

HURRICANE DAMAGE MITIGATION:
FIELD DEPLOYMENT STRATEGIES AND
RESIDENTIAL-VULNERABILITY MODELING

By

FELIX F. RODRIGUEZ

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF ENGINEERING

UNIVERSITY OF FLORIDA

2007

© 2007 Felix F. Rodriguez

I would like to dedicate this thesis to my family, whom without this reality would never have become a dream. This paper will also be dedicated to Dr. Kurt Gurley and Dr. Forrest Masters, for inspiring me to accomplish things I never thought could be done.

ACKNOWLEDGMENTS

Thanks to my family, advisors, and fellow students for the help and guidance throughout my academic career; this accomplishment could not have been completed without their help.

TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS	4
LIST OF TABLES	7
LIST OF FIGURES	8
ABSTRACT.....	10
CHAPTER	
1 INTRODUCTION	11
2 CHASE: TOWER DEPLOYMENT SOFTWARE	13
Introduction.....	13
Tower Deployment Interactive Tool	14
Red Rover Deployment Strategy	15
Cannonball Run Deployment Strategy	15
Ground Zero Deployment Strategy	16
Blue Tarp Deployment Strategy	16
Chase Software	17
Chase Methodology	19
Input Variables	19
Load Track Button.....	21
Load Layout Button.....	22
Write KML Button	23
Conclusion	24
3 NEW RESIDENTIAL HURRICANE LOSS MODEL.....	31
Introduction.....	31
Hurricane Loss Model	33
Housing Trends Study	34
Statistical Model of Hurricane.....	35
Damage Survey Study	36
Updated and Improved Hurricane Loss Model	37
New Roof Layout	37
New Truss Layout	39
Model Calibration and Verification.....	41
Model Consolidation	43
Menu Creation	45
Conclusion	48

4	DEVELOPMENT OF COMMERCIAL HURRICANE LOSS MODEL	57
	Introduction.....	57
	Effects of Wind on Multi-Story Buildings	59
	Debris Impact	59
	Water Intrusion.....	60
	Façade Damage	61
	Fundamentals of Developing the Hurricane Loss Model.....	62
	Modeling Debris Impact.....	62
	Modeling Vulnerable Cladding	66
	Modeling Methodology	70
	Conclusion	74
5	CONCLUSION.....	81
	Hurricane Damage Mitigation	81
	Chase software.....	81
	Computational Model of Structural Vulnerability to Hurricane Winds	82
APPENDIX		
	CHASE TUTORIAL	84
	Example 1	84
	Storm Path Spreadsheet File.....	84
	Initiating Chase Program.....	84
	Loading Hurricane Track	85
	Loading Deployment Layout.....	85
	Creating KML File	86
	Loading KML File.....	86
	Example 2	87
	Loading Hurricane Jeanne Track.....	87
	Blue Tarp Deployment	88
	Red Rover Deployment	88
	Deployment Integration.....	88
	LIST OF REFERENCES	96
	BIOGRAPHICAL SKETCH	98

LIST OF TABLES

<u>Table</u>		<u>page</u>
3-1	Model Calibration Points	50
3-2	Input Variables to Consolidated Damage Model.....	50

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
2-1 Florida Coastal Monitoring Program Instrumentation Tower.	26
2-2 Red Rover Deployment in Google Earth.	26
2-3 Cannonball Run Deployment in Google Earth.	27
2-4 Ground Zero Deployment in Google Earth.	27
2-5 Blue Tarp Deployment in Google Earth.	28
2-6 Multiple Proposed Deployments in Google Earth.	28
2-7 Main Chase GUI Window.	29
2-8 Load Track Process Output.	29
2-9 Load Layout process	30
3-1 Flow Chart of Florida Hurricane Loss Model.	51
3-2 Diagram of Typical Residential Home & Components.	51
3-3 Typical Sheathing Panel Pattern	52
3-4 Wind Load Cases.	52
3-5 Original Truss Vulnerability Curve.	53
3-6 Typical Truss Layouts.	54
3-7 Comparison of Original and New Truss Vulnerability Curves.	54
3-8 Comparison of Vulnerability Curves to Damage Survey Points and Best-Fit Curve.	55
3-9 Comparison of Weak and Strong Models, Old and New Building Code Damage Survey Data Points.	56
3-10 Example Input File for File Menu.	56
4-1 EIFS-clad Building Damaged by Frances and Jeanne, Satellite Beach, Florida.	79
4-3 Flow Chart for Commercial Hurricane Loss Model Debris Impact Model.	80
A-1 Projected Path Spreadsheet.	89

A-2	Chase Root Directory.....	89
A-3	Initial Chase GUI Window.	90
A-4	Loaded Hurricane Track.	90
A-5	Loaded Deployment Layout.	91
A-6	Written KML File.	91
A-7	Chase Root Directory after Completion.	92
A-8	Loaded KML in Google Earth.	92
A-9	Info Box of Selected Tower.....	93
A-10	Google Earth Close-up of FCMP Tower.	93
A-11	Completed Blue Tarp Process and Chase GUI.....	94
A-12	Completed Red Rover Process and Chase GUI.....	94
A-13	Google Earth Screenshot of Mixed Deployment.....	95

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Engineering

HURRICANE DAMAGE MITIGATION:
FIELD DEPLOYMENT STRATEGIES AND
RESIDENTIAL-VULNERABILITY MODELING

By

Felix F. Rodriguez

May 2007

Chair: Kurt Gurley
Major: Civil Engineering

This document discusses various contributions to research in hurricane damage mitigation. A graphical user interface was created to assist the Florida Coastal Monitoring Program in the deployment of wind observation towers deployed during the landfall of a hurricane. The program calculates geo-positional coordinates of observation towers based upon terrain properties and storm characteristics. An updated Florida Hurricane Loss Model was created that re-defined a load path analysis, and improved the program usability and automation. The improvements included a model consolidation into one damage model routine, and introduced menu functions. A literature review of commercial building damage estimation provided information on assessing damage on multi-story buildings in creating a commercial Florida Hurricane Loss Model. A methodology was devised that would consider the damage energy of debris for impact modeling, and the vulnerability of common cladding materials such as exterior insulation finish systems and glass.

CHAPTER 1 INTRODUCTION

Hurricane Damage Mitigation: Hurricanes are of great concern in the Southeast United States, causing an incredible amount of destruction, necessitating immense preparation. Understanding the interaction of extreme winds and structures can help find cost effective mitigation solutions and minimize loss of life and property. The challenge in understanding wind / structure interaction is the large degree of uncertainty in both the loading and the structural response and capacity. The engineer must rely on statistics to estimate probabilities and expectations of events occurring.

It is the goal of the Florida Coastal Monitoring Program (FCMP) to address the issue of mitigating wind damage to residential housing by providing field data on the behavior of winds and wind loading. The data are obtained from installing instrumentation towers near the intersection of the storm's path and the coastline. The type of information that can be extracted from these towers depends upon how they are arranged relative to each other and the hurricane. A program that calculates the coordinates of a proposed formation will facilitate the FCMP team in deploying towers quickly and precisely. The program is simple to understand and use and provides visual assistance to the team in its deployment operations.

Another aspect of hurricane mitigation that FCMP is active with involves modeling and estimating damage of residential homes from hurricane winds. The original Florida Hurricane Loss Model (FHLM) program was constructed as a Monte Carlo simulation program that simulates random loads and component strengths, and records the instances of failure. Many changes and revisions have been made to the original code, transforming the program into one that provides more realistic results and improve organization. New roof loading, sheathing panel failure and truss connection failure methods were created to replace the original algorithms. The

program was also in need of consolidation, which motivated the creation of one file capable of harnessing the entire simulation process for all models. Finally, additional features were added to assist the user in inputting information in an efficient manner. These features are capable of instructing simulation runs to minimize user supervision. Collectively, the new additions make the physical damage component of the hurricane loss prediction model more accurate, efficient, and primed for expansion to commercial applications.

Recently, FCMP has been assigned to develop a damage estimation model for commercial structures similar to the residential model. Differences in residential versus commercial require the development of an entirely new model. Preliminary work has been done to initiate this process. A literature review of information pertinent to high-rise construction and the main components that are subject to wind damage has also been included in this document. The information gathered is assembled to provide a method to identify the threshold of damage and quantify the probabilistic strength of components.

CHAPTER 2 CHASE: TOWER DEPLOYMENT SOFTWARE

Introduction

The main objective of research efforts has been to understand the behavior of hurricane winds as they interact with land and the built infrastructure. These massive storms threaten life and property, and particularly any storm of Category 3 or stronger can generate billions of dollars in losses. It is known that a positive correlation exists between wind speed and the quantity of damage caused by a storm. An accurate calibration of wind to damage is a complicated process that presents many difficulties. This chapter discusses efforts to quantify this hurricane wind behavior, in particular the speed, turbulence and direction of winds over land.

The Florida Coastal Monitoring Program (FCMP) is an effort to measure and model wind behavior during storm landfall. During a storm, FCMP teams deploy wind observation towers in key locations that will assist meteorologists, engineers and scientists in determining wind intensity.

Much information has been derived from this data collection program. The data is used for the calculation of various statistical and stochastic parameters used to define wind behavior, including the cross-correlation, auto-spectrum, and turbulence length scales. These parameters are used to better understand the behavior of the wind during the passing of a hurricane. This information is also used to estimate dynamic wind pressures on structures, a major consideration in the design of buildings and other structures along the coastal United States.

The goal of FCMP has been to position the towers as close to the location of maximum windspeed as possible. Currently, the locations for deployment of the five towers are determined within several hours before landfall, based on the current predicted path of the storm. The

placement of the towers relative to the shoreline, populated areas, and each other depends upon the impact region and storm characteristics as it approaches. Every storm results in a different arrangement of the towers, reflecting the specific parameters of that event. However, there were no previous formalized procedures or tools that allow the teams to investigate multiple deployment strategies.

This chapter presents an interactive tool that was developed to allow the FCMP deployment crews to investigate multiple deployment scenarios. With the advent of Google Earth (GE), it has become very easy to visualize not just the path of the hurricane, but also the characteristics of the terrain, the population densities in its path, and other parameters that can influence the decision that an FCMP team makes regarding tower placement. The creation of this tool allows a flexible deployment strategy that can be adapted to continuously-changing conditions. The benefit is greater control of the experiment, and an improved opportunity to learn more per event.

Tower Deployment Interactive Tool

There would be many benefits of using an interactive tool to assist the tower deployment design. It allows a visualization of a proposed deployment layout, which will help the team determine the optimal position of a deployed tower. It could allow the team to locate an open patch of land near the proposed location, which would eliminate crucial time and resources spent in search of a satisfactory position. Figure 2-1 provides an example of what a satisfactory position for a tower would be. Notice that the terrain is open, and the tower is located far from any wind obstructions, such as buildings, large trees, etc.

Another benefit of having an interactive tool is that it facilitates comparing different proposed deployments. Being able to visualize multiple potential deployment layouts side by

side allows FCMP to determine which tower deployment layout would be most favorable for the given approaching storm and existing safe operational window of time.

Thus far the visualization tool has incorporated four basic deployment strategies that have been used in previous deployments. These are referred to as Red Rover, Cannonball Run, Ground Zero, and Blue Tarp. These strategies are discussed next. However, the visualization tool is designed to incorporate other strategies as the FCMP teams develop them. In each of the strategies described below, the user has the ability to change many parameters, from storm path, size and speed, to the desired spacing between towers. The interactive capabilities will be discussed after the four basic deployment options are discussed.

Red Rover Deployment Strategy

Red Rover is a layout in which the towers are set up perpendicular to the projected path of the hurricane. This is advantageous when the path of the storm is unclear, or when no significant infrastructure is farther inland. The concept is to spread the instrumentation over a large area to maximize the possibility of capturing extreme winds from at least one instrument. Typically the idea is to deploy this layout fairly close to shore, as the wind speeds vary greatly along the coast during landfall. Figure 2-2 provides a GE screenshot of a typical Red Rover deployment.

Cannonball Run Deployment Strategy

Cannonball Run is a strategy designed to answer questions about the storm rate of deterioration after landfall. As a storm makes landfall, the windspeeds in general decay as the storm begins to lose strength and the ground level winds are hindered by terrain. The maps used to determine design windspeeds in ASCE 7 incorporate this concept via contours of decreasing design wind speed. This deployment will help quantify, calibrate and verify this concept.

The towers are to be placed along the projected path of the storm, starting at the coast and moving inland many miles. For this deployment strategy to work successfully, it is necessary that

the storm's path be well defined. This is crucial because deploying towers in a line parallel to the path will result in a "hit or miss" situation, providing low chance of obtaining extreme wind data if the path is not well defined. Inland terrain features are an important consideration, as the ideal placement for any given tower is in a locally open exposure. Data from towers in open exposure are more readily extrapolated to a larger area, as the data is not polluted by the effects of very nearby objects. See Figure 2-3 for a GE representation of the Cannonball Run deployment.

Ground Zero Deployment Strategy

In some cases it may be desirable to cluster the towers in a circle around an area where the maximum winds are expected. The presence of a group of towers in a small area helps to quantify the difference in wind over small area due to both storm features and local terrain effects. Post damage investigations of damage from hurricane winds show that significant changes in damage intensity can take place over relatively small areas, particularly near the center of the path of the storm. Essentially, the Ground Zero strategy is useful for understanding local wind effects that produce these observed differences.

This deployment strategy is useful when the path of the storm is well-defined, to capture a point, hopefully, at or near the band of maximum winds. It is also more desirable when the hurricane has a large eyewall and is very intense. Refer to Figure 2-4 for an example of the Ground Zero deployment. The optimal deployment has towers on both the strong and weak sides of the storm (in the figure, north and south of the westward moving eyewall, respectively).

Blue Tarp Deployment Strategy

The fourth and last tower deployment layout involves one similar to the Ground Zero layout, but differs in that the location of the cluster of towers is determined by the placement of the FCMP's instrumented houses. These houses are collecting the dynamic wind pressure on the roof. The towers provide the approach wind field that produces those wind loads. This layout is

most useful when the storm is expected to pass through a well built-up suburban region near the coastline. The information obtained from the towers in this setting can be combined with the data measured from the instrumented houses to correlate wind speed with pressure on the roofs of one- and two-story residential homes. See Figure 2-5 for an example of a Blue Tarp layout.

Chase Software

Appendix A provides a detailed walk-through of the use of Chase software. The next section discusses the basic inputs and operations of Chase.

