that provide protection can be seen in a typical Puerto Rican housing with the use of balconies or porches. The creation of layers can bring shelter within the shelter.
SOLUTIONS & PROPOSALS
SLOPING SITES

SITE APPROACH
Taking in consideration the topography of the island, the site will be on a slope. Houses with sloping site conditions are protected more with the land and are able to provide shelter against the ground depending on the site approach given. The different approaches to dealing with sloping site are: extra masonry, split level, cut and fill, staggered across section, cut section, and house on posts. The extra masonry is a plinth built up to form a level platform for a normal flat site dwelling (Fig. 1). Split level provides a special plan and section, usually based on half storey change of level (Fig. 2). The cut and fill is site modeled to create level plots (Fig. 3). Staggered across section are offsets that depend on gradient (Fig. 4). The cut section cuts into ground to provide a flat surface for the house (Fig. 5). The house on posts raises the house making it completely independent from the ground (Fig. 6).
A housing complex is more effective than single housing units, since the housing complex becomes a community, where in time of hurricane works as a system and not as a single element (Fig. 1). In the diagrams is shown how a system of houses are more resistable to hurricane than a single detached.

The actual Culebra housing blocks (Fig. 2) do not work efficiently since it deals with independent houses. The integration of the houses in the community works more efficiently since it provides more protection and structural stability of the houses and the community.
Fig. 2 Typical housing block with independent houses.
Keeping in mind the natural environment of this island and that global warming has in effect more and stronger hurricanes, this project needs to embrace aspects of sustainability and sustainable development. “Sustainable development is about maintaining and enhancing the quality of human life-social, economic and environmental – while living within the carrying capacity of supporting ecosystems and the resource base.” (Fig. 1) It is not about choosing one of the three aspects, but it is the integration of all. (Barton, 6) In a sustainable development a community is well integrated and provides a stronger support.

When one thinks of an integrated community, one can think of it as an ecosystem, where all buildings are integrated and interdependent from one another and there is an integration of comunal spaces within the complex. “The neighborhood is an ecosystem in the sense that it is the essential local habitat for humans, providing not only shelter but also a network of social support and opportunities for a wide range of leisure, cultural and economic activities.” (Barton, 22) As seen on the Figures 2 and 3, the community provides one another an interconnection and interdependence.
Taking in consideration how a sustainable development starts working as an ecosystem, it can relate to the mangroves. The community starts working again as mangroves, where this plants roots provide an interconnection and interdependency, creating a structural system for the that holds to the ground. At the end the system is working to provide structure support for one same plant (Fig. 2). This plant creates a network and work as a system and makes it very resistant to hurricane winds. Mangroves is one of the safest places you can leave your boat during a hurricane. During a hurricane, the only part affected of the mangroves is the foliage, which is a part that re-grows very quickly.

The mangrove reflects the community spaces and interaction in the roots, since is the main support, and in the canopy it represents the houses within the community, which is
The precedents in this section look at housing complexes that have conditions of hillside construction, prefabrication, housing complexes, and community integration.
PRECEDE NTS
ITHACA HILLSIDE HOUSING PROJECT
WERNER SELIGMAN & ASSOCIATES

This housing complex deals with similar issues to the ones that my thesis is dealing with, such as hillside construction, stepped housing, and prefabrication.

Typical 3 bedroom plan
5 prefab units compose 2 apartments
Prefab unit at manufacturing site
Housing complex section
Units being assembled at site
Prefab units grid
Typical 3 bedroom plan
Units being assembled at site
Prefab unit at manufacturing site
Housing complex section
Units being assembled at site
Prefab units grid
Typical 3 bedroom plan
Housing complex pedestrian paths

Housing complex places of interaction
This project deals with affordable housing units across a concrete framework while integrating communal spaces. The open space underneath will function as a marketplace, among other uses.
Providing safer structures for informal housing is the main goal of this prefabricated structural member. People will use this piece as a central piece to build around their houses.
PRECEDEENTS
ROKKO HOUSING
TADAO ANDO

Rokko Housing deals with similar site conditions. The inclination of the site provides opportunity to step the housing development permitting that the roof of one house becomes the outdoor terrace of the apartment above. The integration of the complex with the nature of the site can be seen in the use of green roofs.

Section: cut and fill / off sets
Prefab grid as it goes higher in mountain
Prefab concrete modules
In this project the hill construction is applied, not because of the conditions of the site require it, but because the terracing of houses in the scheme. It provides a strip of houses in each level using as outdoor space the roof of the houses below.
PRECEDE NTS
HABITAT ’67
MOSHE SAFDIE

Habitat ’67 can be seen as the mangrove root system, where the housing acts as an integrating system that provides a structure and support. It also provides different outdoor spaces utilizing other people’s roof.
Looking back at the ways typical housing fail in the connections during strong winds, the reduction of connections will improve the way houses react against wind lifting forces. The CNC and Waterjet prefabrication systems provide a way in which design can evolve by eliminating a significant amount of this joints. By creating houses that are composed of vertical sections as see in the images on the right, the probabilities of the housing failing becomes much less. Given the fact that all the material for construction in Culebra is imported from the main island, prefabricated homes become a good option for this island’s housing construction. This way homes can be built prior to getting to the island and then finally assembled on site. This will bring the housing costs considerably lower, contrasting what people are experiencing now with actual costs. There are different prototypes of prefab.
PRECEDE NTS
PREFAB PROTOTYPES
PANELIZED

