# Hydrological Disasters: Designing to Shelter in Place

by

Alejandro Gonzalez- Placito

Submitted to the Department of Architecture in partial fulfillment of
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ABSTRACT

The focus of this thesis is hydrological disasters and the question it attempts to answer is: how can we design and implement housing structures along U.S. coastlines that fully withstand hydrological disasters? Priority and severity is shown by increasing trends in natural disaster occurrence frequency and damage and reconstruction costs. Cost increase is due in part because disaster events are more destructive, but also because of overbuilding and high housing density located within high risk areas. First, using several literature sources, this thesis analyzes various aspects of natural disaster response and education. This paper achieves its goal to increase awareness about the flaws in government risk management and lack of disaster awareness and mitigation design curricula amongst architecture institutions.

As a design thesis, alternative housing models are presented in the later sections. The design process begins with hazard-risk identification and then outlining important building regulations. FEMA Coastal Construction Manual along with other sources were useful in understanding necessary mitigation measures required for coastal development designs. After research, a new design solution is presented. Design inspiration was drawn from similar technology and the need for innovative, resilient, and economical designs. This thesis hopes to use idealized designs to start more conversation about natural disaster defensive architecture.

Thesis Advisor: Leslie K. Norford

Title: Professor of Building Technology

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## I. Introduction

Any media outlet in the U.S today talks about atmospheric warming, sea level trends, and everyday impacts along the U.S coasts. A critical effect of rising sea levels and climate change is that more frequent and more destructive storms and flooding events are occurring. The year of 2017 broke the weather and climate disaster cost record with a total of about $306 billion dollars. In 2017, Hurricane Harvey alone had a total cost of $125 billion and was the deadliest hurricane to hit Texas since 1919. Another unforgettable disaster in October of 2017 was category 5 Hurricane Maria. It wasn't until January of 2018 that power was restored to about 65% of Puerto Rico. Just last year, Hurricane Michael hit Florida, with winds as high as 155 miles per hour (NOAA 2019).

This study focuses on hydrological disaster events, including hurricanes, storm surges, flooding, cyclones, etc. as they make up most overall natural disasters. According to the Federal Emergency Management Agency (FEMA), out of 3,728 federally declared disasters, about 63% are water related (FEMA 2019). This study analyzes various aspects of natural disaster response and education. This study also analyzes possible disaster design solutions. Some sources showcase current design ideas while other articles establish design constraints for future disaster defensive architecture. This paper achieves its goal to increase awareness about the flaws in our disaster management and call designers to action on ideating disaster resilient and disaster proof housing.

First, it is important to look at the data that shows that natural disasters are happening more frequently, and that these storms are more costly. Climate.gov, a subpage of the National Oceanic and Atmospheric Administration, collects and tracks data about all natural disasters that occur around the world and in the U.S. Within a recent report from 2019, the National Centers for Environmental Information (NCEI) present data of all tracked U.S weather and climate events since 1980. Specifically, their report focuses on disasters where the overall costs reached or exceeded $1 billion dollars. Since 1980, there have been 241 events that have reached this cost. The report states that "the cumulative cost for these events exceeds $1.6 trillion" (Smith, 2019). The graph below, Figure 1, summarizes these trends most efficiently, highlighting overall increased frequency in natural disasters. Specifically, as the left axis suggests, the number of overall events by year is increasing.  At the same time, the overall cost of disasters is increasing; cost is adjusted for inflation. This damage cost increase is due in part because these events are more destructive, but also because of overbuilding and high housing density located within impacted areas. Lastly, it is important to note that most of these climate events are hydrological, meaning floods, severe storms, tropical cyclones, and more.

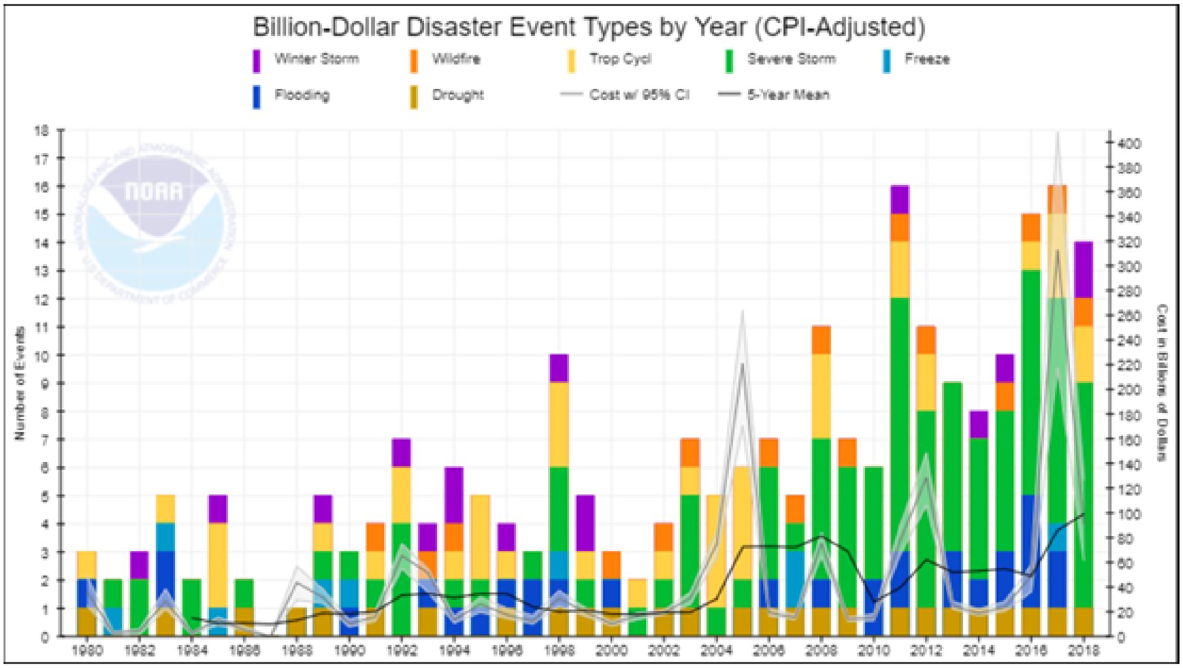



Figure 1: Billion-Dollar Disaster Event Types by Year (CPI-Adjusted). Displays frequency and cost of several disaster types since 1980. Shows the overall increasing frequency of natural disasters over time (NOAA 2019).

According to the National Oceanic and Atmospheric Administration, almost 40 percent of the United States population lives in densely populated coastal areas (US Department of Commerce and NOAA 2019). This means that over 130 million people in the United States are exposed to potential climatological disaster simply by living along the coast. It also suggests that the coast is valuable; for commerce, tourism, travel, and much more. If humans are not likely to change their penchant for living close to the water, one option may be to consider designing our habitats and overall urban, coastal ecosystems to become more resilient to these disasters.

The purpose of this paper is to study the severity and priority of this issue. The literature presented will attempt to identify and explain current flaws in our methods and then offer possible solutions through design concepts. Overall, the question this paper attempts to answer is; how can we design and implement housing structures that fully withstand hydrological disasters along U.S. coastlines?

**Research Question**

How can we design and implement housing structures that fully withstand hydrological disasters along U.S. coastlines?

## II. Literature Review

### Disaster Awareness + Education Gaps amongst Civilians and Professionals

**Civilian Preparation**

The United States Environmental Protection Agency (EPA) has an impressive website where the public can find information, policies, and guidance on an extensive range of topics. Website can be found here: https://www.epa.gov/natural-disasters/general-information-disasters#main-content. Topics range from waste disposal, laws and policies about chemicals, and even guidance on how to prepare and take action during natural disasters. Their website on disaster preparation is well organized with an interactive table of contents and links to numerous sites and resources. In general, EPA recommends that civilians always make emergency plans. For recovery, EPA makes it clear that it is essential to understand the risks of any particular disaster (EPA 2019). In most cases, according to the EPA, the health issues or deaths occur after the actual impact of an event. Recovery is most efficient and safe when people are informed about proper use of generators, heating devices, debris removal, and water purification. After this overview and general safety tips, the site moves on to specific aspects of disaster survival. For example, lists of a variety of phone numbers to national response centers so that people can report oil or chemical spills, environmental violations, or seek help from poison control. Another important section is titled ‘Know how to get emergency alerts and messages before you need them’. Here, there are such resources as FEMA Wireless Emergency Alerts, the Emergency Alert System, and the NOAA Weather Radio.

The contents of this web page have the ability to save many lives and should be advertised heavily.Though this information is useful, there is no guidance on the actual crisis upon impact of a disaster. A lot of resources from the US government and specialized agencies like FEMA only are forced to act during the event of a natural disaster. The survival guide from the EPA is great for those who aren’t directly hit by the blunt force of the disaster event, but a lot more than a civilian’s disaster emergency plan is needed for those fully exposed to the forces of nature. The government has shown little planning for on-site extraction during an emergency, and there is very little effort going into properly educating the public to best prepare to possibly face life-threatening natural forces.