The Chase program will help facilitate the tower deployment process by calculating possible deployment layouts based on user input. It is used to compare and contrast between different layouts, and determine the optimal placements in each scenario. In the future, a layer of terrain exposure information could be combined with aerial photographs and the projected storm path to determine a specific location for each tower. This information is quite feasible to obtain with the help of GIS technology software.

This process can be indispensable to the entire tower deployment operation, saving valuable time and resources in the period before storm landfall. The teams instructed to deploy towers would not need to search around for a satisfactory spot, and instead can rely on the information provided by the aerial photographs to identify suitable patches of land. The operation could be capable of on-the-fly changes in deployment plan based upon an evolving storm behavior. This is crucial to improving FCMP's tower deployment strategies, because the optimal strategy can change continuously over the span of a couple of hours before landfall. The process would end in the determination of a set of GPS coordinates that would represent the positions of the deployed towers.

The Chase program can also be used by partner researchers such as NOAA atmospheric scientists to help determine which deployment strategy would be most useful. The program is

simple enough so that an official, engineer, student or layman would not be confused in its mechanics. This is achieved by a stratification of various input variables, and organization of the entire process into three easy steps. The program produces an output a file containing information that, together with visualization of existing terrain exposure and aerial photographs, could be displayed to anyone instantaneously with an interface such as Google Earth.

The Chase program is a graphical user interface (GUI) written in MATLAB, and compiled so that it may stand alone as an executable program. It is designed so that the necessary inputs can be easily obtained. The process, split into three steps, can be initiated by pressing buttons for each one. The program ultimately calculates the GPS coordinates of each tower placement according to the values of the input variables chosen. This was achieved by use of the mapping toolbox, a library of sub-functions that manipulate and work with distances on the surface of the earth. On the surface of the earth, straight lines in the “plane” become arcs with the center coinciding with the Earth’s. A two-dimensional coordinate set in this context refers to longitude and latitude. Distances are thus calculated along this arc, eliminating the need for survey measurement on the eve of hurricane landfall.

The output of the program is a KML file that may be input into Google Earth (GE). Google Earth is quickly becoming a popular tool for locating landmarks around the world. This output in KML format can literally be dragged and dropped into the GE interface, and will be visualized instantaneously. This makes the tower deployment viewable to FCMP deployment teams.

The KML file contains information about the storm’s projected path, a path offset from the eyewall representing the radius to maximum winds (eyewall radius), and the locations of the proposed towers. It is possible for the user to input various proposed tower layouts

simultaneously in GE, prior to choosing the desired layout. Figure 2-6 displays a GE screenshot of multiple tower deployments viewed simultaneously.

Chase Methodology

The program's input variables are dependent upon the characteristics of the hurricane and the desired layout geometry. It requires an Excel file containing the projected path, downloaded from the National Hurricane Center path projections. These files are updated every six hours prior to land fall. Three buttons trigger main routines which encompass the entire layout design process.

The optimal deployment strategy is a function of storm behavior and the area to be impacted. From characteristics such as translation speed, size and intensity, we determine if the path is well defined, and thus which strategies would be best to deploy. Depending on the terrain characteristics and nearby infrastructure, we further determine which deployment layout to use, what tower cluster spacing is feasible, and what inland distance we would like to deploy the towers at.

Input Variables

Refer to Figure 2-7 for a screenshot of the Chase GUI window. The first set of variables to initiate the Chase program is the hurricane name and season. Together, they will instruct Chase to look for an Excel file containing the projected path of the storm. The projected path will be input and combined with the state chosen to locate the projected path as it intersects the coast and makes landfall. If a state is chosen whose boundary does not intersect the projected path, an error will display on the text window.

With a storm track and state chosen, the user is then able to select the general layout geometry for deployment. The choices are the four layouts proposed – Red Rover, Cannonball

Run, Ground Zero and Blue Tarp. Based upon the next set of input variables, the layout details will be selected, and the deployment layout will be created.

Another input crucial for optimal tower deployment will be the radius to maximum winds and the inland distance. The radius of maximum winds can be obtained from an independent source (NOAA), and input into Chase to establish a path offset from the eyewall center. Figures 2-2 through 2-6 represent this as a colored swath for the storm path. The inland distance input represents the center of the tower deployment along the radius to maximum winds path. With the center point of the tower cluster calculated, the set of coordinates for the towers can be obtained.

The input to the deployment layout also includes the number of towers to be used. This can be any number from one to six. The tower cluster distance will be another input, and can be edited by direct typing into the value box, or can be incremented using the plus or minus buttons. The value of increment (or decrement) is 0.25 distance units, depending upon the units chosen. If the deployment strategy is Red Rover or Cannonball Run, this tower cluster distance is literally the distance between adjacent towers. For Ground Zero, the tower cluster distance will be the radius of the circle the towers will be positioned around. The cluster center coordinates is irrelevant to the Blue Tarp strategy, because it is one which does not place the towers in any set arrangement.

The Units Multiplier box eliminates the user's need to resort to some universal unit. One can choose which unit of distance is most convenient in figuring out the inland distance, radius to maximum winds and tower cluster distance. By default, the choice of units will be set to statute miles, but the Chase software is capable of calculating distances in terms of nautical miles and kilometers. A radio box on the GUI window selects the units desired for determining the

layout geometry. Internally, this will assign a value to the Units Multiplier variable, which converts all distances to be inputted into statute miles.

The Longitude and Latitude edit boxes are used with the Blue Tarp setting to append the list of individual tower coordinates. Since the Blue Tarp strategy is a method for deploying individual towers in no precise arrangement, they must be inputted one at a time. Once the coordinates have been typed, the “Update Next” button will append the list. If a mistake was made, clicking on the “Erase Last” button will erase the last tower inputted. Notice that as the list is appended, the value in the Number of Towers box is adjusted accordingly.

The Tower Locations box provides a list of the GPS coordinates for the set of towers that make up the deployment strategy. This is relevant to all deployment strategies, but only in the Blue Tarp can this list be changed. Verifying the information in this box is the last step to creating the KML file.

Some other buttons on the GUI window are not input windows, but serve miscellaneous functions. At some point during the design process, a value may pop up in the Landfall Heading box, and also in the Tangent Heading box. These values help the user understand what direction the storm will be going after it makes landfall. The Zoom Slider helps the user view the deployment layout farther out or closer in. A message window helps the user stay aware of the status of the deployment design process. It will make the user aware that any of the three main routines carried out successfully, or it could warn the user that an input variable needs to be addressed to proceed.

Load Track Button

Once the hurricane name and season have been identified, and the state has been chosen from the pull-down menu, clicking on the “Load Track” button will provide the user with a map of the Southeastern area of the United States and the storm projected path.

The “Load Track” process involves retrieving the input necessary to begin the tower deployment process. The boundaries of the states are vectorized into longitude and latitude vectors. A user-created Excel file containing the path is located, and is compiled into the MATLAB environment. The projected landfall point will be defined as the intersection point of these two sets of coordinates, and is calculated using sub-functions in MATLAB contained in the mapping toolbox. Next, the landfall heading is calculated using another mapping sub-function. The routine calculates the azimuth based upon two sets of longitude and latitude. The result is displayed in the Landfall Heading box. The value is taken to the clockwise angle of rotation from the north direction. Usually, for a storm intersecting the Florida coast, the landfall heading will be somewhere 270 and 360 degrees.

Finally, the results are plotted. The user will see a map of the state boundary and the storm’s projected path. Refer to Figure 2-8 for a screenshot of a loaded track using Chase.

Load Layout Button

When the “Load Layout” button is pressed, a routine will be triggered to provide the user with a visual representation of the proposed tower layout. The process will retrieve the values in the Radius to Maximum Winds box, the Inland Distance box, the Number of Towers box and the Cluster Distance box for calculation of the tower deployment’s coordinates.

First, an offset path is calculated to determine the Radius to Maximum Winds path. The original projected path, representing the path of the eyewall center, consists of two vectors representing longitude and latitude coordinates. Each component in these vectors is paired with the same component in the second vector to provide a coordinate on Earth. The tangent heading of each coordinate is calculated using a central difference method. From this, the perpendicular heading is calculated, which is be 90 degrees counter-clockwise from the tangent heading of the direction the storm is going. If the storm is heading in the northwest direction, this offset path

will be north and east of the projected path. The offset path is drawn a distance away from the storm path a distance equal to the radius of maximum winds.

Next, a point is located on this path which is determined from the inland distance. That point will become the center of the tower cluster, and the locations of the towers will be determined from this center point. The tangent heading of the storm path is calculated at the center point, along with its perpendicular heading. This will be used to figure out the towers' positioning. The calculated coordinates of the towers will be stored in two vectors, one containing longitude and the second latitude values.

If the user calls for a Blue Tarp deployment, the Radius of Maximum Winds path and cluster center will be defined. However, the vectors containing the towers' longitude and latitude will be explicitly defined by the user.

The last step of the Load Layout process is to display the location of the towers. The Radius to Maximum Winds path will be displayed in red over the state contour and storm projected path, as well as the towers in their determined locations. The center of the tower cluster will be indicated by a blue circle, and the locations of the towers in will be indicated by green stars. Refer to Figure 9 for an example of a loaded layout.

Write KML Button

The final routine of the Chase software prepares and creates a KML file so that the user may visualize the deployment in Google Earth. A KML file is text file saved in a KML extension containing ASCII information that GE reads and interprets. The file defines objects such as polygons and place marks within a folder structure. These objects contain many attributes such as a location on the Earth via GPS coordinates, name tags, look-at information and an object description. The look-at information provides a tilt and heading that the camera (user view point)

will adjust to when the object is selected. Tag information is provided to help the user understand what an object represents, and is available when that object is selected.

Information obtained from the GUI window is retained during this routine to create a unique file for each deployment designed. The file name is created from the hurricane's name, season and deployment layout. Completed text consists of tower information with polygon representation, eyewall center path information, and radius to maximum winds path information.

Tower information is organized into a folder, one for each tower in the deployment layout. Each tower is created as an object, with accompanying nametag information, look-at information, and a corresponding list of polygons that put together represent the tower itself. The polygons are created in three dimensions and scaled down to an appropriate scale. Each tower's polygon group is contained in a separate subfolder.

The storm path information is defined in a separate folder as an open polygon so that the user may visualize the projected path of the storm. The path is outlined in bold black and extruded to perceive height. The path is labeled to identify the path from farther out.

The radius to maximum winds path is created in a third folder, which contains the offset path of the expected maximum winds in the hurricane. This path is indicated in red, and will usually be seen northeast of the storm path.

Conclusion

A program has been created to help FCMP teams make their tower deployment decisions based on all relevant information. A user-friendly MATLAB GUI provides FCMP staff with an opportunity to make an easy transition between the projected storm path to a set of GPS coordinates of proposed tower locations. The program presents this information in the form of a KML text file which is readable by Google Earth so that anyone with an Internet connection can

be aware of tower deployment plans. Ultimately, Chase can improve how FCMP teams use their resources and optimize the collection of perishable data under high-pressure circumstances.

There are several improvements possible to improve Chase. The program can be designed to input translation speeds from the projected path to provide an estimated time of landfall. This may be helpful in providing FCMP a timeframe of when deployments should be completed. It should also be updated to incorporate land use information to better select specific tower locations in open terrain. Chase can also be set up to customize the towers' order in deployment, so that the tower number presented in GE will correspond to the tower number deployed at that location. The KML file can also be updated to provide a link to the tower's 15-minute update files on FCMP's website.

A tutorial of the Chase software in the form of examples may be found in Appendix A for insight into the program procedure.



Figure 2-1. Florida Coastal Monitoring Program Instrumentation Tower.

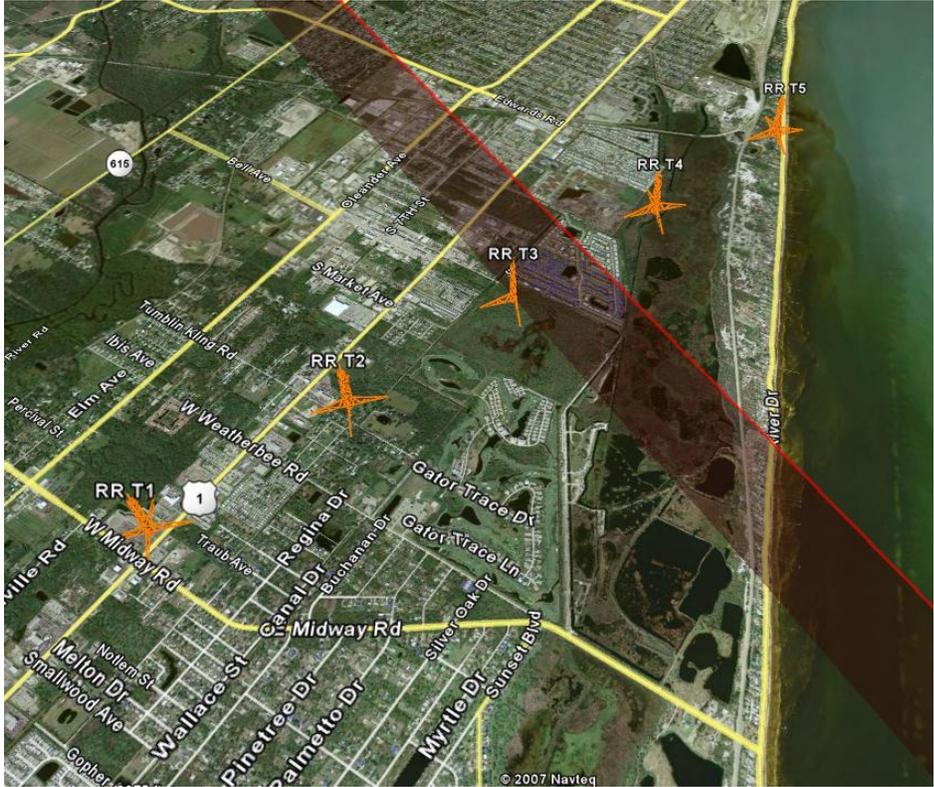


Figure 2-2. Red Rover Deployment in Google Earth.



Figure 2-3. Cannonball Run Deployment in Google Earth.