PREFAB PROTOTYPES
CNC TIMBER FRAMING

The steel frame prototype provides a structure that could provide a change of skin after a hurricane passes by. This structure could be made to be set and not to be affected by the hurricanes but its skin at the same time could be designed to collapse to prevent a further amount of flying debris. After the hurricane passes, the outer shell of the house can be re-assembled.

PRECEDENTS

PREFAB PROTOTYPES

MODULAR

Having different modules and integrating them to the terraced site in different ways and where needed.

The first part of this section is dedicated to a general analysis of the island, which is a guide to the selection of the specific site. It takes into consideration aspects such as flodable areas, topography, and housing settlements. Then with the specific site of design, it starts analyzing it in more detail with site sections and plans.
SITE ANALYSIS
HOUSING DENSITY

The island analysis is very important in order to select an appropriate place to locate the project. It needs to be studied where the local people live and the housing densities.
Flooding is not a big issue in this island because of its topographical conditions, but it needs to be considered, given that the rise of sea level and storm surge affects the coastal construction.
Site Analysis

Topography becomes a critical issue to take into consideration, given that during a hurricane the mountains and topography of the island serve as protection. Mountains can act two ways. They can protect the house or expose them to strong winds. The area of actual housing that is protected the most by mountains is highlighted in the diagram.
The Municipality of Culebra has a land distributing program that provides residents an area to build their houses. In this map it is shown the areas that are already developed with houses, the areas where the municipality has given recently, and where they are planning to give land to its residents in the future. This is an important issue, since there should be in a place where the people live and possibly a land that the government is planning to give the residents.
SITE ANALYSIS
ELECTRIC SYSTEM

generator
substation

underwater
cable coming
from Vieques
SITE ANALYSIS
HOUSING GROWTH

How the housing communities have been expanding is shown in this diagram. This lets us know in what direction the island density is growing and to where the future housing settlements are going to be.
Looking at the island density areas it can be seen in this programmatic study, how most of the commercial and touristic shops are located in or near town, while near the housing communities it is mostly houses, local residents shops, and small supermarkets.
The roads system is very small; there are two main roads in Culebra shown in red in the diagram. There are secondary roads, which are the ones that go to the different communities.
FLOODABLE AREAS NEAR HOUSING

SITE ANALYSIS
SITE ANALYSIS
SITE SELECTION

The site selected takes in consideration all the factors mentioned before as part of the site analysis. The site is located on the hill of mountain, which provides protection from the strong hurricane winds, and its terrain inclination is safe from the sea rise and storm surge. The site is located on recently distributed parcels, which provide an opportunity to develop housing for the people that were just given the land.
This section shows how the mountain protects the site from strong winds, while it still has an amount of weaker winds.
SITE ANALYSIS
SUNANGLES

June 21
85°

December 21
50°
SITE ANALYSIS
PASSIVE COOLING

Keeping in mind the climate that Culebra has, passive cooling becomes an important aspect that needs to be integrated into the design.
SITE ANALYSIS

VIEWS TO SITE
SITE ANALYSIS

VIEWS FROM SITE

[Images of views from the site]

63
There are two different hurricane shelters in Culebra, the elementary school and the church.
SITE ANALYSIS
COMMUNITY SPACES
Culebra Island, as many residents say, lacks communal spaces where people can interact and where children can play. Currently the only communal spaces are the Plaza in the center of town, the children’s playground next to the school, and what they call the municipal gymnasium.
SITE ANALYSIS
SITE APPROACH

Terracing of the site has already been started by the streets that run through it as seen in the first section. This site approach will provide for a better integration of the design with the land and a safer shelter for hurricanes.
Given the terraced approach given to the site, the housing will follow the same pattern. The residents of Culebra have expressed the need of outdoor communal spaces. Given the warm climate of the island year round, outdoors spaces are very important. People enjoy going to the Plaza in the center of town, and every house in the island has a terrace or balcony that people use on a daily basis. The program that the housing community calls for is outdoor spaces, which include parks and plazas and gazebos. Outdoor kitchens could be also implemented in the gazebos, since many of the local residents lack a space where they can clean and cook their fish after fishing. These communal spaces are like the mangrove roots, which will be what survive hurricanes. They will become shelters for hurricanes when needed.
The sustainable hurricane housing complex will integrate housing with community creating a network of support, where community is the root system of support. These community spaces will become shelter when a threat of hurricane exists. In the series of diagrams it is shown how the housing complex would evolve and react during a category 5 hurricane and what are the surviving spaces. After a hurricane passes, the community spaces, will be used as places where the community of people can live and perform their daily activities while they rebuild their houses.