**Disaster Management**

Though public education and awareness is critical in disaster mitigation, another topic of great importance is how the government and overall national disaster relief system responds to natural disaster risk. There is a formal and legal process for a disaster to become federally declared. Overall, the timeline of technicalities before the President of the United States declares disaster and begins relief efforts occurs during or after impact of a disaster event. By the time States receive support from the government, most of the efforts focus on search and rescue; aftershock preparation; and clean up and reconstruction. Ultimately, impacted regions end up preparing for the next disaster without possibly having prevented some damage or deaths. In a report commissioned by the Inter-American Development Bank (IDB), Paul K. Freeman and other authors were tasked with examining national systems and institutional mechanisms for management of natural disaster risk. The report is titled, 'Disaster Risk Management- National Systems for the Comprehensive Management of Disaster Risk and Financial Strategies for Natural Disaster Reconstruction'. The overall theme of this scholarly article is to analyze and discuss government disaster risk management systems. The article contains two chapters: one on national systems and the other on financial strategy. Supporting evidence for the article was gathered by analyzing multiple nations and their old, current, and or new risk management methods (Freeman et al., i-iv). First is the pre-disaster phase of risk management, the government must be able to identify risk, vulnerable regions or groups of people, and possible interventions. However, the next most important topic is funding. Currently, reconstruction and disaster relief funds come from international banking/loan systems and nongovernmental organizations. Governmental and nongovernmental organizations (NGOs) play key roles in risk management and disaster preparedness.

Hurricane Katrina is still considered one of the worst natural disasters in the U.S. The chaotic national response to Hurricane Katrina surfaced many administrative failures and flaws in our overall disaster mitigation planning. As a result of poor coordination by the federal and local government, many International NGOs were pressured to contribute and take action with little guidance from the government. Media portrayal of the disaster along with staff and donor pressure led to response by international NGOs (Eikenberry, 2007). Humanitarian relief efforts during Katrina occurred at a large and unprecedented scale. Many INGOs realized that the U.S government has rarely dealt with the magnitude of destruction that Hurricane Katrina left behind.

NGOs were able to provide shelter, medical assistance, and raised charitable funding despite the added challenge of a disorganized administrative response (Eikenberry, 2007). There is much to analyze during the deployment of humanitarian disaster relief to better understand the raw chaos that a natural disaster can produce. On the ground, there is an overall sense of confusion due to the lack of organization. NGO volunteers and staff at emergency relief sites and shelters are often simply following instructions from supervisors in these NGOs. Unfortunately, when NGOs are forced to work independently, much human effort, emergency supplies, time, and lives are lost due to inefficiency and misinformation (Perry, 2007). As shown, one of the greatest weaknesses in the United States' natural disaster management planning is the lack of coordination and cooperation between participating parties. Government systems must provide an infrastructure that facilitates how organizations contribute to emergency disaster relief and reconstruction to prevent unnecessary duplication of effort and wasting resources.

The post-disaster phase is an optimal opportunity for implementing better structural standards and necessary policy reform to promote stronger administrative preparedness for future natural disasters. Risk management and risk reduction policy is a complicated topic due to the uncertainty of natural disaster. In a similar manner, NGOs do not fund disaster mitigation and prevention efforts because of the uncertainty of disaster. It is clear that new policy must include a flexible framework that will encourage NGO cooperation in disaster management planning and preparation. Just as importantly, there is a necessary shift towards more sustainable development through building policy reform that will allow for integrating disaster risk reduction into human development. A false sense of security is created when decision makers excuse urban expansion in areas of risk. The excuse is that there could be structural engineering that could prevent and reduce damage risk (Raikes, 2019). It is counterproductive to human development if urban planning and engineering can't successfully prevent exposing people to high risk areas without a proper engineering design solution. As mentioned earlier, coastal regions and cities are important to several aspects of human infrastructure. Decision-makers, businesses, homeowners, and more will try to justify occupying high risk urban areas. This thesis proposes safe human development can be achieved with proper sustainable, risk-reducing, urban planning and architectural design. Below are some recent and innovative disaster mitigation engineering solutions. And later, this thesis will explore some iterations of an idealized disaster-resilient residencial design solution.

**Design and Engineering Education**

There is a lack of disaster awareness courses and an overall gap in institutional education towards designing disaster-defensive architecture projects. On the topic of education gaps amongst professionals and designers, we must also analyze how prepared humans are to adapt and design for a better future. Disaster-defensive architecture pertains to shifting our design of buildings towards being able to withstand the increasing intensity of climatic disasters. Not many architecture and engineering curricula teach the importance and relevance of natural disasters and their potential effects. Design for disaster resilience seems to only surface or become important after a catastrophe strikes. Currently, as it pertains to disaster mitigation, most of our architectural design has only considered creating safe spaces, bunkers, and shelters. We haven't really thought about thoroughly redesigning the way we inhabit Earth: our housing. As climatic tough times draw closer, we must be able to build resilient shelters in order to survive natural disasters. I was not able to find many research initiatives or projects about new and innovative disaster-proof, permanent housing. Dr. Sudarshan Krishnan and Mr. Yuan Liao wrote a conference paper for the American Society for Engineering Education. Dr. Krishnan is currently an assistant professor within the architecture program at the University of Illinois. Dr. Krishnan specializes in lightweight structure and serves on several professional bodies like the International Association of Shell and Spatial Structures (IASS) and the American Society of Civil Engineers (ASCE). The overall goal of their paper is to encourage an increase in research and design solutions with regards to natural disasters and shelter architecture. Within this article, major topics include the context of natural disasters, characteristics of disasters, shelter design, guidelines for design, and framework for future shelter design education. Natural disasters are divided into three phases: pre-disaster, impact phase, and post-disaster or reconstruction phase. As Table 1 below shows, each phase pertains to different aspects of a disaster, for example, the pre-disaster phase is about predictability, impact phase describes the physical damage ongoing, and the post phase is concerned with recovery and reconstruction. Emergency shelter design must consider these different types of natural disasters and how the needs of affected humans change per location and/or event. Fundamental characteristics in shelter design are modularity and deployability. Safety and functionality depend on each type of disaster. For example, in a flood you would need waterproof materials whereas in a megafire you would need fire resistant materials (Krishnan & Liao, 2019). Humans have realized that we can't control natural disasters, and we should also realize that we aren't always prepared for disasters. This paper aims to inform and thereby encourage that architectural curriculum educate students in these topics. Educating young professionals and forcing them to think critically about Earth's instability can result in important research and breakthroughs with regards to natural disaster defense.

**Table 1: Characteristics of Disasters**

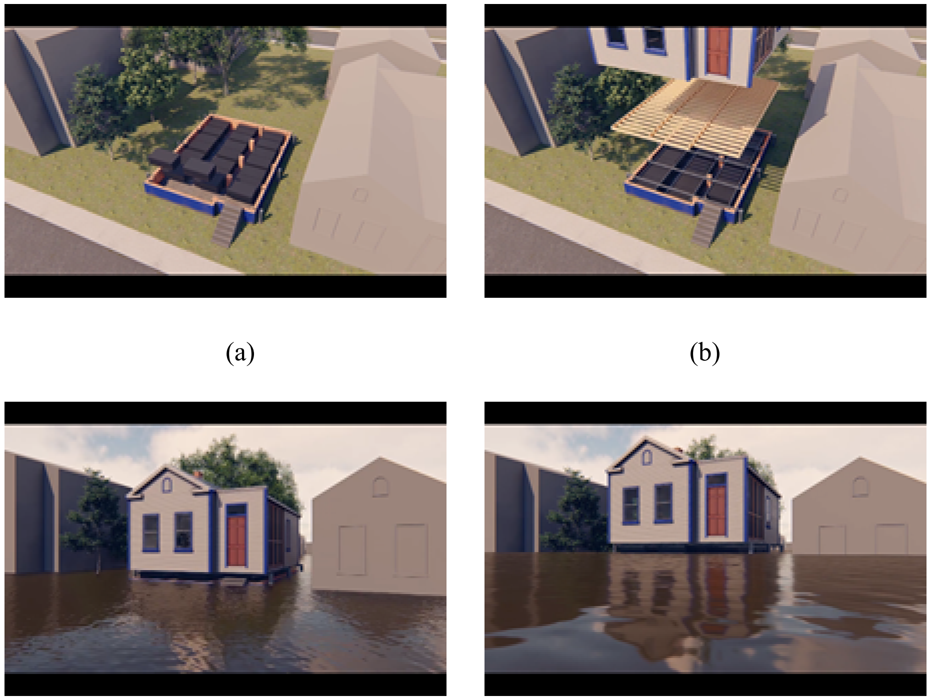
| Disasters | Earthquakes | Floods | Megafire | Hurricanes |
|---|---|---|---|---|
| **Disaster category** | Geophysical | Hydrological | Climatological | Meteorological |
| **Effects** | Damage to structure due to intense ground motions and aftershocks | Ruined structure and inundation by flood | Charring, spalling, and melting due to high temperatures | Flying roofs, broken windows |
| | Fire caused by collapse | Rainstorm, thunder and lightning accompanying floods | Smog and smoke | Rainfall, thunder and lightning accompanying storms |
| **The pre-disaster phase** | Very short and unpredictable | Usually predictable | Prevention and warning system can extend the escape time | Usually predictable |
| **Disaster/impact phase** | Short but aftershocks may continue for years | Land may be covered with water from days to months | Could last long, spread far and wide | Relatively short |
| **Post-disaster and reconstruction phase** | Long term reconstruction and recovery | Long term depends on the intensity of flooding | Long term reconstruction and recovery | Long term reconstruction and recovery |

## Current Disaster Mitigation Design Initiatives

After studying the disaster cycle and the mechanisms for response to natural disaster, there appear to be several gaps in architectural research. These gaps point toward real-world design constraints for the design and construction industry of disaster resilient homes and shelters. In an article on ThoughtCo.com by Jackie Craven, an important point of critique is raised about our current preferred evacuation strategies for cities and towns (Craven, 2019). Dr. Jackie Craven is an art and architecture expert with over 20 years of experience writing about architecture. Dr. Craven's observation is that contrary to the common method of horizontal evacuation, where residents are encouraged to get out of their homes and travel to shelters, perhaps we could shift our thinking and consider vertical evacuations, where residents shelter in place in their homes in safe rooms or spaces. If we can build stronger buildings, then people can simply move to higher levels, and take shelter (Craven, 2019). For this reason, it is important to promote and encourage design initiatives that improve our disaster resilience.