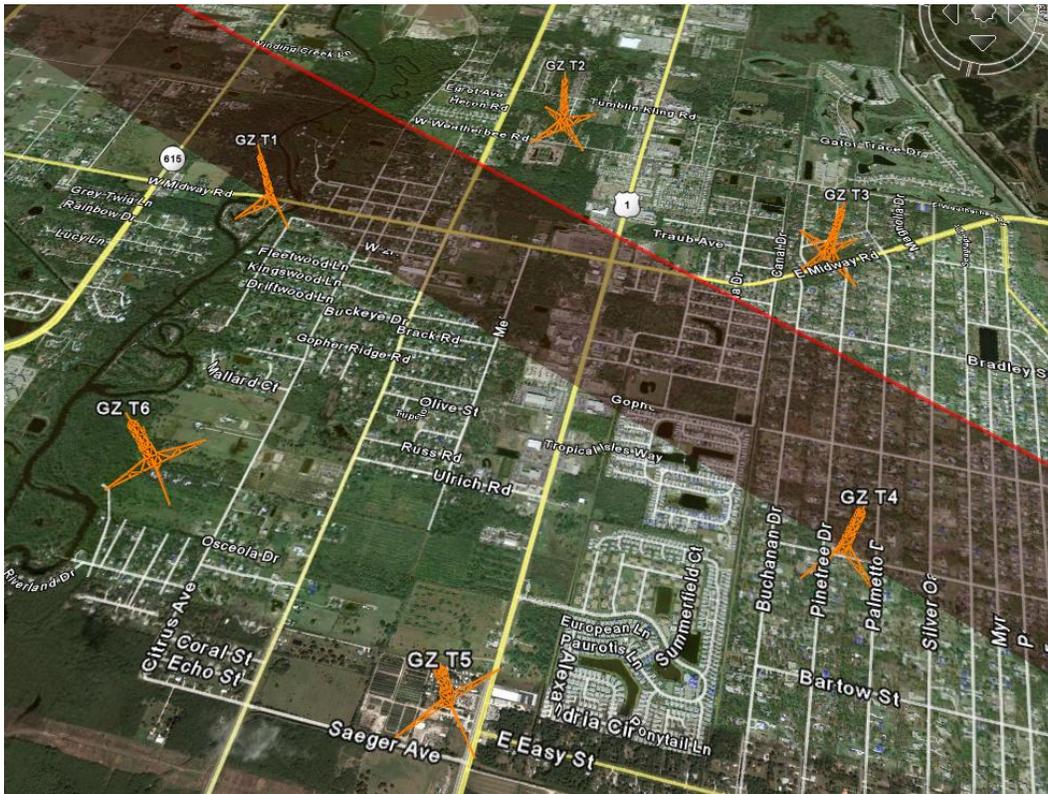


Figure 2-4. Ground Zero Deployment in Google Earth.



Figure 2-5. Blue Tarp Deployment in Google Earth.



Figure 2-6. Multiple Proposed Deployments in Google Earth.

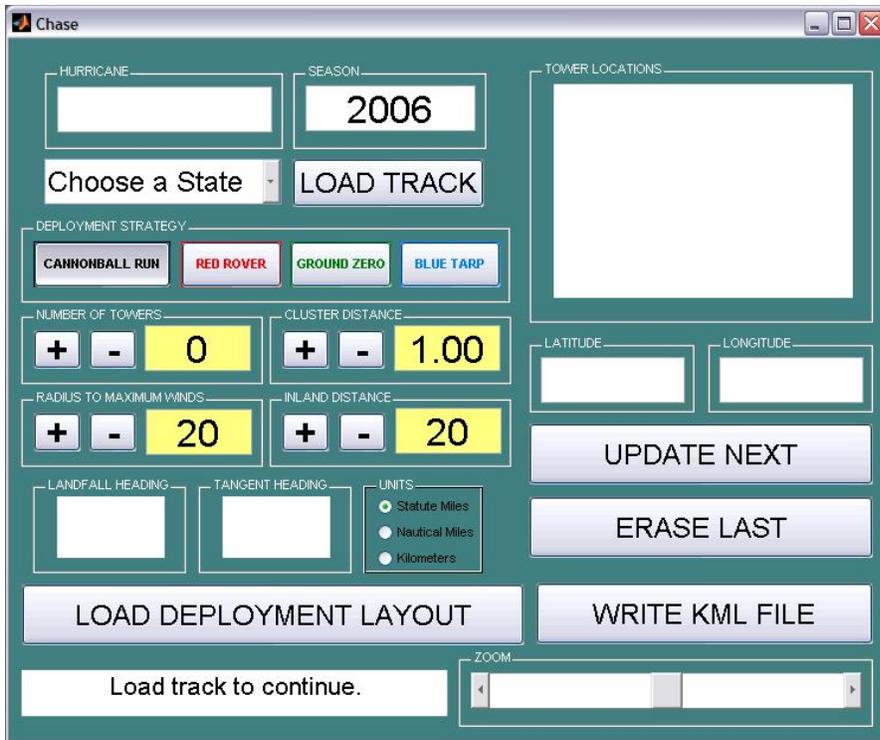


Figure 2-7. Main Chase GUI Window.

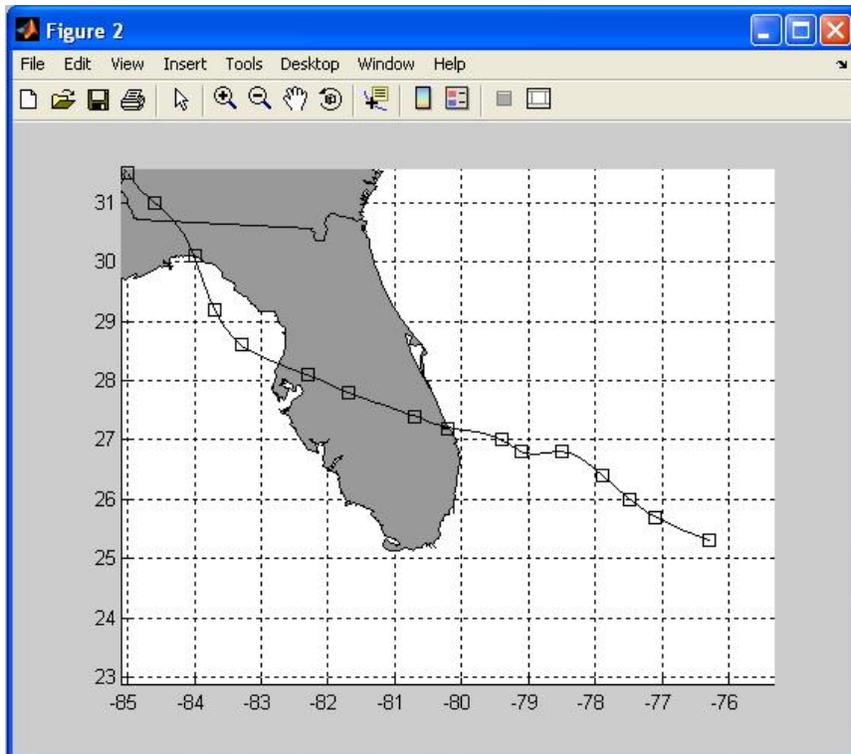


Figure 2-8. Load Track Process Output.

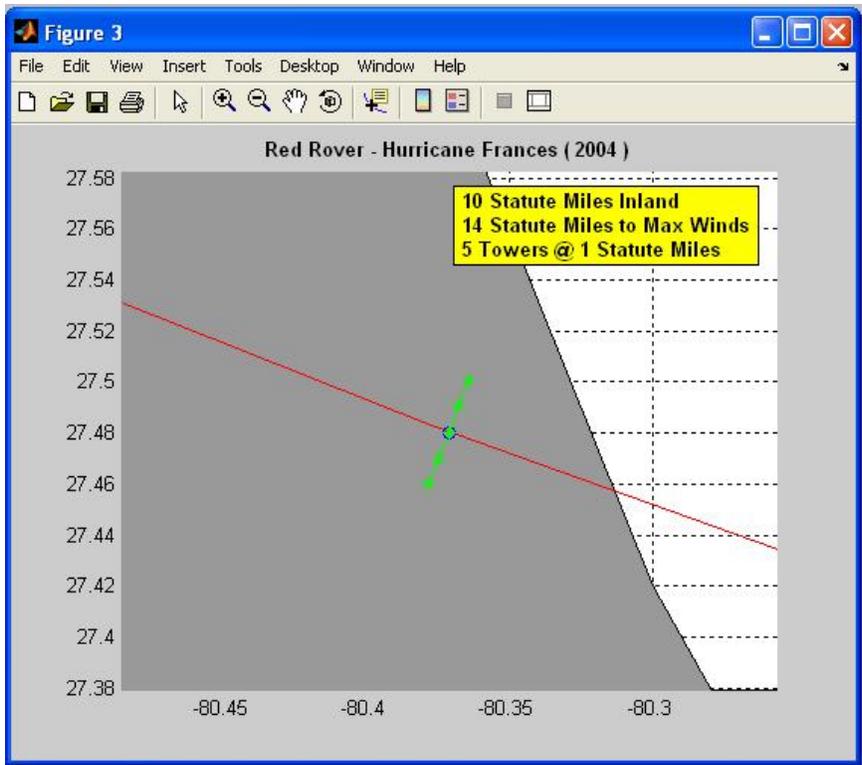


Figure 2-9. Load Layout process

CHAPTER 3 NEW RESIDENTIAL HURRICANE LOSS MODEL

Introduction

Improving the resistance of residential housing to hurricane winds is driven in part by the financial impact of such improvements. Property insurance rates are based upon predicted insured losses, and improvements to design need to be cost-effective to be accepted. The ability to predict both the physical and financial vulnerability of housing to winds has been improving in the last decade as the predictive models have grown more sophisticated in their use of engineering principles and observed data. This chapter addresses modeling (predicting) the physical damage to residential homes to hurricane winds. A structural vulnerability model was developed at UF as a component in the Florida Hurricane Loss Model (FHLM) by Dr. Anne Cope (Cope, 2004). This model has recently been revised to incorporate additional information on load paths, and to make the architecture more user friendly and adaptable to the rapid influx of additional field data with each hurricane land fall.

The progressive failure that a home can experience is a process that begins at the top of the structure, and ends at the foundation. A typical residential home is constructed with a concrete slab foundation, and wood or masonry walls which harness the building roof trusses and covering. The covering is made up of plywood sheathing, a water resistant layer, and shingles or tiles. The roof layout geometry may be gable end, hip, or some combination.

The wind flow pattern depending on the direction of the storm, determines the roof and wall pressure. The component feeling the most extreme pressure is typically the roof along the corners and edges where uplift is strong. A roof can be made up of asphalt shingles, which are flat on the roof, or they can be made of flat or curved ceramic tiles. Numerous documented

damage investigations indicate that the roof cover is among the most vulnerable component of a home, frequently torn from the roof and becoming air-borne.

Simultaneously, the sheathing panels below the shingles are subjected to uplift. These panels can also come off, exposing the trusses underneath and permitting water intrusion.

Without the sheathing, the trusses are vulnerable to toppling.

The loads on the roof are transferred to the walls via the roof to wall connections, which range from nails in older construction to clips and straps designed to resist hurricane loads in modern construction. The failure of roof to wall connections can have significant impact on the resistance of the home against winds.

The windows and openings around the house become vulnerable to the windborne debris created by roof cover and vegetation, increasing the probability of breaching a home. If a window or door is penetrated, the inside of the house is subject to water intrusion and internal pressurization, and the home is now experiencing a more vulnerable load scenario.

Each of the components described above (roof cover, sheathing, roof to wall connections, walls, and windows and openings) can vary in their capacity or ability to resist wind loads. This is dependent upon the construction practice common at the time the home was built, the quality of construction, the building codes enforced at the time, the effects of aging of structural materials, fasteners and connections, and the load sharing among components. It is not possible to precisely quantify each of these issues for any given home, thus it has been common practice to model the vulnerability of residential structures in a probabilistic format. Random capacity values are sampled from an appropriate distribution for a given component, and compared to randomly assigned loading sampled from a distribution that represents the loading. A Monte

Carlo simulation is then used to produce a statistical assessment of the likelihood of the quantity of damage to various components to a series of wind speeds and wind directions.

Several such models already exist, including one created at UF by Dr. Anne Cope during her Ph.D. research program. This chapter discusses upgrades that have been made to her original model.

Hurricane Loss Model

The model created at UF to predict damage on a residence is known as the physical damage component of the Florida Hurricane Loss Model (FHLM). In addition to the physical damage model developed at UF, the FHLM also includes a wind field prediction component, an internal damage component, and a financial and actuarial component developed by partnering researchers.

The relation between damage and windspeed is an output to the physical damage model, and is referred to as the vulnerability curve – that is, damage versus windspeed. These curves vary based upon the construction of the house being modeled (wall type, roof cover type and age, roof to wall connections, the nailing in the sheathing, the use of shutters on windows, etc.)

The Hurricane Loss Model is an example of a Monte Carlo simulation, useful for tracking phenomenon with many random variables. For complex systems with many interacting components, it is typically not possible to derive a closed-form solution relating expected outcome as a function of the input variables. Monte Carlo simulation is practical when the interaction between the many variables are non-linear, or if they are described in terms of non-normal distributions. The advent of computers has also driven the popularity of this method.

A flow chart of the program developed by Dr. Cope can be seen in Figure 3-1. The fundamental concept is to apply a specified 3-second gust wind speed to the model home. This 3-second gust represents the peak value experienced by the house for a given storm or period of

time (e.g. one year). The loads from this gust are determined and applied to the structures. Each of the components of the structure has a load capacity assigned to it (each shingle, each window, each sheathing panel, etc.), which is compared to the wind load. Those components whose capacity is exceeded by the load are then damaged. The process is repeated many times, with a new set of capacities randomly assigned to each new model. After many simulations the output is a statistical description of the vulnerability of that model home to that wind speed from that direction. The process is completed for eight different wind directions at each wind speed, and includes wind speeds every 5 mph from 50 to 250 mph gusts. Figure 3-2 provides a diagram of all components in a typical residential home considered for damage (Cope, 2004).

Ultimately the output provides the probability of component failure conditioned upon wind speed and wind direction. The wind field modeling group then provides the probability of these various wind speeds occurring. A given house model can be varied in many ways to reflect the differing methods of construction. For example, very weak stapled roof sheathing as well as very resistant nailed sheathing using modern practice are both options for the model. Unprotected windows and protected (shuttered) windows can be modeled. Different uplift roof loading is provided for hip and gable roofs.

Housing Trends Study

Prior to the development of the original model, a study of the construction methods of the state of Florida provided information to make assumptions about the model. Many counties throughout Florida provided detailed and thorough information about the structural characteristics of homes through a database. The study was used to determine, for example, typical square footage of residential housing.

A building component study was undertaken to assess the strength variability of many parts composing the fabrication of a house. Sources of information include literature relating results of

laboratory testing, literature from existing vulnerability models such as the FEMA HAZUS hurricane model, information from damage studies, and manufacturer's information (e.g. roof to wall connection capacities provided by Simpson Strong Tie, garage door pressure ratings, etc).

Statistical Model of Hurricane

A list of model parameters determine the different permutations of models, such as the house location (e.g., North, Central Florida), wall material (wood frame or concrete block), roof type (hip or gable roof), roof to wall connection type (nails, clips, straps), window size, distribution and protection, and the number of stories.

Identification of failure has its roots in reliability theory; that is, the probability of failure may be expressed in terms of the loads and resistances of the system under consideration:

$P(\text{failure}) = P(R - L < 0)$. MATLAB synthesizes random values using a random number generator, which is capable of producing random numbers that fit a section of many common distributions (uniform, Gaussian, lognormal, etc.).

Loads simulated in the Model are based upon guidelines from ASCE-7. Pressure coefficients are factors used to relate the measured mechanical pressure on a surface to the velocity pressure: $C_p = (p - p_0) / (1/2 * \rho * v^2)$ (Simiu, 1996). The pressure is calculated at mean roof height with unit surface roughness. Different pressure coefficients are used to distinguish different zones around a house exhibiting unique flow patterns: interior, edge and corner roof zones; interior and edge wall zone; and windward, leeward and side wall zones. All these factors taken from ASCE-7 are assumed the mean coefficient values, and the COV is assumed to be 10%. The topography and direction factors are assumed to be unity for the residential model.

Losses identified in the model are conducted by tracking forces down to the ground. Failure checks commence on the roof, and as the roof cover and sheathing panels are lost, it

affects the truss performance and connection uplift. Because these calculations will be done at least once per simulation, and assuming there will be thousands of simulations, the computation speed of these operations becomes very important. After the set of calculations to determine all failure is completed, the percentage of loss for each component is compiled into a saved file for further analysis. The model outputs the archives for each windspeed and direction increment.

Damage Survey Study

The occurrence of new observable wind damage data is an important aspect of model calibration and validation. A survey was conducted to assess the effectiveness of the 2002 Florida Building Code. This survey was motivated by the 2004 hurricane season, in which four hurricanes (Charley, Frances, Ivan, Jeanne) created observable damage to Florida residential infrastructure.

Homes affected by these storms were investigated. Information was organized by GIS technology to create wind swath maps, reporting the highest windspeed experienced in an area. The regions were stratified to classify homes and their locations. Randomly selected homeowners for each region were called to authorize our inspection. It included an interview that gathered information about homeowner evacuation procedures and the amount of damage that occurred. The surroundings were observed and noted.

The information provided modelers with the opportunity to verify the vulnerability of homes due to the storms predicted by modeling. The models report expected damage at a particular windspeed. Statistics obtained from inspections help in calibration of the resistances of windows, doors, garages, and roof covers (i.e., tiles or shingles). The points created could be used to reinforce or update the results that were produced by the FHLM.

Updated and Improved Hurricane Loss Model

Since the development of the FHLM (Cope, 2004), additional improvements to simulation have been considered. These additions are due to an evolution of the thought process in the model, by a need for a more user-friendly and easily adaptable architecture for the program, and the need to incorporate additional data on housing performances collected during the 2004 and 2005 hurricane seasons.

The improvements made to the model can be fit into three categories:

- Load path and capacity upgrades;
- Improved architecture to streamline use and further development of the program;
- The creation of a manageable user interface.

The finished product is one that will facilitate the user in many aspects of the simulation process, including managing the various input variables that go into the program, cataloguing the various simulation runs, and conducting sensitivity studies.

The rest of this chapter describes the updates made to the UF physical damage component of the FHLM.

New Roof Layout

The updates commenced with a refinement of the roof layout and geometry. Overall dimensions of the roof were verified and compared to the original roof layout. These were determined based upon house dimensions, a 2-ft overhang, and a 5-on-12 roof pitch. The overall roof area was found to be inconsistent with the original sheathing area matrix. A flattened roof was drawn in AutoCAD, and a sheathing panel layout was created. The staggered panel pattern drawn is characteristic of residential home construction, and can be seen in Figure 3-3.

The area of each sheathing panel was obtained in AutoCAD, and a sheathing area matrix was created for implementation into MATLAB. Each entry in the matrix represents the area of

one sheathing panel on the roof. Panels in the corner, typically cut smaller to fit on the roof, will have less tributary area.

The process continued with a verification of the pressure coefficients for the original roof layout. The load cases used to model wind flow from different directions were adapted from ASCE 7. In the original model, there was no distinction between edge and corner pressure zones. In reality, corners will experience more uplift than between corners along the edge. There was a possibility that FHLM was underestimating the roofcover failure. This loading also affects the sheathing failure and roof-to-wall connection failure.

A new process incorporated three pressure zones for modeling – interior, edge, and corner zones. To model 8 possible load cases where wind is directed at 0 to 360 degrees in 45-degree increments relative to the house, three load cases were created:

- winds perpendicular to the ridgeline;
- winds parallel to the ridgeline;
- wind cornering the ridgeline at an oblique angle.

For each of these three load cases, the edge zone distance was calculated, based upon recommendations from ASCE 7 and dependent on the roof's dimensions. Each load case was drawn up in AutoCAD over the existing sheathing panel layout. The reader may refer to Figure 3-4 for a schematic of the wind load cases on both gable and hip roofs.

The entire roof was then broken down into three areas, and it was observed that some panels lay in one, two, or even all three pressure zones simultaneously. The overlapping of the pressure zones with the panel layout made easy the process of determining the overall pressure on any panel. The pressure coefficients attributed to each sheathing panel became a weight coefficient based upon its contribution by area from each zone. Finally, an interpolated pressure coefficient was calculated for each sheathing panel.

Results of using this new roof layout were compared to the original model's results. It appeared there wasn't much difference between the two, because as ASCE 7 recommends that the corner and edge zones remain equal, the means and COV's for the edge and corner zones were set equal in the new FFLM. However, the program is now capable of assuming a higher corner zone pressure coefficient. The results from new wind tunnel studies of wind pressures on housing can be easily incorporated.

New Truss Layout

The original truss failure analysis relied upon the sheathing panel load analysis to direct the uplift damage to connections. As a sheathing panel failed, the pressure on it was set to zero, and therefore would relieve some uplift pressure on a truss whose tributary area coincides with that panel. Thus, the failure of a 4-foot by 8-foot panel could affect as much as 4 trusses when spaced at 24 inches. As all trusses are checked for failure (at the wall connection), almost every sheathing panel pressure would have been accounted for four times. The tedious process motivated the introduction of a more efficient routine, perhaps curbing the lengthy process of checking every relevant sheathing panel for every truss.

Failure of the roof-to-wall connections in the model could be categorized into two mechanisms, uplift failure or toppling. Uplift is a function of the amount loading on sheathing panels attached to the truss. Toppling is identified when a significant amount of sheathing panels have been pulled from the truss, leaving it to stand free in the wind without lateral resistance.

The vulnerability curve of the truss failures was examined, and revealed there was a modeling issue in the routine. At a certain velocity, usually past 150 mph, the failure of the trusses did not increase with increasing velocity, but actually decreased. As sheathing panels were dislodged from the roof frame, the amount of load transferred to the trusses decreased.

Figure 3-5 shows a vulnerability curve for the roof-to-wall connections obtained from the original Model.

A more reasonable vulnerability curve would exhibit monotonic behavior as the windspeed increased. The solution was therefore to modify the truss failure check process so that results would appear more plausible. The truss vulnerability curve may even be expected to act increase independently of roofcover and sheathing failure, because roof-to-wall connection failure can occur before there is any roofcover loss.

An overhaul of the original truss failure check routine eliminated the need to check for the uplift pressure on every sheathing panel. A truss layout for the typical residential home was created and drawn in AutoCAD. Trusses were spaced at 24 inches, meeting the Florida Building Code requirements. The three wind load cases were drawn up and laid over the new truss layout to see how the truss tributary areas overlapped with the three different pressure zones. The percent area of each truss under a zone was calculated using AutoCAD's polyline area property, so that a weighted pressure coefficient was obtained for each truss on the roof. The process of obtaining the weighted pressure coefficients followed closely with the process used to create the new sheathing and roofcover pressure matrices. The subfunction *r2w_conn_uplift*, whose purpose is to obtain the uplift force in each truss in the form of array, contained a 3-column matrix containing weights by area of the contribution of a pressure zone to a truss's uplift. The 1st column of the array contains contributions of the interior pressure zone, the 2nd column contains information about the edge pressure zone, and the 3rd column contains information about the corner edge zone. The array is multiplied with a 3-row column vector containing the random pressure coefficients simulated by MATLAB to represent the pressure coefficients per zone. The matrix product of these two arrays becomes the weighted pressure coefficient for each

truss along a side of the house. The output of this subfunction includes two 2-column arrays containing weighted pressure coefficients for the trusses along the front and back of the house, and another for the side trusses, whether gable-end or hip trusses. Figure 3-6 shows the typical truss layout for gable and hip roofs.

The new method was found to run significantly faster, utilizing efficient matrix operations in MATLAB, and eliminated the need to check values in the sheathing pressure matrix multiple times. It also corrected the errant trend of the vulnerability curve at high windspeed, where a higher speed led to a lower number of damaged trusses. Figure 3-7 presents the vulnerability curve obtained from the new algorithm, in comparison to curve from the original model, and the roofcover and sheathing panel loss.

Model Calibration and Verification

Observed damage data after the 2004 hurricane season is an appropriate data source to calibrate and validate the FHLM results from the physical damage model. The inspections included houses affected by Hurricanes Charley, Frances, Ivan, and Jeanne. Building components such as roofcover and windows were compared to FHLM results.

Homeowners in the vicinity of the hurricane path were stratified into regions based upon maximum windspeed at that residence. The houses were separated in terms of old and new construction practice, where the older homes were identified as those which were built prior to the 2001 Florida Building Code. For each windspeed region, the shingle loss was classified into six cases of shingle loss, as can be found in Table 3-1. Each case corresponds to percentage loss range. The frequency of each case was obtained, and multiplied by its expected shingle loss percentage, then summed down to obtain the expected shingle loss for that windspeed region. The windspeeds were finally divided by the terrain roughness in the area. The results of these calculations can be seen in Table 3-1.

Three windspeed regions provided three calibration points that could be plotted with the vulnerability curve. A least-squares method was used to produce a theoretical best-fit curve to the set of three points. The derivative of the vulnerability curve closely resembles a Gaussian curve, and so the appropriate model curve to go by would be some version of the error function. Thus, the function that was to be modeled takes the form: $f(x) = 0.5 * [erf(Ax - B) + 1]$, where

the error function is defined as: $erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$. The parameters A and B are subject to

least squares optimization, to determine the best-fit curve.

Once the parameters *A* and *B* were obtained for a set of data points for old and new code, the model curve with the corresponding model parameters were plotted with the data points and results from the FHLM. The curve obtained from older homes was compared with vulnerability curves for buildings simulated with weak mitigation. Similarly, the model curve for newer homes was compared with building simulated with strong mitigation. Figure 3-8 presents a visual comparison between the data points obtained from the damage surveys, the best-fit curve, and the vulnerability curves obtained from simulation. In Figure 3-9, the reader can see that comparison of the data points for old and new code sample homes, with the vulnerability curves for strong and weak mitigation.

Interpretation of Figures: Figures 3-8 and 3-9 demonstrate the proximity of the results from FHLM simulation of weak and strong mitigation to the expected loss determined from the damage surveys. The weak model appears more conservative in estimate to the damage survey. This is due to fact that the weak mitigation simulation represents construction using much older methods, such as toenail connections in the trusses. The damage survey points representing the old building code are in actuality homes built between the 1994 and 2001 building codes.

Buildings satisfying this criterion can be expected to perform significantly better than what the FHLM predicts.

Damage survey points obtained for homes built after the implementation of the 2001 Florida Building Code share a stronger resemblance with strong mitigation results from the Model. The strong mitigation results are based upon construction modeled by current construction practices. The homes with the strong mitigation package, for example, are constructed with Simpson Strong Tie roof-to-wall connections. As a result, the total loss for any given windspeed is substantially less.

Model Consolidation

Originally, the model was created to handle different building characteristics individually. Three regions (south, central, north), two roof types (gable, hip), and two construction materials (wood or concrete block walls) translated into 12 separate model files that were created, and would need to be run separately with different mitigation parameters. The original Cope Model evolved from a single structural type to many structural types with many mitigation scenarios. The most expedient way to expand the original model with additional structural types was a cut-and-paste procedure, where the original model is saved under a different name, and modifications are made. However, this ultimately produced many models that were difficult to track when using the Model to simulate many possible mitigation options. The process of running 12 different files for 12 combinations with the same mitigation setting could become tedious and time-consuming, and would require supervision throughout simulation time. Much user time was spent organizing and tracking the running of 12 separate models with many combinations of mitigation. This was an impractical situation with a high degree of likelihood of user error.

Another feature of the new model is that it has been consolidated, capable of handling all regions and types, dimensions and mitigation parameters. To do this, the main processes were identified that were common in all 12 damage model files. This included the random generation of the pressure coefficients, the creation of the pressure matrices, initial failure check, internal pressure check, and reiteration until no further failure is identified. Some priority variables designate the general direction of the model – model location, wall type, and roof type, and mitigation. The mitigation was consolidated into a vector containing scalar values representing different settings for the homes' storm preparation. Formerly, the mitigation vector was created inside a switch statement. The new FHLM calls the mitigation vector at the function's calling.

Some values are read through a text file to allow for sensitivity analysis. These variables were organized into different categories, and the sets of values are contained in individual text files to be read by the main damage model function. These include the pressure coefficients (i.e., roof pressures, wall pressures), the COV for the pressure coefficients, internal pressure, and the ASCE K-values for topography, directionality, height and importance. The variables were set up in such a way that they may be edited without changing the actual damage model files, although can only be changed between simulations.