The most notable design breakthroughs for flood-resilient architecture all feature a reduction in surface area exposed to water forces. One example is the popular 'house on stilts' approach. Where houses are elevated to a second level, any water from flooding is immediately redirected under and around the structure, not into the structure. A prototype is shown in Figure 2 on the next page, taken from the same ThoughtCo.com article. Another design approach is the floating house technique developed through Dr. Elizabeth English's research on amphibious foundation systems (Buoyant Foundations Project, 2019). Figure 3 is a series of animation screenshots from a video by the Buoyant Foundation Project. The animation shows the process and mechanics of how the foundation of a retrofitted house can be lifted by high buoyancy floating devices during floods. Structures are more often being designed to be versatile with regards to where the essential housing components like water heaters, and electrical are located. Structures are designed to move up and down according to tidal motion or overall flooding.

**Figure 2**: "Prototype tsunami-resistant shelter in Car Nicobar in the Bay of Bengal, India. Photo by Pallava Bagla/ Corbis Historical/ Getty Images. Features the 2nd level safe rooms for better tsunami and flood resistance. (Craven, 2019).



(a) (b)

(c) (d)

**Figure 3**: Buoyant Foundations Project. Animation of the amphibious retrofitted house in Charleston. “The following is an animation showing the assembly of a buoyant foundation retrofit for a typical Freedman’s Cottage”. (a). Buoyancy devices under structure. (b).House on top of steel supports and wooden substructure. (c). Initial flooding, water level below windows. (d). House on the left floats, water level up to windows on house to the right. (Buoyant Foundation Project, 2019).

The design approaches mentioned above take careful prototyping and testing. Properly studied research initiatives positively impact construction standards, overall improving our building technology. One example of an initiative gone wrong is Brad Pitt’s non-profit ‘Make It Right Foundation’. In December 2006, Brad Pitt along with William McDonough teamed up with Graft Architects to rebuild 150 homes in the Lower 9$^{th}$ Ward in New Orleans after hurricane Katrina. The Lower 9$^{th}$ Ward reportedly lost close to 4,000 homes, yet the Make It Right Foundation chose to focus on making homes LEED certified and aesthetically pleasing (Firestone, 2011). As of January 2018, only 109 of the 150 homes had been fully constructed. In September 2018, residents began to file lawsuits against the Make It Right Foundation. The allegations include the use of defective or inappropriate materials, electrical, plumbing, and ventilation issues (Menza, 2019). The Make It Right Foundation held a design competition where top designs got featured by being constructed as part of the rebuild project in the Lower 9th Ward. A competition is a good media to encourage designers to think in this field of architecture. However, Katrina left many people without homes, and in an emergency, reconstruction efforts are most effective when homes and shelter are rebuilt quick, cheap, reinforced; all while considering any new safety measures triggered by the disaster.

As a slow research field, design initiatives and innovation in disaster has immense boundaries. A futuristic approach to disaster resilience is referenced in a 2013 website article from BBC's 'Future' site talks about current underwater architecture applications and presents the feasibility for humans to live underwater. This reference by Rachel Nuwer, a scientific journalist who works for BBC Future, offered another perspective on human survival. Interestingly, this idea of underwater living still falls under the alternative evacuation strategy discussed earlier in this review. Living permanently underwater is still a form of vertical evacuation.

Living underwater is far in the future, but the key takeaway is that innovation within the field of resilient housing is capable of shifting towards improved construction methods. New design solutions might break away from traditional construction only to create better techniques. The design initiatives referenced have the common goal to improve resilience during the reconstruction phase of natural disasters. An innovative approach requires a new design process that considers new materials and defensive approaches for coastal residential architecture. New technology and new ideas tend to raise many concerns and questions for policy makers and government agencies. One of the biggest concerns is flooding insurance policy and maintaining compliance with government flood mitigation regulation.  A direct example occurred in 2007 when FEMA contacted Dr. English, founder and director of the Buoyant Foundations Project (BFP). FEMA was concerned that promoting and publicizing the concept of a new floating home would jeopardize the local community's good standing with the National Flood Insurance Program (NFIP). Dr. English responded by acknowledging that BFP is unprecedented engineering in the United States, overall understanding the reluctance by FEMA and NFIP to accept the new method (Fenuta, 2010). In 2009, BFP proposed adjustment plans to satisfy FEMA objectives, which ultimately allowed for proper compliance and then permits for implementation (Fenuta, 2010). This was a necessary step in proving to the government that new engineering solutions can in fact meet regulations. Nonetheless, the research and iteration was slowed down, preventing an efficient design process. New technology can be strange at first, but limiting innovation with current laws and policies prevents efficient research towards resilient human development.

## III. Methodology

### The Design Problem - Context + Constraints

The previous sections have contextualized the need for improved disaster management and risk reduction via innovative residential architecture. This last section of literature review will present the design constraints and regulations involved with designing disaster-resilient structures. The design methodology I have chosen takes into consideration the most common weaknesses in current disaster mitigation methods. In addition, regulations from government organizations like FEMA can be considered minimum requirements and constraints to my proposed designs. This section is divided into design constraints most relevant by the type of disaster, including hydrological disasters and geological disasters. Though my thesis focuses on hydrological disasters, earthquakes are still relevant within the context of tsunamis. Often, it is an earthquake offshore that triggers a tsunami. It is important for my design iterations to take seismic force loads into consideration.  Constraints and regulations through this methodology will narrow the focus and best inform the designs to be presented later in this paper. Although I have not chosen a specific case study site, the proposed designs follow local Massachusetts building codes.

**FEMA Coastal Construction Manual**

One of the best sources for water related building regulations and construction considerations comes directly from the U.S government. This publication is by the Federal Emergency Management Agency (FEMA). The entire two volume document is around 650 pages long. Volume I gives a more conceptual perspective on hazard identification, economical impact, and more. Volume II is more specific, and its preface reads,

> *"Volume II contains in-depth descriptions of design, construction, and maintenance practices that, when followed, will increase the durability of residential buildings in the harsh coastal environment and reduce economic losses associated with coastal natural disasters. The primary audience for Volume II is the design professional who is familiar with building codes and standards and has a basic understanding of engineering principles." (FEMA, ii,* 2011*).*

In the second chapter of Volume I, FEMA provides the context that justifies the need for a 'Coastal Construction Manual'. At the beginning of the chapter there is a timeline from 1900 to 2010 that maps out all major coastal disasters and the policies and construction standards that were adopted as a result. The chapter organizes all U.S disasters into separate coastline regions, from the North Atlantic coast to the South Atlantic coast, Gulf of Mexico, and the Pacific coast. Within each section, major disaster events are explained in detail; FEMA describes the location of impact and the specific construction weaknesses observed. With each disaster, there is usually an act, agreement, or implemented building codes for future construction. (FEMA, i, 29-40, 2011)

After all the coastal regions are discussed, the chapter switches its focus towards 'Breaking the Disaster- Rebuild- Disaster Cycle'. FEMA suggests that it is most important to understand the potential dangers of any given coastal region. Hazard identification allows designers and architects to make the safest and best-informed decision for construction siting. The later sections of the manual include topics pertaining to siting, design, construction, enclosures, and maintenance. When considering a construction site, the important message is for designers to realize that siting near the coast is inherently a risky idea. It is most important to find the best zones geographically/topographically suited for constructing ideal foundations without much risk of landslides, erosion, or flooding. This then informs design by imposing some important constraints. These include elevating buildings, spread footing and slab foundations, corrosion resistant materials, and more. The major concern with construction specifically is poor connections of important structural columns and beams. Any weak points within the infrastructure make buildings sensitive to minor land shifts, wind, or water forces. The later sections talk about situational building features like breakaway walls on lower enclosed structures like garages. Lastly, for maintenance, it is important to note that if buildings are not properly repaired and protected against corrosion, they will be particularly vulnerable in future disasters. (FEMA, i, 40-60, 2011).

**Building for Hydrological Disasters**

Volume II of the FEMA Coastal Construction Manual gives designers an outline for necessary considerations in coastal development. Chapter 7 covers several topics ranging from design requirements and determining hazard risk to cost implications and hazard insurance. This section of the construction manual puts great emphasis on the importance of planning prior to designing a building. Designers must be well aware of local building regulations, construction codes, natural hazards, and must be ready to show compliance with insurance agencies (FEMA, vol. ii, 2011). For the purpose of a thorough case study, I will be following local building codes and regulations by the State of Massachusetts. Now that a general location is selected, the next step is to decide building placement, orientation, and design. All of these decisions should be guided by realistic estimates of natural hazard risks, aesthetics, intended building use, regulations, codes, and cost ( FEMA vol. ii, 2011). My design recommendation is intended to mitigate hurricane, flooding, wind, and seismic forces; all forces that have precedent in several Massachusetts counties. The purpose of my building designs is primarily residential. The idea is to optimize the current coastal development situation along Massachusetts coast lines by maintaining a presence along the coast while minimizing natural disaster risks with innovative architecture.

FEMA's manual provides general recommendations based on international building codes and federal regulations. Examples of such resources are the hazard tools provided by the American Society of Civil Engineers (ASCE). It is stated multiple times that the manual should not be the only guiding document when designing or deciding to build. A responsible approach must also research documentation that dictates state and local building codes and implement in design and construction. Not surprisingly, building codes are spread across many sources. Going through this design process has also shown the weakness and need for better organization of important regulation information. With some difficulty, finding Massachusetts-specific flood standards took me to several documents on the Mass.gov website. Agencies on the Mass.gov site include the Office of Coastal Zone Management (CZM), and the Floodplain Management section of the Massachusetts Flood Hazard Management Program (FHMP). Both the CZM and the FHMP have gathered Federal regulatory documentation and summarized the information along with amendments specific to Massachusetts. In the design proposal section of this thesis, relevant flood standard codes will be referenced as necessary. The methodology is to study coastal zones and use building codes to adjust design aspects of my building proposal.