The final step of the consolidation process was the separation of different processes in the code depending on roof type and wall type. A home with a hip roof does not contain any gable-end trusses, and likewise the gable roof home does not contain any side trusses. At the appropriate location in the code, a switch statement diverts the flow of code for either a hip or gable roof. A similar situation at a different location occurs when the wall type designates the existence of stud-to-sill connections. A wood-frame building requires checks for these

components, but need not be checked for concrete masonry, since they are non-existent in concrete masonry.

The consolidation of the different model files into one allows that a function can call these damage models within a loop, and can run a list of simulations without the interaction of the user. Further, the values of the input parameters can be determined in this higher-class function, and be called down to the main function. The largest benefit of this function is that it removes the need to edit the text inside the code prior to every simulation run.

Menu Creation

In addition to consolidating the 12 models into a single more flexible model, it became necessary to simplify the means of establishing user input to control the specifics for a given simulation run (i.e. what kind of model with what mitigations in place). The idea is that a single simple set of commands can be issued to run several models in sequence. These models may have some input parameters in common, and other that are unique to that model. A significant portion of the modification made to the Cope Model allow for such sequential runs to be easily declared by the user.

The physical damage model, which is capable of being called by the user in a MATLAB environment, is written so that any editing of the script itself is unnecessary. The list of input variables can be organized into scalars or vectors for easy transfer. In such an environment, it would be very easy to develop another task that could load this file multiple times, with different sets of information. A manual menu allows for the user to input the variables sequentially and display it back. A file menu function reads the instructions from a text file, which contains a sequence of key characters and numbers. The objective was to develop some routines which can be instructed to call the main damage model files, and simulate many runs at once.

Table 3-2 lists the variables and type of all the input variables. Instructions may be given in such a way that a variable can be defined once the first time, and be repeated for every run thereafter. Each run is identified by a delimiter.

Manual Menu: The manual menu is a method of instruction where the Model receives input from the keyboard. For example, suppose a user wants to run two models sequentially. The first is a southern concrete block model that uses hurricane shutters, and the second is a wood frame northern model that uses a different type of window protection. The menu requests simulation details one variable at a time for the first model to be run, until all details have been acquired. The menu repeats the details for the latest run back to the user, and then the process can repeat or continue to the simulation step. The mitigation vector can be customized, or it can be defined in terms of the standard weak, medium, or strong mitigation. If a custom mitigation has been defined, then on the following step, the menu will remember the mitigation settings, and will allow as a choice, to repeat the same mitigation vector created. After the list of simulations is created, the list is displayed back to the user for final approval. Upon approval, the simulation run begins.

File Menu: To speed automation a file menu was created for a savvy user that wants to avoid pressing all the necessary buttons to instruct the simulation details. The function inputs a file with a sequence of letters and numbers that the function is instructed to recognize as different desired properties. The user designates the number of simulations on the first line, and subsequent lines would contain information pertaining to one simulation detail. For example, the fourth line represents the roof type. Depending on the number of runs desired, the information on that line can be set to be “g h h h.” This tells the program that the user wants the first model to have a gable roof, and wants the second, third, and fourth simulation to have hip roofs. Of

course, it is necessary that the information in the first line be “4,” representing four simulations. If the roof type line is defined with one letter, “g” or “h,” it gives instructions that all four simulations are instructed to be with one roof type. These instructions are typical of the region line, wall type line, roof type line, garage line and story line. An example of the input file’s format can be seen in Figure 3-10.

The seventh and subsequent lines are unique in the manner the instructions need to be written. The simulation number line must contain one number that will be consistent for all simulations. The windspeed vector can contain the text “default,” “d,” or three numbers representing the lowest windspeed, highest windspeed, and windspeed increment to create it. An example is “50 250 20,” which simulates all wind speeds from 50 to 250 mph, at increments of 20 mph. Thus, the vector would appear to be 50, 70, 90, and so on until 250 mph. The delimiter line must contain alphanumeric strings, one for each simulation desired. The delimiter is an information tag used to identify the MAT-file containing all the information about simulations results. The final line, or lines, will contain information about the mitigation. Information for mitigation can be written in one line to be repeated, or can be written, simulation at a time, in the following lines. The information read can be “w,” “m,” or “s,” depending on the mitigation package desired. Another option would be to input a delimited string of 11 numbers which designate the set of mitigation one setting at a time. Finally, if all information is inputted correctly into the function, then the simulation information will be displayed and will ask the user to affirm the instructions.

There are numerous benefits to running the simulations using the menu files. It eliminates the need for tedious clerical work, in which the user needs only to press a few buttons, and the rest of the work is done by the menu functions. It facilitates information management and

mitigation sensitivity. Because it can be instructed to run multiple simulations back to back, it eliminates the supervision previously required on the hour. Thus the modified physical damage component of the FHLM has been transitioned from its original state as a development tool and into a form capable of simulating a multitude of mitigation measures at one instruction. The Model is now more suited for generation of a high volume of output.

Conclusion

The updated and improved physical damage component of the Florida Hurricane Loss Model has been created to facilitate the entire simulation process. The new damage model file is capable of simulating all permutations of the input variables. Higher-class files have been created which allow the user to instruct multiple simulations at once. This has largely facilitated the management of simulations with different settings, allows the program to run for days on end without running out of instructions.

The sensitivity analysis could continue to determine how the model responds to changes in windows and openings strengths to match information obtained from the damage surveys. This aspect of the damage model can be conducted in the same manner as was conducted for the roofcover analysis. The increased breakage of windows will affect the internal pressure of the house. It may be of interest as well to check the history of the internal pressure as damage around the house is recognized.

Another direction the model can take is to incorporate irregular shaped homes into the model. The original model was developed with rectangular-shaped homes.

Further development of the model can lead to improved information about component strengths, particularly from windows, doors and garages. This may begin with some destructive testing. Also, analysis of the pressure behavior measured on the instrumented roofs from the

FCMP program can be used to assess the precision of pressure coefficient values adapted from ASCE 7 for use in this Model.

To improve the functionality of the Hurricane Loss Model, it may be advantageous to create a graphical user interface in MATLAB to manage the simulations, replacing the menu functions created. A GUI can assist the user in seeing all the simulation details simultaneously. The interface can be a system of click-boxes and radio buttons, representing each simulation detail, such a roof type. Much of the code for this GUI can be acquired from the original menu files.

Finally, a more significant overhaul of the FHLM could be undertaken to allow the inclusion of wind speed duration and the accumulation of damage to the same model from multiple wind speeds and directions. The current approach simply applies a single speed and direction to a given model to tabulate total damage to that sample home. A more realistic scenario would include damage as it accumulates from low winds speeds through the peak winds from a given hurricane, including the directional changes. This will require the wind field modeling team to work in concert with the physical damage modeling team. Currently these two model components (wind and damage) are being developed separately. This was important to the overall model development process to avoid the assumptions and shortcomings of one model component to affect the development of the others. However, each component has now been sufficiently developed that such interactions between model components can now be investigated.

Table 3-1. Model Calibration Points

Case (mph)	Old Code			New Code		
	110-120	130-140	140-150	110-120	130-140	140-150
0%	9	8	2	8	6	9
0-2%	3	9	4	4	4	2
3-5%	0	5	3	0	0	8
6-10%	0	5	6	0	2	1
11-25%	0	7	4	0	0	1
26-50%	0	7	4	0	0	1
Total	12 76	41	23	12 46	12	22
Expected Loss (%)	0.50	15.07	16.65	0.67	2.33	5.86

Table 3-2. Input Variables to Consolidated Damage Model

#	Variable Name	Data Type	Example Values
1	Number of simulation runs	Integer	10
2	Region type	Character	'n', 'c', 's'
3	Wall type	Character	'c', 'w'
4	Roof type	Character	'g', 'h'
5	Garage	Character	'y', 'n'
6	Number of stories	Integer	1, 2
7	Number of simulations per model	Integer	1000
8	Wind speed vector	3x1 Integer, String	50 250 10, 'default'
9	Delimiters for simulations	Nx1 String	'delim1 delim2 delim3'
10	Mitigation vector	11x1 Integer, Character	's', 'm', 'w'

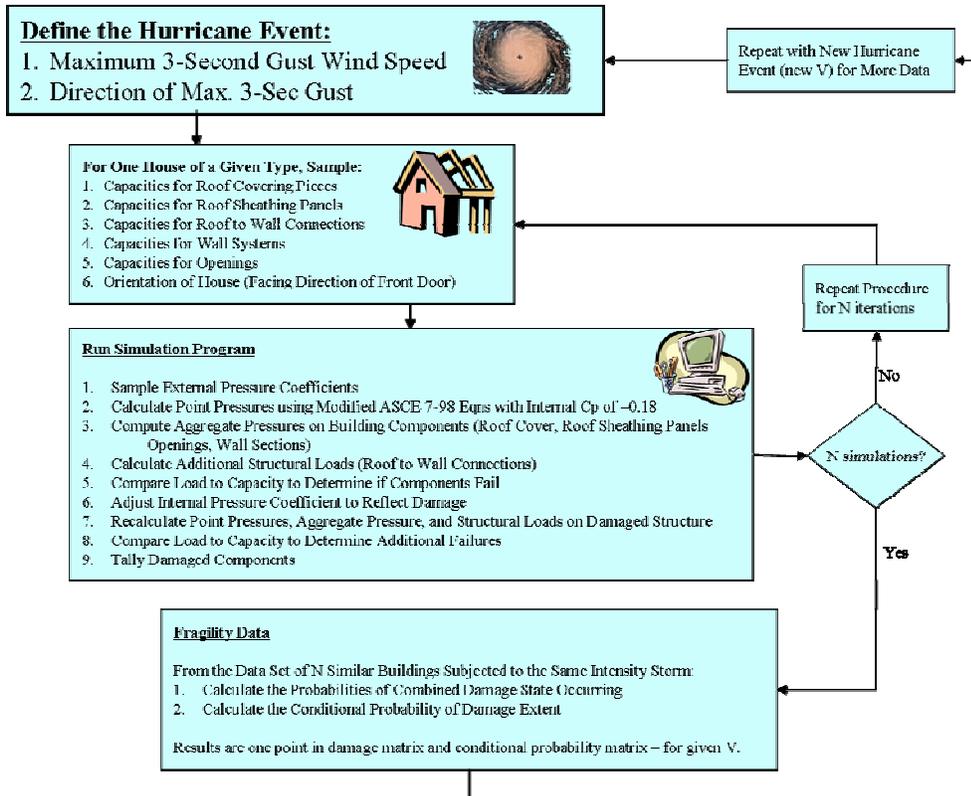


Figure 3-1. Flow Chart of Florida Hurricane Loss Model.

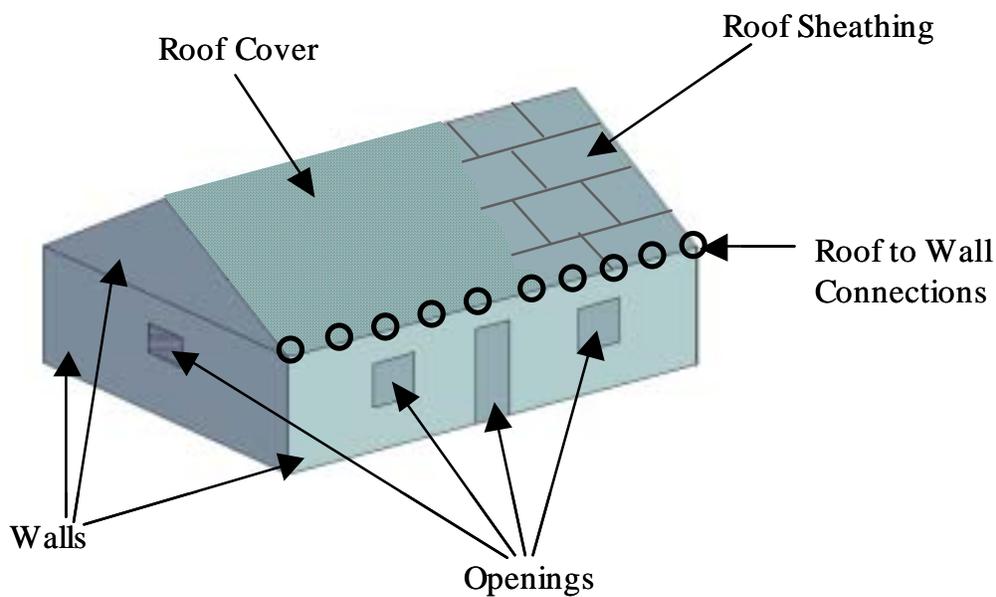


Figure 3-2. Diagram of Typical Residential Home & Components (Cope, 2004)

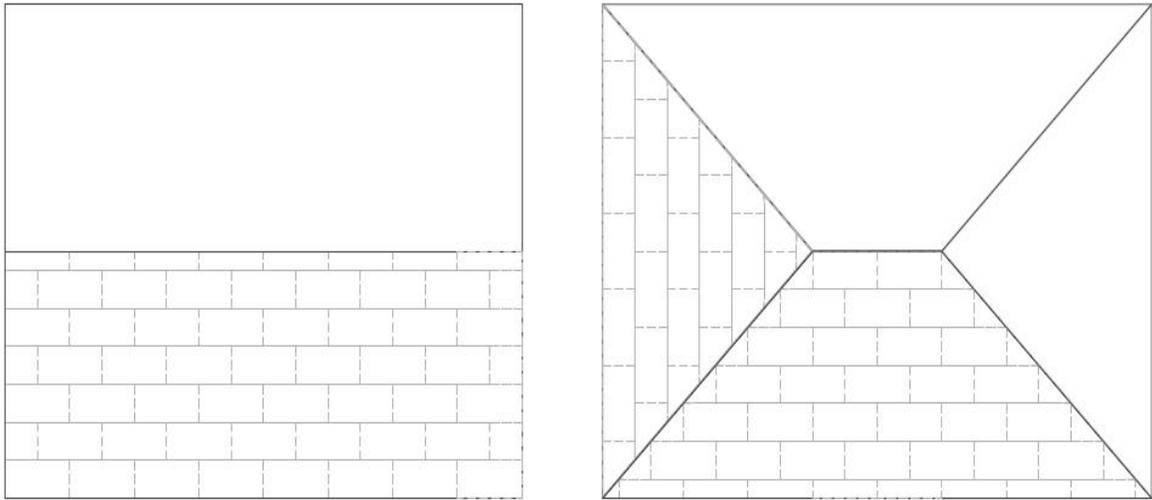


Figure 3-3. Typical Sheathing Panel Pattern. A) Gable Roof. B) Hip Roof.

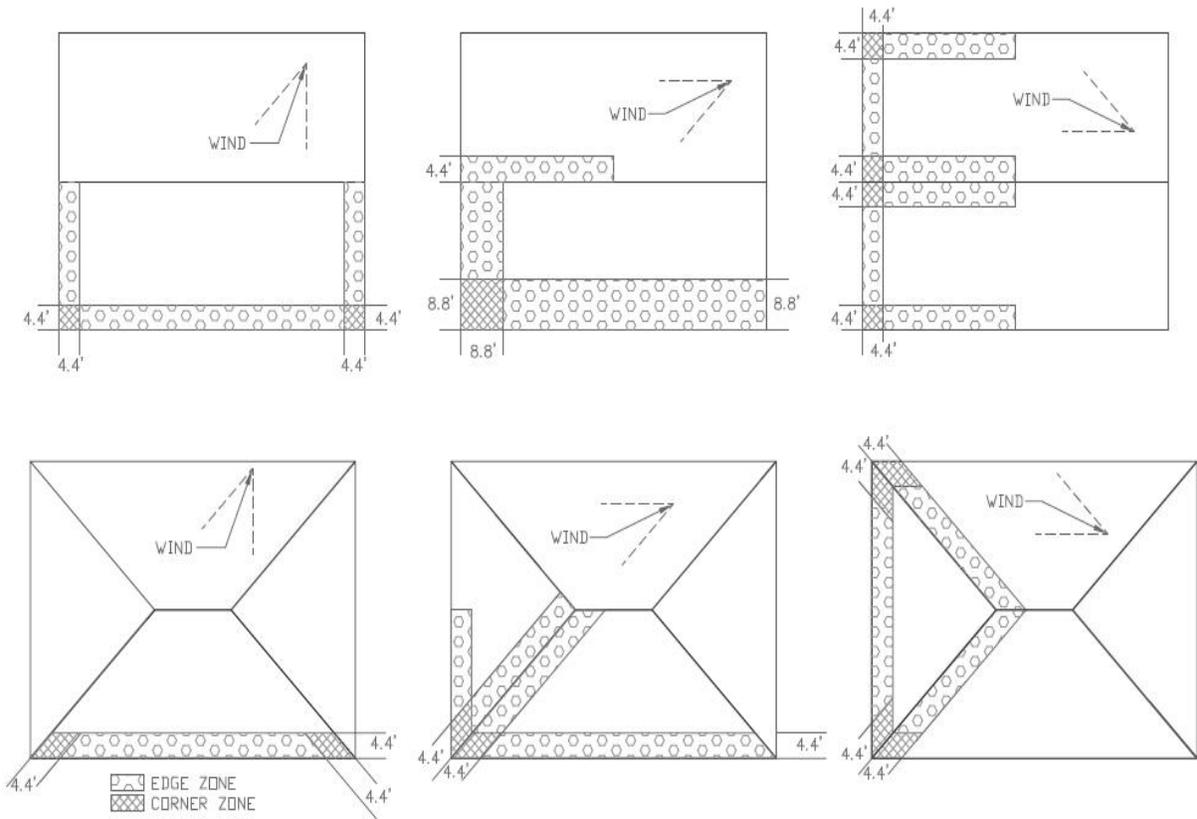


Figure 3-4. Wind Load Cases. A) Gable Roof . B) Hip Roof.

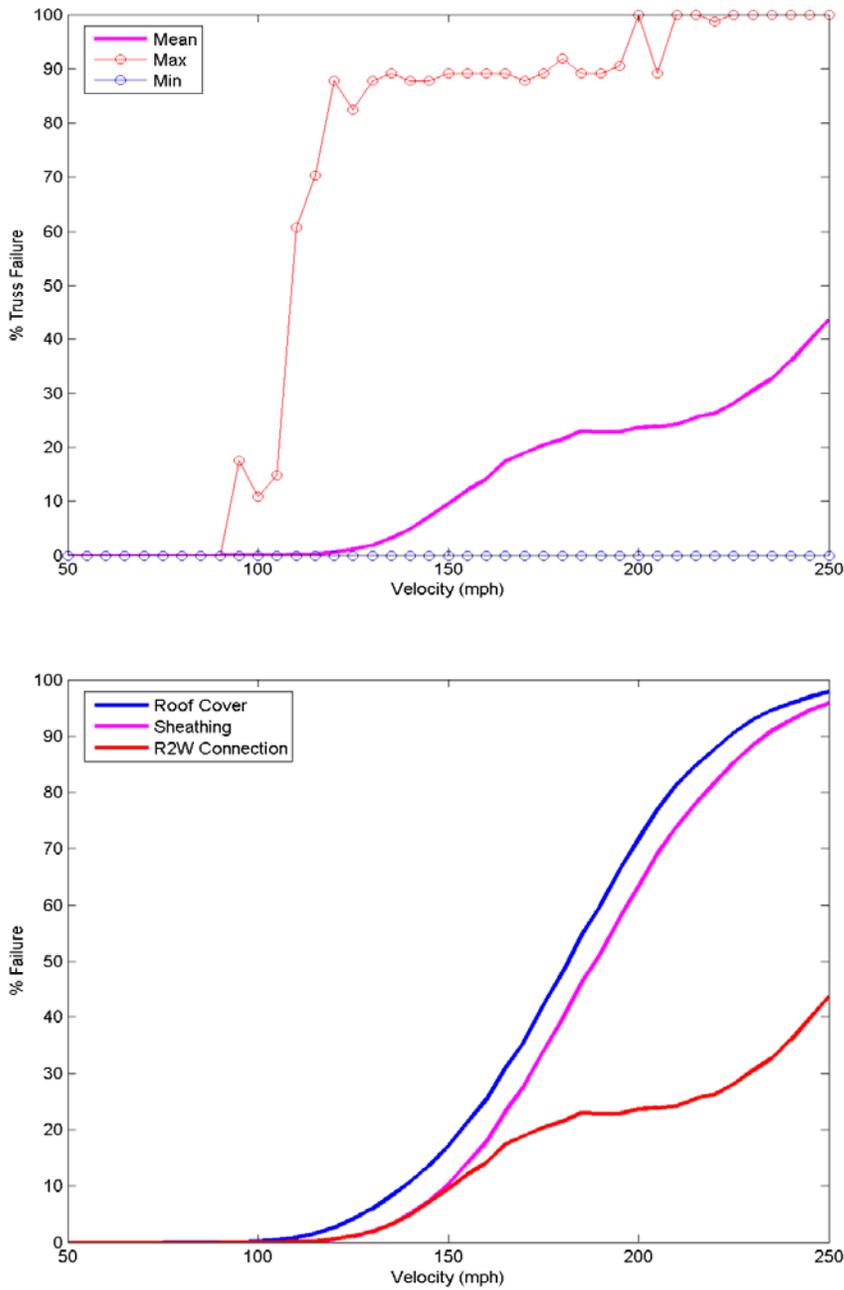


Figure 3-5. Original Truss Vulnerability Curve. A) The Max and Min lines represent the maximum and minimum truss failure simulated for a given windspeed. B) The Roof Cover and Sheathing Panel is presented in comparison with Roof-to-Wall Connection Failure.

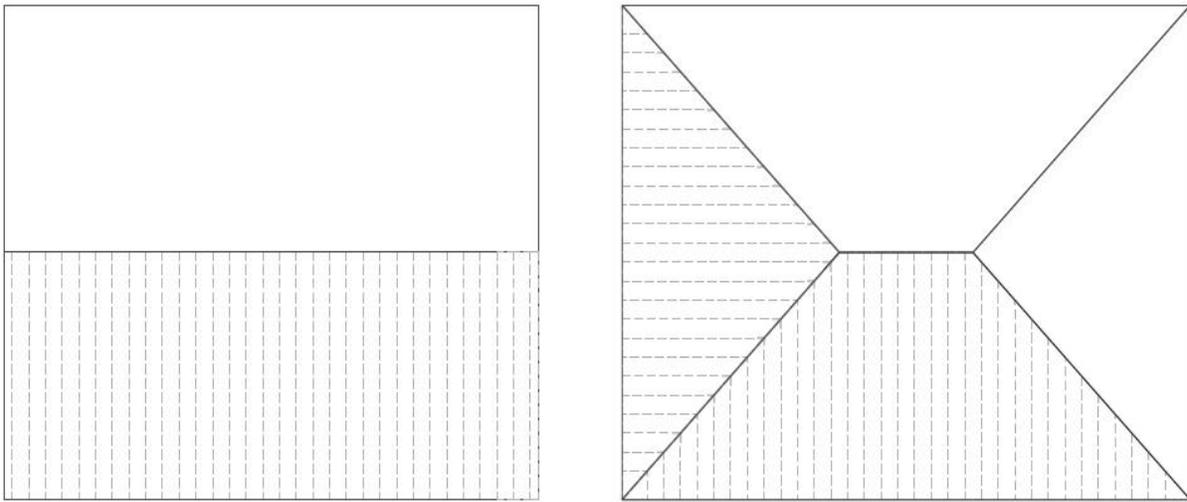


Figure 3-6. Typical Truss Layouts. A) Gable Roof. B) Hip Roof.

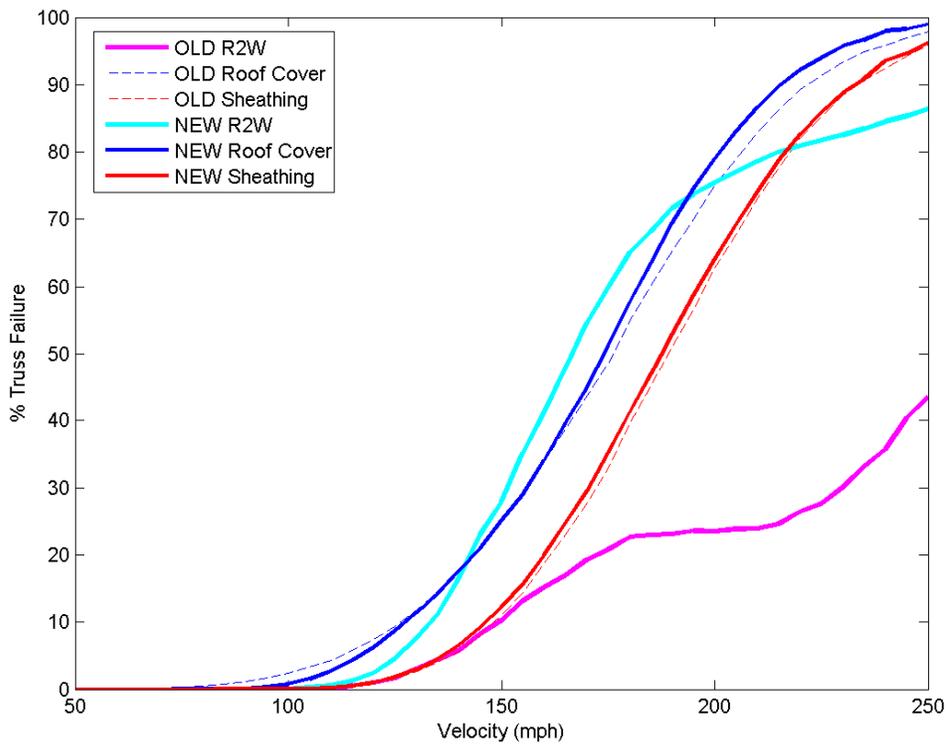


Figure 3-7. Comparison of Original and New Truss Vulnerability Curves.

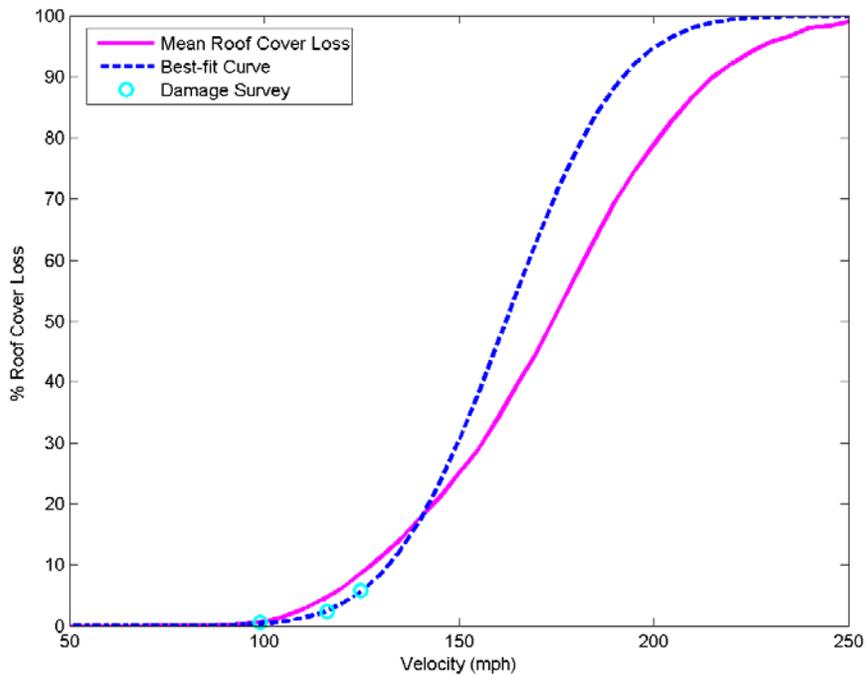
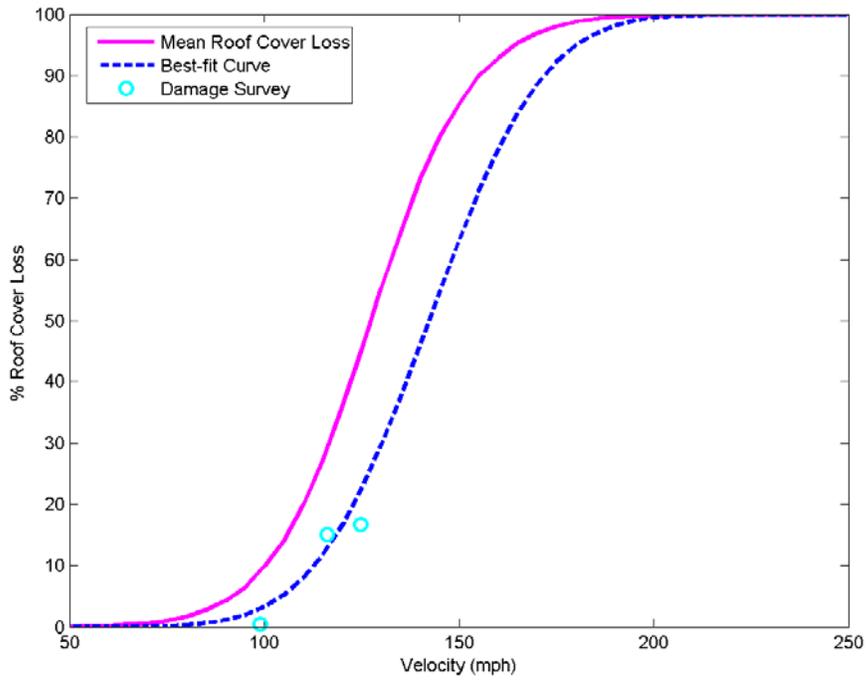


Figure 3-8. Comparison of Vulnerability Curves to Damage Survey Points and Best-Fit Curve. A) Weak Model to Old Building Code. B) Strong Model to New Building Code.