Hazard risk analysis should be the baseline and starting point to any coastal development. The nomenclature within flood hazard regulation documents pertains mostly to classifying geographic locations by level of risk and exposure. Hazard maps are an important and common tool for identifying risk within any location. In an effort towards a holistic design process, additional research is necessary to understand recurrence trends and other factors like seismic risks. After proper consideration, an acceptable level of risk should be established, and if the risk is too great, the location is not ideal for development. Understanding the Base Flood Elevation (BFE) at a given location is one of the most important ways to reduce possible flood damage. A BFE is a measurement and estimate of water level elevation during a flood that may have a 1% chance of occurring (FEMA). Although a BFE is a minimum height, buildings that are raised even above the BFE are likely to take less damage than simply building at BFE. Decisions like building above the BFE offer a building owner several other benefits like saving a good amount of money due to reduced insurance premiums.

The National Flood Insurance Program (NFIP) bases flood insurance rates on hazard maps which classify regions near water into flood insurance zones. Locations are grouped into lettered zones. Zone V or Zone VE are the areas closest to water and considered high flood risk. Waves have a chance of reaching more than three feet in elevation, making this area the most expensive for development with regards to insurance premiums. Zone A, or slight variations like AE are flood zones where wave and flood elevation are unlikely to reach three feet. The last common lettered zones are Zones B, C, or X. Any of these letters or other variations signify that a region is located outside of the 100 year floodplain. The variation in lettering would be subcategorized zones where it might still be possible to determine a BFE for construction. A Federal government website where the zoning information is available is the FEMA Flood Map Service Center at the link : https://msc.fema.gov/portal/home (FEMA Flood Map Service Center (MSC), 2020). This archive can generate a flood map by specifying a location and clicking on a specific map quadrant. The report contains a note to the user and a small map section labeled and color coded. Figure 4 below shows an example map of downtown Boston and Boston harbor. Designers and builders do not control insurance rates, but must be responsible for understanding the implications of insurance zones. Designers must also make property owners aware of the risks before making siting or construction decisions.

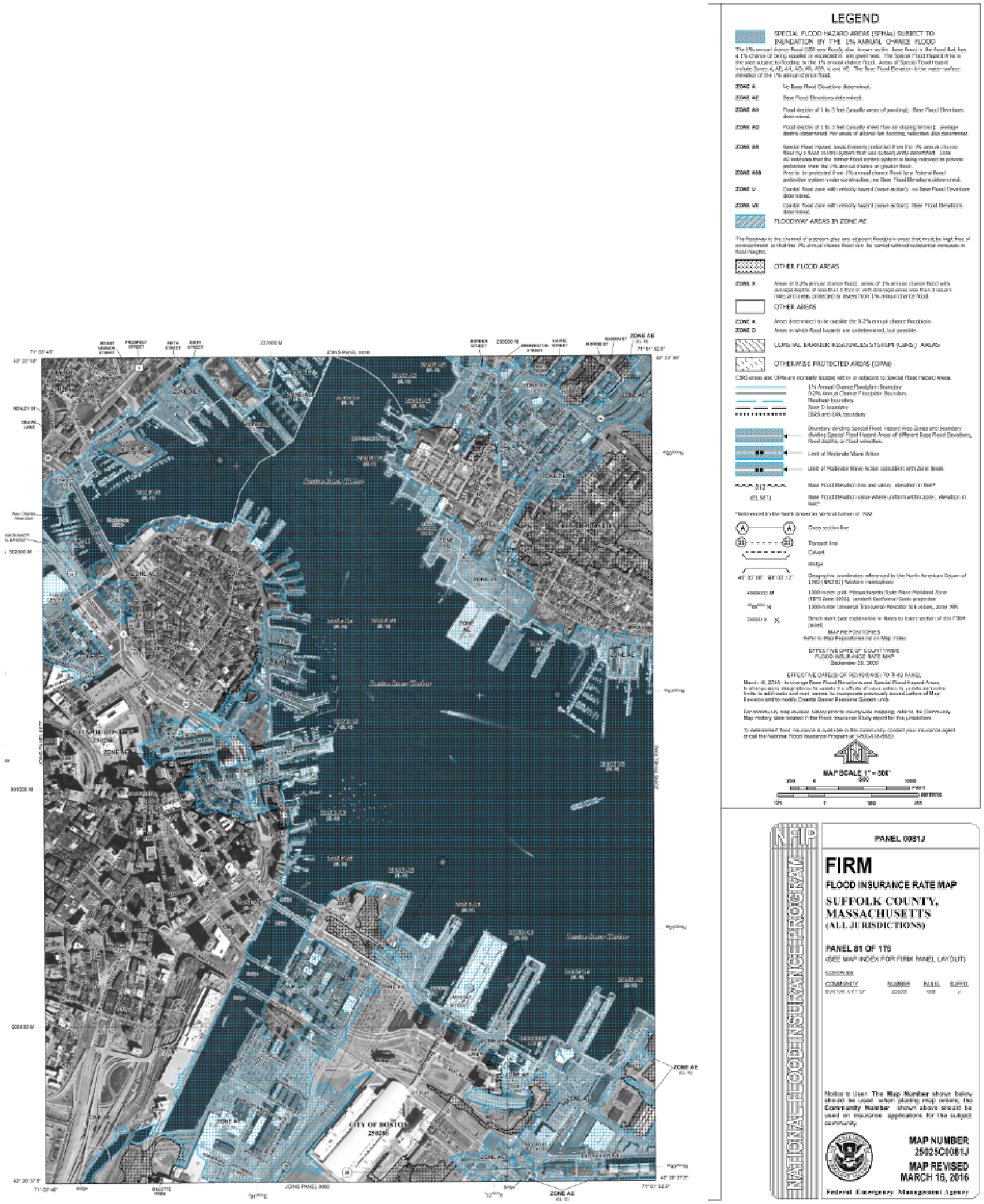



**Figure 4.** Flood Insurance Rate Map for Suffolk County, Massachusetts. This is a small section of Suffolk county divided for easier reading by FEMA. The legend gives information about what the Zones and the color shading indicated Zone borders (FEMA MSC, 2020).

If the risk is acceptable and the project continues, there are many important decisions left to make. Resilient structures are most successful after holistic consideration for construction, inspection, and future maintenance (FEMA, vol. ii, 2011). Designers are taught to implement more sustainable construction materials and methods. However, some methods are not adequate for siting near the water. For example, roof overhangs or even solar panels may be considered bad ideas due to the fact that at high wind speeds these force resistant surfaces could unintentionally act as 'sails', further increasing the overall wind loads on a building. Another example is that it might seem intuitive to try to minimize a building's footprint and cost by optimizing or reducing material usage. At flood prone sites, the long-term cost and consequence of conservative designs will be much higher. The point is that construction decisions are important and compliance with minimum code and regulatory requirements does not make a building risk immune (FEMA, vol.ii, 2011). Designing beyond minimum requirements and implementing innovative measures will increase safety, but inevitably increase the cost of construction. The designer must be able to show that the benefits outweigh the higher upfront cost.

# IV. Design Proposal

## "coast" Pod Elevation System

An alternative housing model featuring safety pods. (untested concept)

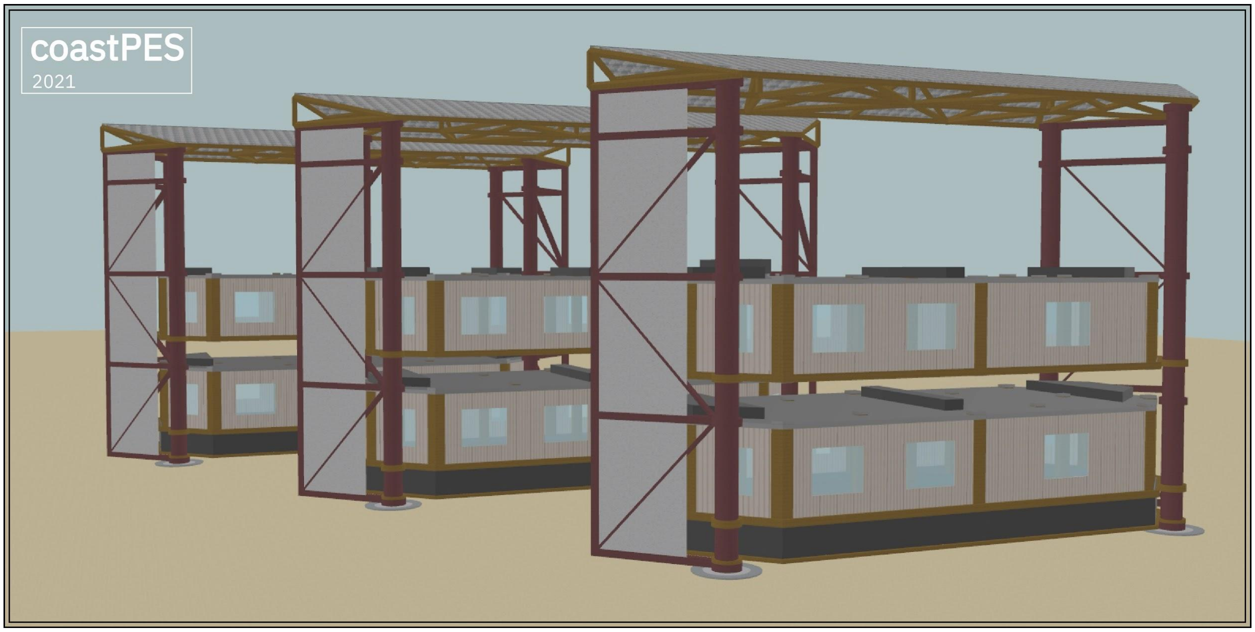



**Figure 5**: coast Pod Elevation System Render. Perspective view of 3 coastPES systems side by side. Depicts rail structure and 2 pods per system.

After reviewing several innovative design ideas and FEMA's guidelines, this thesis presents original concepts and design ideas for an alternative and resilient residential building system. My designs are largely speculative due to my lack of experience in coastal development engineering and lack of resources to properly prototype and test my designs. Simulations are a good tool to understand general behavior, but scaled prototyping and live testing are required for this complex system. In this section I will be presenting the most current design iteration. Throughout the design explanation I will be referencing the relevant building regulatory codes that informed any design decisions. For my thesis proposal in 2019 I designed an initial prototype called SurVibe. This first iteration features a large pentagonal central structure with large steel truss arms. The arms hold in place several apartment-sized pods that can rotate and detach in case of emergency (Figure 6). SurVibe was focused on an idealized solution to surviving natural disasters. The scale and cost would be high to be considered and an easy to deploy system. For my final thesis I gathered feedback, suggestions, and new research to inform an improved iteration. My next iteration is called "coast" Pod Elevation System (coastPES), inspired by the verb definition of the word coast; the ability to move easily without power. First, I will present the new iteration and then briefly show the 2019 version.

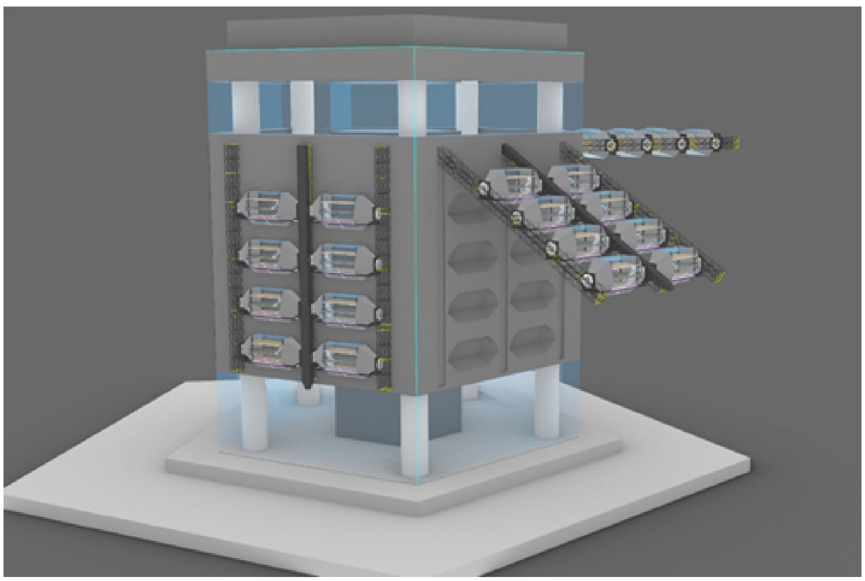


**Figure 6**: SurVibe Render. Isometric view of truss arms at different extension angles.

### "coast" Pod Elevation System - New Design Proposal 2020

The new pod system is a refined version of the initial iteration, 'SurVibe'. Perhaps the most important change was to greatly reduce the size of the project. SurVibe was a building designed to hold up to 40 individual pods, all attached to a large central structure. CoastPES is a significantly smaller system for only two or three pods. Each pod is a small, one-story apartment designed for one family at around 1,100 square feet. Pods will be arranged vertically on reinforced metal rails. The underside of the lowest pod will be equipped with a flotation system made up of inflated rubber and expanded polystyrene (EPS). When water reaches the underside of the first and lowest pod, the pod will begin to float to maintain itself above the water. The first pod will push the pod above it until they are floating above the water. The elevation mechanism is a system of 4 steel piles/rails that control the speed at which the flotation happens. As buoyancy forces push the pods, counterweights will offset the pod weight in order to stabilize the upwards motion and minimize turbulence inside the pods. As shown in Figure 7, the sides of the structure will cross-brace the rails and also house stairways, counterweights, and utilities. Utilities will be located either at the top or bottom of the building in a separate pod, and pipes and sewage should be designed for flexibility given the moving nature of the pod system. The objective with coastPES is resilience to coastal hazards while featuring cost efficiency, rapid construction, and easy scalability and deployability. Below is a labeled prototype rendering and the following sections will explain design specifications.

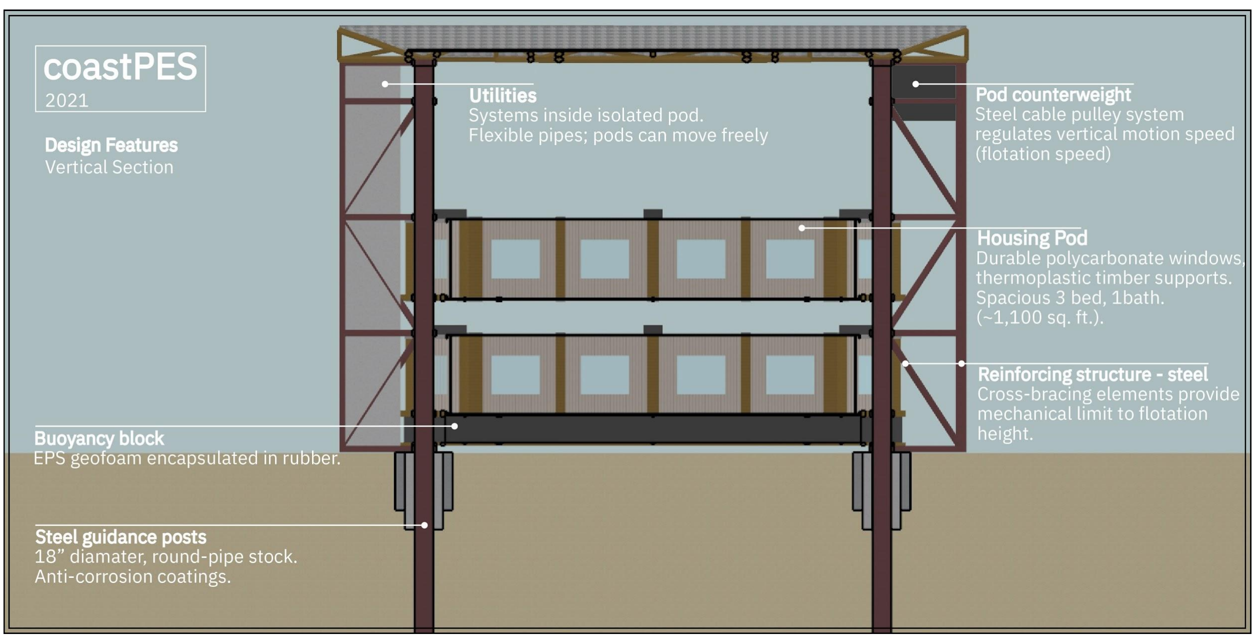



**Figure 7**: Vertical Section of coastPES. Labeled diagram of system features.

**Designing Resilience**

Building close to water has been a challenge for a long time. There are many factors that could weaken and damage any structure, such as wind, water, corrosion, and erosion. Most of these design challenges can be solved by using a reverse design approach. Rather than starting with a full structure, the materials should be selected first, based on environmental factors. The next step would be to design the methods in which the materials are aggregated, joined, and configured, based on the predicted force loads. Lastly, these connections make up the full building system that could even relate to nearby structures.

Materials are often selected for convenience and familiarity. However, conventional materials have several disadvantages when exposed to the harsh coastal elements. For example, wood is prone to decay and termites; steel is prone to corrosion; glass is brittle and requires reinforcement during hurricanes; and concrete can deteriorate due to water intrusion. The proposed materials for coastPES are uncommon materials that could have a useful application in coastal development. Anchoring the rail structure will require reinforced concrete footing and corrosion resistant steel rails that are driven deep into the ground. Some added cross-bracing reinforcement will also make the lower part of the structure robust and bottom-heavy. Thermoplastic timber can be an efficient and sustainable replacement for wood in the actual construction of the pods. This form of timber is resistant to decay and is typically stronger than wood. Polycarbonate sheets can be an adequate replacement for glass windows. Polycarbonate is clear and significantly stronger than glass. Lastly, for buoyancy, EPS blocks can be attached to the underside of the pods. Materials introduced here will be further explained later in this thesis within the ‘Material’ section of part 5- ‘Construction + Scalability”.

After selecting materials, the next step is to begin designing the structure based on the possible force loads that might act on the building during a given disaster. First, as with any building, the dead loads of coastPES are the overall force loads from the weight of the unoccupied building. CoastPES attempts to minimize the dead load of the pods by implementing lightweight and easily deployable structures. For this, coastPES promotes a tiny-home approach for the individual pods; occupiable space is reduced to essential living space. A cultural shift is implied here, and it encourages families not to need and want the amount of space traditional American home culture has treated as a luxury.

The live load is the weight during occupancy determined by human weight and the weight of objects inside the pods. The structural members must not only be able to hold dead and live loads, but it must also be significantly stronger to withstand external force loads. Figure 8 summarizes all force loads considered for coastPES. Below is a list of coastal site loads and how coastPES plans to mitigate forces like flood loads or wind loads.