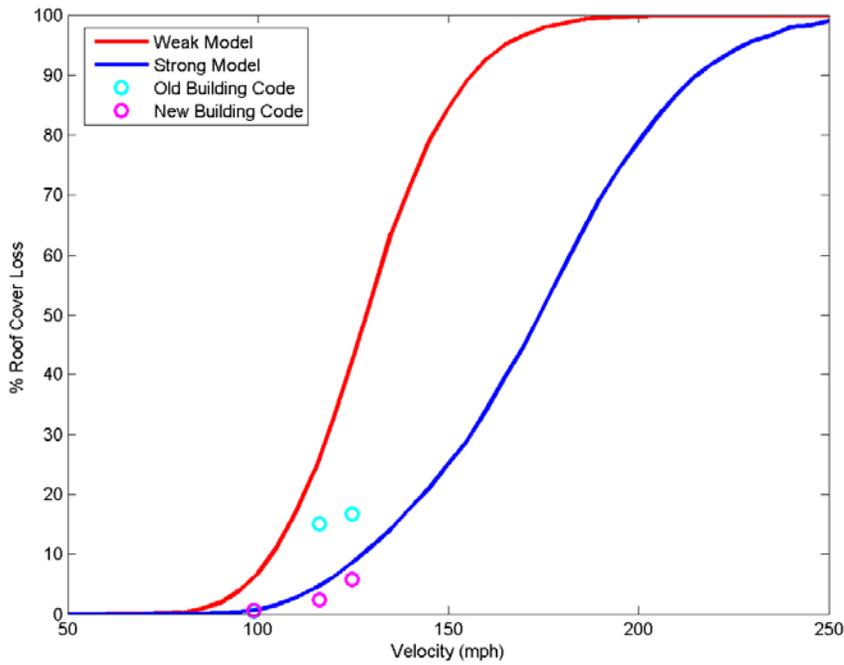


Figure 3-9. Comparison of Weak and Strong Models, Old and New Building Code Damage Survey Data Points.

```

input_sim.txt - Notepad
File Edit Format View Help
3
s c n
b
g
n
1
1000
default
weak_s weak_c weak_n
w

```

Figure 3-10. Example Input File for File Menu.

CHAPTER 4 DEVELOPMENT OF COMMERCIAL HURRICANE LOSS MODEL

Introduction

The State of Florida has contracted the consortium that developed the Florida Hurricane Loss Model (FHLM) to extend the model from residential to commercial structures. The construction methodology for residential housing differs greatly from that used for commercial structures, and thus this expansion of the physical damage component of the FHLM is a significant undertaking. This chapter addresses the beginnings of the process needed to assemble the probabilistic physical damage model for commercial structures, and will serve as a roadmap for the next student.

Other than residential buildings, what other types of buildings claim significant losses from tropical storm damage? Examples of structures not included in the scope of the residential model are condominiums, office buildings, warehouses, hospitals, schools, and many others. Most of these buildings are multi-story, and can be located in a variety of different terrains. They can be located near other multi-story buildings, or in open land where the nearest building is far away. The majority of exposures are classified somewhere between these two extremes. In the case of residential housing, it is a reasonable assumption that the vast majority of homes are located within a suburban setting with similar structures surrounding it. Commercial structures can be much more variable in their surroundings, from being the highest building for miles (e.g. three-story condos in a mostly single family home suburban setting), to being a relatively small building in the immediate vicinity (e.g. three-story condo near taller office buildings near a city).

Commercial structures also offer a greater variety of building styles and construction materials relative to residential. For example, curtain walls may be glass, brick, or many other options, each with a different set of vulnerabilities to be considered in high winds.

The effects of wind on commercial structures are quite different from one-story residential buildings. Because they are much taller, the variation of wind in the vertical direction is much larger. The wind flow around the building has high amounts of turbulence due to the larger obstruction of the commercial building. Turbulence has the capability of lifting objects off the ground. Objects which have become air-borne become projectiles and can potentially impact the curtain wall. In the case where the curtain wall is made of glass, the building envelope can be penetrated, and would invite water intrusion. Moreover, equipment on the roof is vulnerable to impact breakage because of high wind flow and pressure.

Repairs associated with this amount of damage can be very significant. Any windows impacted and breached will need to be replaced. Interior renovation is possible because of water penetration. Office equipment, including computer hardware and furniture, may need to be replaced. Also, if the structure is adorned with exterior insulation finish systems (EIFS), the façade will need replacement. The mechanical equipment will also need to be inspected for damage. Damage will necessitate repair or replacement.

Aside from component damage, interior or exterior, a damaged building is outside of its functionality. Inhabiting residents are displaced from their dwellings. Potential patrons are deterred from appealing tourist spots. An office building out of commission may be unfit to serve as a place of work until repaired. This can result in a business being unable to perform normal day-to-day operations, and lose potential business.

All of these considerations must be accounted for when projecting insured losses due to hurricane winds on commercial structures. The UF team contributing to this multi-university effort is again focusing on the modeling of the physical damage to the exterior of the building. This chapter will address the work that has begun along those lines.

Effects of Wind on Multi-Story Buildings

Damage measured on a multi-story building is the combination of different failure types. The structural frame of the building is not likely to collapse from even very severe wind. However, there are many components on the exterior of the building that can fail at modest wind speeds and produce insurable losses. The building envelope, designed with more aesthetic priority, is modularized. The loss of a unit glass wall cover should not contribute to the collapse of the structure, but will permit water penetration, content loss, and loss of functionality.

Sources of damage were categorized to commence the development of a multi-rise building model. They may be organized into three contributing sources:

- Debris impact;
- Water intrusion;
- Façade damage.

Debris Impact

The flow of wind provides an energy source that is dissipated into various mechanical processes. It holds the capacity to transport objects of significant mass. For example, water may be regarded as a particle. Wind certainly has the ability to drive the particle through the air. Eventually, the water may collide against some surface, and will transfer energy-momentum to that surface in the form of some concentrated pressure. Cladding materials such as glass and EIFS will be subjected to that concentrated pressure. The goal will be to analyze the energy-momentum that an air-borne particle can transmit, and how much a cladding material can resist. The concept is expandable to other objects such as cladding materials from nearby damaged structures, gravel ballast on nearby roofs, vegetation, etc.

An object becomes air-borne from the wind flow interacting around it as well as with the surface supporting the object. The wind energy around the object is enough to overcome its inertia. The transfer may be expressed in terms of its energy or momentum. For example, the

wind energy may be expressed as: $\frac{1}{2} \rho v^2 * V$, in terms of the density of air, velocity, and the volume of air. It is also possible to calculate the inertia of an object. The wind energy and the object inertia in the volume displaced can be compared to identify if objects are capable of becoming air-borne.

Realistic components of debris can be identified and analyzed to determine its inertia. The common things that compose debris in general consist of roofing material (gravel, shingles), temporary construction material, and cladding materials (e.g. broken glass).

An object that is traveling through the air is available to strike against the surface of some building cladding material. Window glass, brittle in behavior, can shatter upon impact. EIFS, or synthetic stucco, can be impacted and expose the foam material underneath the base coat, making it vulnerable to water, and long-term deterioration. Window strength must be considered from a statistical point of view, and phenomenon of failure will be a consequence of its comparison with debris impact statistics.

The terrain surrounding the structure being modeled is a critical component for determination of vulnerability to windborne debris. A 10 story condo surrounded by 5-story buildings with gravel ballast roofs will be subjected to a heavy concentration of debris.

Water Intrusion

Water intrusion is a consequence of debris impact, performance of exterior windows and doors, and the performance of the roof membrane. Debris impact can produce breaches in the building envelope that permit wind driven rain to enter. The water membrane on the roof may be torn from loading or debris and permit water to enter from the top down. Windows and sliding glass doors that fail under cyclical wind pressure loading can also produce significant water penetration. However, physical failure of components is not the only cause of water penetration.

Larger surface area windows and double sliding glass doors on condo balconies can flex under high winds. This flexure may not cause the failure of the door or window, but the deformation may provide a path for water penetration through the separation between frame and wall. This has been observed in many hurricanes.

Water penetration can cause interior contents of the building to be damaged to the point of repair or replacement, and lead to premature deterioration of metal fasteners in the building framing and curtain wall systems.

The UF efforts on the commercial modeling addition to the FHLM will focus on the physical damage to the exterior of the building and the failure of components. Other model development teams will specifically address the water penetration issue on interior losses.

Façade Damage

The building envelope provides aesthetic appeal and protects the interior from damage. It may also provide assistance to the structural frame in resistance shear and moment. Typical façade materials of multi-story buildings in Florida are stucco, glass, brick veneer, and exterior insulation finish system (EIFS). Synthetic stucco is a material that is applied to concrete masonry to provide additional thermal insulation to the building. Glass allows transmittance of light and other aesthetic appeal. Brick veneer also provides aesthetic appeal and a second layer of structural protection over the concrete masonry. EIFS provides thermal insulation, more so than stucco, but is vulnerable to impact from debris or even vandalism.

Damage to a building facade can be caused from a variety of things. Wind suction on the leeward side of a building can undo adhesives or mechanical fasteners binding the exterior wall to aesthetic cladding, such as EIFS. This occurrence is accompanied with water penetration which can compromise the performance of EIFS and brick veneer, if constructed with poor

craftsmanship. Debris impact, already discussed, can penetrate the façade to expose the interior, if the striking object transfers enough energy-momentum.

Fundamentals of Developing the Hurricane Loss Model

The commercial FHLM will be developed in similar manner as the residential Model was constructed. The model program is a Monte Carlo simulation, randomly generating wind loads and wind-borne projectiles, and randomly assigning component strengths. A check will identify if a component has failed under the wind forces. The load side of the equation will be developed from ASCE 7 for acquiring wind pressure, along with a suitable debris impact model, encompassing many types of objects relevant to multi-story buildings. The resistance side of the equation will be developed based upon statistical strengths of glass and EIFS. In a departure from the modeling assumptions used for the residential model, the failure of doors and windows will be expanded to include not only physical breakage, but also sufficient deformation to permit water penetration.

Modeling Debris Impact

Much like the residential Hurricane Loss Model, impact damage is positively correlated with windspeed. A higher windspeed will induce more movement of objects which potentially can become missiles. As the objects increase in velocity, they gain more kinetic energy. The probability of the missile impacting something vulnerable may be considered proportional to the vulnerable area as a fraction of the entire envelope.

To develop a debris impact model, it would be necessary to consider the list of objects which compose debris observed in the aftermath inspections of multi-story buildings. To properly simulate debris affecting these structures, it would be proper to stratify different classes of these objects, based upon distributions of certain properties. These properties ought to be identified in terms of density and object dimensions.

It would be necessary to identify the source of each class of objects. For example, gravel is found on the roof top, but may also originate from the building landscaping scheme at the ground floor. Garbage and temporary construction material may usually be found near the ground floor. After the wind picks up the object, it has the capability of traveling up or down, depending on the object's initial position.

When air-borne, the object inertial energy can be determined. Variables such as the object density, dimension, and relative speed affect its energy. The probability of breaching a window or penetrating a building's vulnerable façade will depend on the possible breaching area, and the strength of the vulnerable façade.

The different classes of objects which will be considered by the model to have the possibility of becoming air-borne and impacting can be broken down into four distinct groups. Gravel from the roof of a building and adjacent buildings can compromise the life of its cladding. Timber material is also capable of penetrating windows. Plywood material is a flat object which has an ease of creating lift when wind is passed underneath it. Shingles made of ceramic or asphalt composes the fourth category of debris that can collect in the air and wreak havoc on multi-story buildings.

Gravel Ballast: Gravel is the only category of these four that is considered round. These small rocks composed mainly of limestone have been modeled in the past with a mean diameter of 12 mm (HAZUS, 2000). This was measured in inspection of the Marriot-Datran Complex in Miami, Florida following Hurricane Andrew. The unit weight of this limestone gravel can be assumed to be 122 pcf (19.2 kN/m³) (Suiker et. al, 2005). The gravel ballast is also assumed to be uniformly graded, which implies the COV for gravel density is fairly low. Because of

uniformity, the distribution of gravel diameters would be appropriately modeled as a uniform distribution.

Timber Members: The second category of debris to be modeled is timber material composed from temporary construction material. In the state of Florida, the most common wood used is Southern Pine, which has a dry specific weight of 0.55 – equivalent to 34.32 pcf. The variation in weight of timber can be assumed to be between 0 and 20% moisture content, and this is plausible due to rain and increased humidity during a storm. At the highest water content, the unit weight increases to 41.18 pcf. If the probability of a random timber object having density between 34.32 pcf (dry weight) and 41.18 pcf (20% moisture) is assumed to include 95% of all possibilities (4 standard deviations, assuming a Gaussian distribution), the mean unit weight could be assumed to be 37.55 pcf, with a COV of about 5% ($= 1.715/37.55$) (NDS, 2005).

Dimensions for a timber member consist of one long dimension, and two relatively short dimensions. The two shorter determine the size of the timber. For example, a 2x4 member typically has actual dimensions of 1½ inches by 3½ inches (NDS, 2005). As the member flows in the wind, the direction of flow will probably be parallel to its longitudinal axis. The smaller dimensions will be in the plane normal to the velocity, and because of its geometry will catalyze air viscosity. The characteristic length of all timber members can be modeled as a normal distribution, taking the average of the shorter lengths. The COV of this length should be fairly large to consider a variety of cut sizes. This would provide a realistic distribution of all timber members in its possibility of comprising the debris cloud, because the characteristic length is related to the radius of impact, to be considered later on.