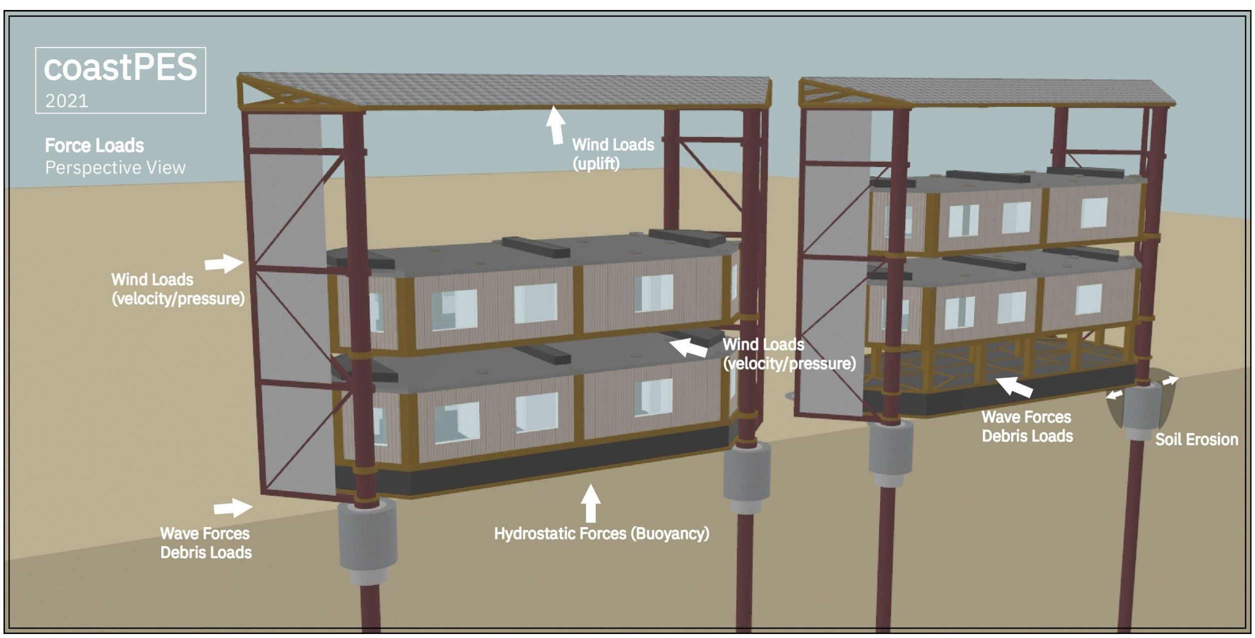



**Figure 8**. coastPES Force Load diagram. Two different models for site specific hazard risks. Model on the right provides debris clearance and pods begin at a ~6’ft. elevation.

## a. Flood Loads

During a flood event, there are typically several forces that will act on a building. Storm surges and high-wind coastal storms will raise overall water levels and generate waves. The wind will intensify the speeds and turbulence of the water.  This combination of loads can have the following impacts:

Hydrostatic loads

A vertical hydrostatic force is also known as buoyancy or flotation force. When water comes in contact with a building, the behavior of submerged portions can change. The weight of a foundation or submerged structural element decreases (FEMA, vol.ii, 2011). This shift in weight means that structural elements offer reduced protection from upwards water forces. In the case of coastPES, the pods will need to take advantage of the upward forces to slide up and away from the water. However, the foundation and rails must be well footed so that the building does not fail. Pods will require a 'buffer' gap between each other so that the force onto one another causes no harm to either pod structure.

Wave Forces

Force loads from waves can impact a building in a few ways depending on the action point of the wave. One, the wave is flat and moving towards and around the structure. Two, the wave is reaching a peak and breaks into a short burst of high magnitude force onto a vertical element. Three, the wave has already broken, but still carries a higher lateral force. And lastly, smaller waves can form under a structure due to water turbulence. Large and lateral water pressure forces can be avoided by elevating the lowest floor high enough about the BFE. By only exposing columns and piles with costPES, the wave crests can break without hitting solid walls where a pressure force would be greater.

Debris Loads

This next force load is more difficult to predict because the impact load of objects carried by water depends on the size and the shape of the debris. As FEMA also explains, another factor is the velocity of the object which is also situational and almost random. Other buildings, trees, or even rocks could potentially slow down an object. Despite the unpredictability, design methods can offer some protection against debris. The only variable that is known is that debris will most likely hit at the height of the water level carrying it. This assumption allows the designer to predict where the debris will impact the structure. CoastPES pods are designed to float above that water. The flotation device can be a separate platform some distance below the first pod. The vertical connections between the buoyancy platform and the pod must be columns that can break waves, but hold the weight of both pods. Other than the pods, the rails themselves are exposed to debris and other lateral forces. Some exploration can be useful in determining whether physical 'shielding' could be necessary around the base of the rails.

Soil Erosion/ Scour

One more relevant flood load is soil erosion and scour. This phenomenon occurs when waves and currents hit the vertical supports and columns of a structure. As the water impacts the support, turbulence from the impact force will displace the soil or sand away from the support. The soil around a vertical element often offers some lateral support, and when more of the column is exposed it could weaken the overall structure. Lateral forces on the higher part of the building could create unwanted torque forces without a proper and steady foundation. To mitigate scour, the coastPES foundation design will include shielding underground and around important structural elements. One method is concrete bases around the buried vertical support. A secondary defense would be stones and gravel around any buried building elements; that way if soil erodes, larger rocks still keep some ground integrity around the piles and columns.

**b. Wind Loads**

<u>Velocity, Pressure, and Uplift</u>

High-velocity wind typically occurs during storms, so it is likely that flood loads will occur in combination with wind loads. However, wind loads can also occur independently. Load forces on a building are typically created from the wind hitting continuous surfaces. Depending on the speed and direction, wind can damage vulnerable areas. One vulnerability is caused by roof overhangs. At an overhang, the horizontal part of the roof meets the vertical wall elements. This corner allows for a pocket of air that can create an upward pressure force on the roof. Without durable and proper connections to the walls, roof systems can be severely damaged. Pod designs can be optimized to not need any overhangs. The pod's vertical wall panels will be protected from debris and water by impermeable plastic-fiberglass caps at both top and bottom; the hard shell will also act as collision protection between pods. Overhead protection will come from the cross bracing truss structures at the top of the building.

Wind and water forces are similar when they interact with other objects. Both natural elements often flow in a specific direction. When the direction of flow hits an obstacle, the force load onto the object will be greater on perpendicular, higher surface objects. Keeping this in mind, proper design strategy could help reduce flow forces from either wind or water. After site research, it is possible to choose building orientations that are safer than others. For coastPES the profile of the structure is designed to taper on the sides. With proper orientation, coastPES will be able to break waves and high wind flow.

**Pod Design**

CoastPES pods are the main feature of the design proposal as they are equipped to provide shelter and withstand high intensity storms and hurricanes. The priority with the pods is to create a waterproof and lightweight structure that is safe and easy to deploy in emergency reconstruction sites. Each pod will need to have emergency power and basic survival supplies like water, food, and oxygen. In case of a prolonged flood and power outages, coastPES pods will remain over the water and be able to provide shelter until the local government establishes control and emergency services arrive. A design inspiration for the pods comes from Survival Capsule, a company that has developed one of the first emergency capsules. The survival capsule system is based on aircraft construction methods to provide a durable and watertight structure. Aluminum tubing is used for the frame and aluminum sheets line the outer shell. Inside, there are safety seats, emergency supply storage, air vents, and water storage. The capsules are designed to withstand the initial impact of a natural disaster, object impact, heat exposure, and rapid deceleration (Sharpe, 2010). Technology built for emergency situations requires heavy duty materials. And as shown, applying robust, yet unconventional fabrication is more likely to ensure safety. A similar approach to the coastPES pod design is mostly unprecedented for residential units. Below is a labeled diagram with construction and material features for the pods.


**Figure 9:** coastPES Pod design diagram. Labeled key resilience measures.

## coastPES Summarized

The main objective for coastPES is safety. A dynamic system offers resilience throughout the unpredictability of hydrological disasters. Survival and safety should be culturally accepted as more of a living standard along hazard-prone regions. As a method of vertical evacuation very little time is lost during preparation and evacuation. Families will be able to live in the coastPES knowing they no longer need to seek state or local shelter; they will already be living in an adequate shelter. The basic function of a home is to be an isolation and protection from the outside environment. Natural disasters are quickly becoming more and more destructive, design should then also adapt to break the build-destroy-rebuild cycle. CoastPES seeks to minimize damage and require less long-term cost due to maintenance and repair. A modular pod construction strategy can also solve a major issue for disaster recovery: rapid and cost efficient redevelopment. A pod and rail system is a new method that will most likely meet some permitting and licensing difficulties. Building code and regulation does not allow for much flexibility and innovation. Through more design iteration and adjustment to site-specific conditions, coastPES will become a scale-able solution to the increasing need for disaster resistant housing.

**SurVibe - 2019 Iteration**

In a method exploration during thesis ideation, my initial design method was quickly nicknamed SurVibe, a word combining survive and vibe. The structure at the center is a pentagonal building with the capacity to hold about 40, apartment-sized pods. Families are meant to live in the pods and have access to the public central structure which would host recreational areas, shopping centers, communal lounging, and more. Pods are waterproof and independent, with life support systems on board. Ideally, if the central structure begins to fail, these pods would be able to detach and float or become anchored. The pods rest on large steel truss arms with the ability to rotate and adjust the orientation mechanically with buoyancy forces. Figure 10 shows the basic ideation of this design.

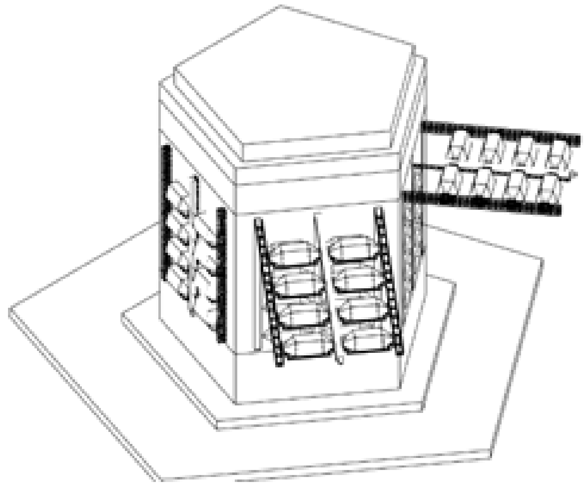


**Figure 10:** Exterior perspective rendering of SurVibe pod system. Image shows the central structure and the triple arm system, safely holding the pod cradle and drum brake assembly.

**SurVibe Resilience Measures**

i. *Pentagonal central building.* The edges of a pentagon occur every 108° degrees. More directions are protected from full horizontal forces, the peaks break the water force loads and prevent building damage.

ii. *'Breakaway', glass lower levels.* If the façade of the lower levels is designed as a breakaway grid of glass, then the building can relieve all water forces around the building, reducing the chances of structural failure.

iii. *Multi-purpose central space.* The central building space can be filled with areas for recreation, dining, shopping, lounging, cooking, resource centers, etc.

iv. *Large foundation.* The pentagon foundation shape is wide and makes for a more structurally sound foundation.

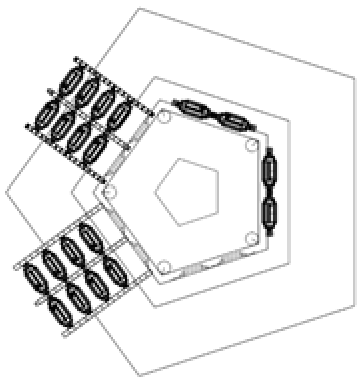
**Pods**

v. *Brakes for pod rotation.* If a flooding disaster occurs, the water would lift flotation devices around the steel truss arms. The pods will be lifted up and away from the building's façade. They must rotate to remain upright and an adequate brake system prevents the pods from rotating too fast.

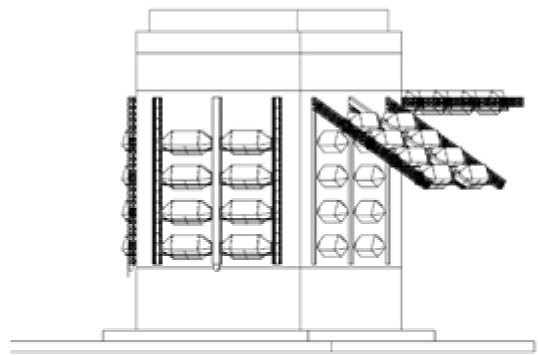
vi. *Life support system onboard.* Each pod will need to have emergency life support systems installed. This system must include oxygen supply and scrubbing, ventilation, emergency generator, and temperature control.

vii. *Weighed bottom for buoyancy/ anchoring.* The underside/peak of the pod can be adapted to be heavy for anchoring, the top/roof can be adapted for flotation.

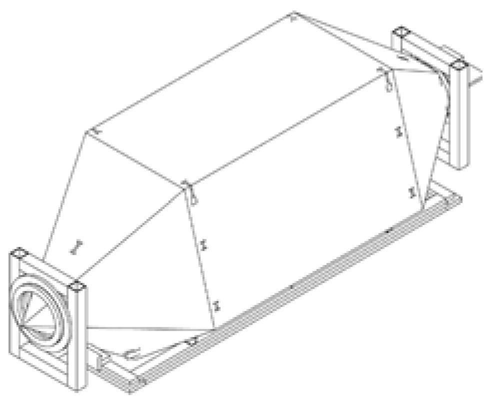
viii. *Watertight and durable*. Designed like a submarine, the hull and metallic side cap joints are watertight. It is critical that there are never any leaks; likely there will be a form of required inspection for pods. The structural acrylic hull is considerably thick, relatively flexible and overall durable.



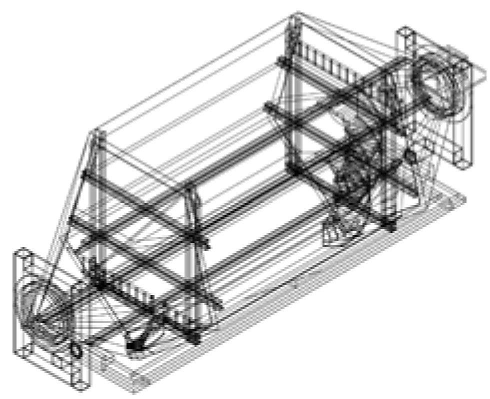
(a) Top View



(b) Front View



(d) Pod Isometric View



(e) Pod Isometric (Hidden Lines)

**Figure 11**. Design drawings SurVibe

## V. Construction + Scalability

After presenting the general concept for the pod elevation system, this part of the thesis will focus on the construction and logistics of deploying coastPES. The material section will analyze all material selections and outline advantages or disadvantages. Then, the construction cost section will identify design decisions and their cost implications. To summarize, the scalability and deployability will be discussed in the last section.

### Materials

One of the most important parts about architectural design methodology is the materials that the designer chooses. The hydrological constraints suggest materials that can withstand horizontal water forces and resist natural destruction processes like corrosion. Material configurations that are optimized for aerodynamics are typically preferred for water and wind forces. For seismic load forces, it is important to choose light materials that are structural, yet elastic. Materials should be able to deform slightly without critically fracturing. Some materials selected for my design proposal are: EPS Geofoam blocks for buoyancy, thermoplastic timber for structural design of pods, and polycarbonate replacement for glass windows.

<u>Thermoplastic Timber</u>

Wood is a traditional material choice in coastal development due to its low cost and versatility. Walls and structural elements made from wood are easier to join with reinforced fasteners. Another important factor is that wood is lightweight and easier to manipulate on-site during construction. By comparison, working with steel often requires heavier machinery and welding. The biggest concern with wood, however, is that it will most likely come in contact with water. Moisture is absorbed by wood, leading to issues like rot. Just as importantly, pests eat away at the wood. With time these forces could make wood structurally unsound and require maintenance and replacement. Therefore, one solution is to adopt a new material that offers similar advantages but can also resolve the weaknesses. A more recent development is the use of thermoplastic timber. This new form of timber can be produced entirely from reclaimed, post-consumer plastic waste. Plastic waste is shredded, blended, and heat-shaped with the use of molds. One of the biggest advantages to using thermoplastic timber is that the ideal cross-section shape can be selected for any specific purpose (Jackson and Nosker, 2009). As a largely experimental material, there is much ongoing research about structural performance. So far, it is understood that the best use for thermoplastic timber is under compressive or tensile forces perpendicular to the grain. Thermoplastic timber is significantly stronger than wood under perpendicular to grain forces (Dias and Alvarez, 2017). As this mechanical behavior has been established and understood more, there have been more engineering and construction applications.

One application is its use by the Department of Defense as an effective solution to corrosion. In a technology innovation demonstration project at Fort Bragg, the U.S Army Construction Engineering Research Laboratory approved a bridge project in order to test the strength and durability of thermoplastic timber. The new bridge supported by plastic timber was able to hold 71 ton tank traffic and it was estimated that the plastic material would not need maintenance for over 50 years (Jackson and Nosker, 2009). The Buoyant Foundation Project (BFP) uses thermoplastic timber as a sustainable and weather resistant alternative to wooden piles/columns. BFP uses a round cross section of thermoplastic timber for the vertical column guides. The house structure is bound and guided upwards during flooding along the plastic timber columns (Fenuta, 2010). The application of plastic timber in coastPES would be similar to the BFP's method of using the waterproof material for external structural support. CoastPES is a structure with a taller profile, so steel rails are necessary to withstand higher bending moments. The thermoplastic timber would be best used as a pod substructure and for the interior frame structure of the pods. This construction decision makes the pods require no steel supports, making the pods more lightweight and cost efficient.

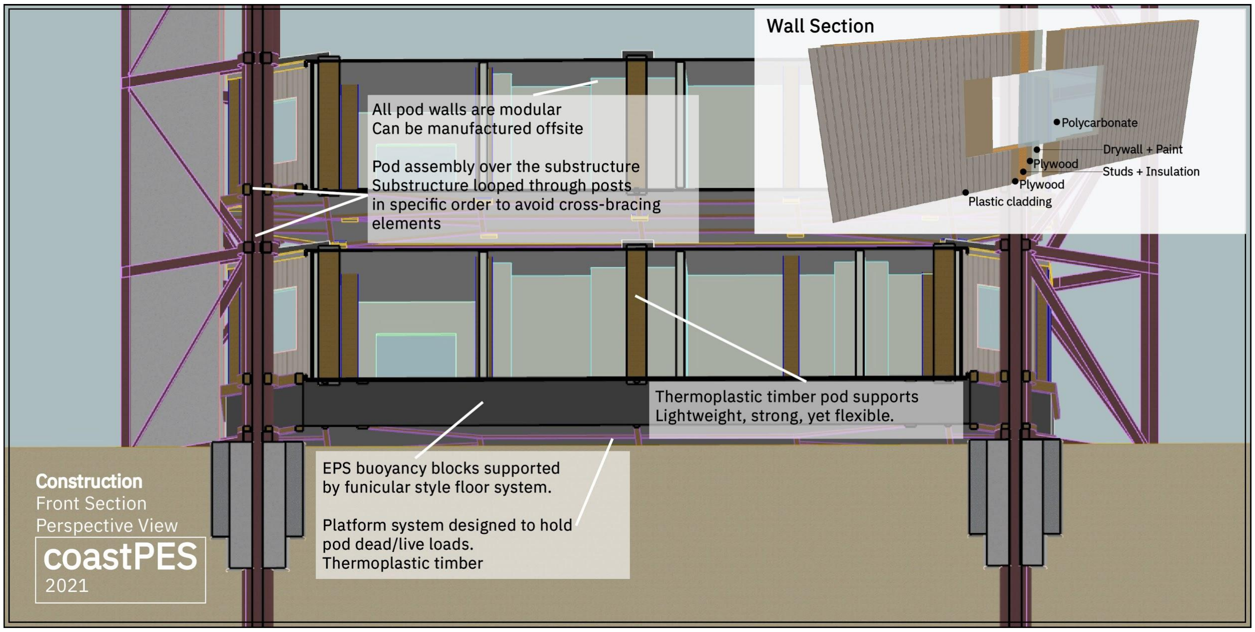



**Figure 12**: coastPES Construction specifications and wall section.

<u>Polycarbonate Windows</u>

Polycarbonate is a thermoplastic polymer that has increasingly been used in construction applications. To synthesize this transparent plastic material, a complex process is used that distills and refines raw materials like crude oil and natural gas. Through life cycle assessments, it is shown that adopting the use of polycarbonate over tempered glass is more sustainable in the short term (Kua, 2016). In the long term, global warming potential is higher for polycarbonate due to the sourcing of raw materials like crude oil. In other aspects like human toxicity potential and marine ecotoxicity potential, long term impacts of tempered glass are higher. (Kua, 2016). Tempered glass has traditionally offered clean transparency and elegant window design. There are several key material properties that make polycarbonate a suitable replacement for glass in disaster resilient design. The most important advantage is that polycarbonate has higher impact strength, making it significantly more shatter resistant (Agarwal, 2011). Under hurricane weather and high winds, it is crucial for windows not to break, otherwise there is no longer a barrier between inside and outside. Another important quality is flexibility and convenience. Polycarbonate is less expensive to produce, lightweight, and can be molded into complex shapes. These make it easier to manufacture and install during construction. Some of the disadvantages in using polycarbonate could be discoloration and low scratch resistance; two issues that also have recent solutions like protective coatings. In the case of coastPES where sites are near water, polycarbonate can provide crucial properties like moisture diffusion, UV resistance, antimicrobial properties, and corrosion immunity. The specific application of polycarbonate in the pods is windows. Although polycarbonate is not entirely more sustainable, its durability will prevent frequent replacement. Glass is often delicate, and difficult to install, but with polycarbonate being lightweight, the idea of modular design is more achievable. Pod wall-panel design will have slots where the polycarbonate sheets can easily slide in and be mechanically sealed in place. Rapid manufacturing is truly possible with the pods now that parts will not be as delicate and will not require extra installation during construction.

EPS Geofoam

Expanded Polystyrene (EPS) is a type of plastic foam also derived from petroleum products. After small styrene plastic beads are produced, other agents are used to expand the beads into larger yet extremely light beads. EPS is a chemically stable foam that does not decay and is resistant to water absorption. This plastic foam has proven useful in several engineering and construction applications. Most common applications are seen in road and infrastructure construction like bridges and tunnels. More specifically, the expanded foam is a lightweight material that can shape the landscape without the need of shifting rocks or soil. Another important mechanical property is the compressibility and flexibility of EPS. Blocks of foam can be used for load reduction, energy absorption, and seismic mitigation (Aabøe, 2018). Lastly, EPS blocks can be manufactured in large shapes and with varying densities. Variables like density of EPS foam change the buoyancy properties. When EPS is submerged the foam has a great capacity for flotation. In infrastructure projects with unexpected flooding, foam without proper drainage can unintentionally damage the bridge or road structure. The buoyant force per unit of volume can be determined using the difference in unit densities of EPS foam selected and the unit density of water (Aabøe, 2018 ). The equation is shown below:

$$F_B = \gamma_{foam} - \gamma_{water}$$

$F_B = Buoyant\ force\ per\ unit\ volume\ (kN/m^3)$

$\gamma\ =\ Specific\ weight\ in\ kN/m^3$

$\gamma_{water} = 9.8\ kN/m^3$

$\gamma_{seawater} = 10.1\ kN/m^3$

$\gamma_{EPS} = 0.11 -\ 0.32\ \ kN/m^3$

The primary use for EPS in coastPES is flotation. Lower density foam results in a higher buoyant force. So, rather than prevent it, blocks of expanded polystyrene must contribute buoyant force. Estimated buoyant force for coastPES is around $9.9 kN/m^3$ given the lowest specific weight of EPS and the specific weight of seawater. For a safe net buoyancy force there should be more than enough volume quantity of EPS foam. However, the flotation platform must have an adequate method for attaching the foam securely. As a flammable material, there is high importance to the proper installation of the foam. In a block of EPS, air occupies the majority of the volume, making it an inexpensive and optimally buoyant material.

**Construction Cost**

Cost for a residential project can be divided into initial, long-term, and continuous operational costs. Development along any coastline will inevitably increase the costs in all aspects mentioned. In part, this is due to the extensive hazard research, site planning and permitting required for producing a disaster-resilient design. With proper risk assessment and a competent design, some of the maintenance costs and operational costs can be reduced. A sustainable and resilient design starts with economical, yet strong and appropriate materials. To reduce construction labor costs, the onsite labor should mainly be constructing the foundation with installation of the pod rails. Pods and utility units will be manufactured off site only to be assembled over the rail system. In addition to structural design, resilient design includes site preparation and construction planning. By collaborating with other professionals, the execution of coastPES can be more cost and time efficient. Nonetheless, resilience is a collective of risk mitigation decisions,for example, increasing embedment depth of the rails or ensuring a robust airtight seal around windows. Both require a higher upfront cost, but could cost significantly less money in the future. If either the structural rails or the windows fail, the destruction and damage would be more expensive than prevention.

Materials like thermoplastic timber and polycarbonate are not as commonly used in construction, making it slightly difficult to estimate an overall material cost. One way for estimating the cost of coastPES is to compare with other similar ideas. In Elizabeth Fenuta's thesis on amphibious architectures, referenced earlier, there is a comparative analysis of flood resilient, floating or amphibious designs. Cost estimates are also provided. For the Buoyant

Foundation Project, the estimated cost is over $20,000 dollars (Fenuta, 2010). This includes the material and construction cost of retrofitting an existing home with a steel substructure, guiding piles, and coated EPS blocks under the substructure for buoyancy. However, the design method that most resembles coastPES is called FLOAT house. This design solution by the Make It Right Foundation involves the construction of a new, one-story home. The building itself was designed to be more of a raft that can float up to 12 feet along large, steel posts. Unsubsidized listing price for FLOAT house is not disclosed by the Make It Right Foundation, but the subsidized cost is $150,000 dollars for roughly 1,000 square feet of space (Fenuta, 2010). FLOAT house follows a similar design, deep embedment of guidance posts, and a lightweight construction for greater buoyancy.The exact cost for coastPES is difficult to calculate because of numerous variables that are site and location specific. Uncommon materials could require unexpected costs when regions are not equipped with manufacturing for plastic timbers for example. Although some aspects of the design might be expensive, other costs are being reduced in the long term. An innovative design that can resist natural disasters requires less maintenance and damage repair; a safe building consequently has lower insurance premiums (FEMA, vol.ii, 2011).

**Scalability + Suitability**

Scalability is the ability to grow operation size to meet increasing demand. With increased resource quantities, coastPES is a system that is easy to deploy. Regions undergoing natural disaster recovery need homes that can be built quickly and safely. Coastal regions at risk for disaster could also prepare to deploy coastPES if any homes suffer overwhelming damage. Some factors that make coastPES a scalable system are: simple pod assembly, modular components, low-cost and durable materials, and an overall flexible design. Suitability then refers to how prepared and appropriate coastPES is for a coastal setting and possible natural disaster risks. It is often at a micro scale where buildings under high load stress begin to fail. Material failure, joints/ connections, and fasteners are some of the possible weakness points. Selecting appropriate materials contributes to disaster resistance and the overall competence of the system. As a buoyancy system, coastPES is suitable because the pods are never submerged and the system can adapt quickly to changing water levels. The reinforced rail structure is robust and designed to withstand stronger than 'normal' force loads. Design specifications that go beyond the minimum requirements require larger material volume and upfront cost. The life-saving and durable design make coastPES a system worthwhile long-term and more importantly, during potentially life-threatening weather events.

## VI. Conclusion

The references discussed within this literature review tackle various aspects of natural disasters. For a holistic analysis, one must consider all that contributes to advancing research in disaster resilient architecture. One key aspect is to address the systemic issues that slow down progress in this field. Secondly, it is important to stay informed about any current projects or new initiatives that attempt to solve this resilience question. Third and last, the physical constraints for designs are crucial. These are the historical hazard risk data and building code and regulations surrounding coastal construction standards. The goal is to offer a new and alternative, disaster-defensive human housing model.

It is human nature to work hard towards sustainability and survival. For the more overwhelming and frightening forces, it is human nature to find safety and shelter. For a long time, we have been obsessed with making bunkers, designating government shelter areas, or installing 'safe' rooms in our homes. This tendency makes sense when events like the many natural disasters, diseases, pollution, several warfare tragedies, and so much more threaten our safety. Realistically, we should be living defensively all the time. When done correctly, defensive living won't mean constant worry and planning. The goal is to integrate safety so smoothly, that people will simply be prepared and still live in comfort and style.

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