Plywood Members: A third category of potential missiles are sheets of plywood, large and small, that become air-borne from the effects of hurricane winds giving it lift off the ground.

The material density can be modeled to the same distribution for timber – i.e., mean unit weight of 37.55 pcf \pm 5%. Typical dimensions can be anywhere from 4 feet by 8 feet for one complete sheathing panel, down to a piece small enough to create uplift at 50 mph. Juxtaposing the timber material, plywood will have two long dimensions and one short one. The characteristic length, related to the inertial energy of the object, could be modeled to take the average of the longer dimensions.

Roof Cover: The fourth category comprising the classes of debris is shingles. This category may be opened up to two types of shingles, asphalt and clay. They are made up of different materials, and also have distinct geometries. Asphalt shingles have been modeled in the current FFLM (Cope, 2004), but may require some modification.

Now with a survey of different objects that can be flying through the air, capable of creating damage on the modeled structure, it is possible to establish some criteria to determine flight. This flight occurs when the velocity energy surrounding the object is able to counteract its inertia. The criterion is dependant on the modeled wind speed, air density, object density and characteristic length.

Determining Uplift: The density of air varies with relative humidity, but the dry weight of air at standard temperate will be approximately 11.7 kN/m³. This quantity may want to be modeled as a normal distribution. An increase in relative humidity will increase the air density, which would improve the object buoyancy. This could improve the chances of liftoff. The criterion in equation form can be expressed as: $U^2 \geq 2 \left(\frac{\rho_m}{\rho_a} \right) \left(\frac{I}{C_F} \right) * \ell * g$ (Lee & Willis, 2002). The object density and air density, ρ_m and ρ_a , respectively, are compared in ratio. The constants I and C_F are related to the object's ability to resist the flow of air. I is considered the ratio of force required to overcome the object weight. This variable takes the value greater than

or equal to unity. It could be modeled as some lognormal distribution with unity as some value less than the mean. The aerodynamic force coefficient, C_F , is related to the curvature of the face of the object in the direction of flow.

Determining Damage Energy: If an object satisfies the above condition, then the probability of the object striking the model building's cladding would be non-zero. The damage equation would depend on the object and air density, weight ratio and aerodynamic coefficient as before, and introduce a ratio of the object to wind speed J . The damage energy of an object can be designated as: $D = \frac{1}{16} * \rho_m [(C_F \rho_a) / (\rho_m I g)]^3 * J^2 U^8$ (Lee & Willis, 2002). This quantity will be expressed in units of energy. This way, it can be compared to impact energy of cladding material.

An alternative approach to estimating damage from air-borne objects was also provided by Lee and Willis (2002). A linear relationship is obtained in terms of the windspeed and the characteristic length and ratio of object density to air density. This relation applies well to sheets and cubes: $U \propto \sqrt{2 * \ell * g * \left(\frac{\rho_m}{\rho_a} \right)}$. A reference point can be used to establish the proportionality constant. Knowing an object's length and characteristic length, the necessary windspeed for liftoff can be calculated as a check.

Modeling Vulnerable Cladding

The impact resistance of cladding materials must be considered to successfully model damage from debris impact. It has been discussed that the main types of cladding that will be modeled will be EIFS and glass. Synthetic stucco is a composite material of organic plastics and cement. Together, they provide thermal insulation when applied to the exterior of a building, as

well as aesthetic appeal. Glass is a brittle material allowing transmittance of light, and is perhaps the most common noticed component of any multi-story building.

Exterior Insulation Finish Systems. Synthetic stucco is known to have frequent failure in every day function (Lampo & Trovillion, 1996), and is amplified with the event of a hurricane. Main causes of failure include poor workmanship, thin base coat application, low resistance to suction pressure, and water intrusion. Impact damage increases synthetic stucco's probability of failure. Cracks peel off from the puncture hole created by impact. Water may enter through the opening, and will be absorbed by the foam material beneath. Eventually, the humidity inside the foam will affect the adhesive material bonding the substrate wall to the synthetic stucco finish, and will cause delamination. This will necessitate replacement of the exterior finishing material. Figure 4-1 below shows a damaged EIFS system on a hotel after the 2004 hurricanes in Florida. Significant damage from water penetration occurred to the building after the EIFS system failure.

Investigation of synthetic stucco's strength from impact was thoroughly conducted. Two engineers wrote three papers regarding EIFS properties and strength (Lampo & Trovillion, 1996). One surveying its impact resistance included three tests: the Falling Weight, Falling Ball, and the Perfotest. The Falling Weight test involved a ball tied to a string to be dropped onto a sheet of EIFS. The Falling Ball test dropped a ball vertically over a sheet of EIFS. The Perfotest involved a rod projectile connected to a machine from a certain height above the stucco.

Of the procedures investigated, one is of most interest – the Falling Ball Test. Two modes of the test used two balls, one heavier than the other, to punch through the EIFS. The lighter ball of 2 pounds and 2-3/8 inches in diameter was dropped from a height of 30 feet. A second ball of 4 pounds and 3 inches was dropped from 15 feet. The ball's energy-momentum was calculated.

The investigations tested two standard types of synthetic stucco, namely type PB and PM (defined below). EIFS is constructed with a plastic in foam form covering the substrate wall, providing excellent thermal insulation. Within the foam is a reinforcement mesh of one or two layers, to absorb shock from impact. There are predominant types of reinforcement – standard mesh and impact-resistant mesh. The side of the foam touching the wall is covered with an adhesive for application. The foam assembly is covered with a cementitious base coat, with hints of polymer as well. The base coat protects the vulnerable foam underneath. PB, standing for “polymer-based,” is usually constructed with the inside foam made of molded expanded polystyrene (MEPS). PM, standing for “polymer-modified,” contains extruded expanded polystyrene (XEPS), or polyisocyanurate (PIR).

One property that has best correlation with impact resistance is the base coat thickness. A thicker base coat increases the impact resistance of EIFS. PM is much stronger than PB, but because of economy, PB is much more common in the market. In general, increasing the number of layers and improving their quality increases the strength of the finish system. However, results of the exam indicate that the type and amount of reinforcement in the synthetic stucco finish does not necessarily improve the material’s impact resistance (Lampo & Trovillion, 1995). A few instances occurred where finishes with less reinforcement performed better than samples with more reinforcement.

Presentation of the results in the report by Lampo and Trovillion give excellent leads into modeling EIFS. Trends of mean failure energy (MFE) versus base coat thickness were plotted. There exists a significant positive correlation, and the failure of the synthetic stucco is measured in units of energy. The linear trend was combined for PB and PM systems. The relation between *MFE* (in Joules) and thickness *t* (in millimeters) is: $MFE = -0.642 + 1.847t$. The correlation

coefficient for this relation is $R^2 = 0.770$, which is moderately high. The correlation justifies using a high COV in relating strength to thickness of EIFS.

Glass. Glass is perhaps the most noticed cladding material of most structures. It provides an aesthetically pleasing decoration to the exterior to the building, and essential for satisfactory light transmittance and energy savings. It is a crucial component of an architect's design. Engineers must design glass cladding to transfer stresses to the frame.

Because glass is a brittle material and can shatter upon impact, the Florida Building Code sets requirements for impact-resistance windows. Particularly, the South Florida Building Code obligates windows in the lower 60 feet of a building to be designed for impact resistance. This is due to the higher expected 50-year windspeed in the region (ASCE, 2002). Recent observed failures of glass cladding from impact higher than 60 feet after hurricane Wilma in 2005 is now driving the Florida Building Commission to reconsider the 60 feet height limit on impact protective glass systems.

Glass used as cladding on multi-rise structures can be constructed in several ways. Monolithic glass can be attached to multiple stories. Glass can be attached to one story at a time. Engineers must design for appropriately-sized expansion joints, more crucial for monolithic glass. Treatment of glass for increased resistance includes annealed, heat-strengthened, and tempered glass. Impact resistant glass, also referred to as sacrificial ply, contains two layers of soda-lime glass plies, and one layer of polyvinyl butyral (PVB) (Saxe et. al, 2002). The PVB layer acts as resistance to the breach of the window, in that it holds the two plies together in the event of impact. Normally, an impacted window will shatter, but with the help of the PVB there is decreased likelihood of this happening. This can prevent breach and water intrusion to the

building's interior. Despite savings of interior furniture and equipment, the window would need to be replaced after the storm.

Failure of glass in the event of a hurricane could be attributed to the combination of out-of-plane forces, such as pushing or pulling pressure, and impact breakage from debris. Load-deflection relationships are available for windows (Minor & Norville, 2006). These may be superposed with a concentrated pressure from impact to obtain the deflection of a window.

The HAZUS Manual (2000) presented some ranges of momentum breakage of windows used in their modeling of some case studies. Momentum breakage values of a variety of window types can be anywhere between 0.01 to 0.08 kg-m/s, units of momentum. The energy breakage derived can be compared to the damage function for debris objects (Lee & Willis, 2002).

The impact resistance of sacrificial ply windows was investigated by Saxe and others (2002). The test involved impacting the surface of the glass with steel balls of various sizes and weights. The balls were impacted at various velocities, until a mean minimum breakage velocity (MMBV) was obtained. Knowing the object's mass and velocity allows for both an energy and momentum approach to window breakage. The paper also provided vulnerability curves for probability of failure versus MMBV. It was concluded that increasing the steel ball size brings down the MMBV. Attempts to fit the MMBV to probability distributions were unsuccessful. The paper stated that the Weibull distribution was conservative compared to the normal and lognormal distributions.

Modeling Methodology

The information described above was noted because of its potential to help create a Monte Carlo simulation that could estimate damage on multi-story buildings. The process, similar to the residential model, will involve random simulation of the load, and random simulation of the resistance, where the randomness is described by an appropriate statistical model. The

identification of damage or failure involves comparison of the load and resistance. If the load exceeds the resistance, then that constitutes failure of the component.

A flow chart of the debris impact model for the commercial FHLM can be encountered in Figure 4-2. The debris model should somewhat resemble the residential model. It would be necessary to establish the number of objects, which initially stationary, can potentially become air-borne and compose the debris cloud. An energy approach to flight and failure will be composed. This would also require the strength of the cladding materials to be associated with maximum absorbed impact energy. The damage energy will be compared to the resistance energy and damage if any will be identified. The damage of windows may be expressed in terms of breach of windows. If one window is impacted twice, only one window will need to be replaced. The summation of damaged EIFS may be calculated in percent of envelope area.

The program must assume a certain amount of each type of debris available for impact. For example, if the class of debris considered is gravel, then an appropriate amount would depend on the roof's square footage covered with gravel ballast, and how deep the layer of ballast is on the roof. The amount of timber material will depend on the presence of some formwork, tents, or garbage somewhere in the vicinity. Timber material will usually be encountered at ground floor. Once this number is determined for the class of debris, then a density and characteristic length vector should be created, representing one row for every object that will be considered in the debris impact model.

For each object to be considered, for every class of debris, the process would continue with the random simulation of characteristic lengths and object densities. The aerodynamic force coefficient may be determined once for each class of object. This will vary from class to class, but probably not from object to object in the same class. For example, the gravel ballast can be

modeled as spherical particles, and so the aerodynamic coefficient will be unique compared to timber members and plywood. These two classes have predominantly flat faces, normal to the wind in flight, and so will assume a different aerodynamic coefficient C_F . The ratio of force required for lift to inertial energy is a value that must be greater than unity, and can be assumed to be less than some upper limit, say 1.4. These values may serve as the 2 standard deviations below and above the mean value (95%), and be calculated back to obtain the mean and COV for this variable.

The variables considered so far are the object's density and characteristic length, the force ratio, and aerodynamic coefficient. Of these, the first three should be randomly simulated vectors, one for each object to be considered for lift. The fourth should be determined as a constant depending on the class of debris being considered. To check for lift, the relation by Lee and Willis should be considered (2002).

The final ingredients to input into the relation are the windspeed and air density. Windspeed can be modeled in similar fashion as in the residential vector. A specific 3-second gust wind speed value at 10 meter elevation is assigned, and the resultant load over the surface of the structure determined using ASCE 7 pressure coefficients with some randomization added. The increase of wind speed with height will also be accounted for.

With all of the ingredients generated, the equation above can be implemented into the model. A factor equal to the right-hand side of the relation can be determined for every object considered, and be compared to the square of the velocity on the left-hand side. The identifier for lift can be obtained in this manner, and objects not containing lift will be disregarded for the remainder of the model.

Next, the probability that an air-borne object will impact the building envelop must be considered. The definition of this number calls for further development and search for statistics. This value can trim down the list of objects that are flying through the air down to objects that will be assumed to strike building exterior. The damage energy of each object assumed to strike the building will be calculated.

It has been mentioned that the largest factor related to impact resistance of EIFS systems is the base coat thickness. Relations between base coat thickness and mean failure energy have been discussed for exterior insulation finish systems (EIFS). However, a suitable distribution for EIFS base coat thickness needs to be created. Typically, polymer-modified stucco is stronger than the polymer-based version, although PB is found to be much more common in practice. The threshold of thickness for synthetic stucco's coat thickness between PB and PM systems is about $\frac{1}{4}$ " , which is equivalent to 6.35 mm. Base coat thickness of PB stucco is below this threshold. It might be logical to implement two mean values for the base coat thickness of EIFS, one for PB and another for PM. The COV can be the same for both, but it may be recommended to see a high value to incorporate the inconsistencies in workmanship. The mean failure energy of the finish can be derived from the thickness. Finally, when there is impact, it can be assumed that there will be an area of impact centered at the contact between debris and finish. A radius of impact could provide a way to calculate the damaged area, and express it as a percentage of the total EIFS area that will need to be replaced.

Another avenue of EIFS damage that could be considered is from suction pull-off. The delamination of stucco from the substrate wall is something that is not so easy to identify as is debris impact, but is consequential of water intrusion into the MEPS foam beneath the cementitious base coat (Cheple & Huelman, 2000). There are numerous modeling challenges in

identifying and quantifying delamination. The phenomenon of delamination is caused by water penetration beneath the base coat, and is a gradual process that eventually undoes the effectiveness of the adhesive binding the finish to the substrate wall, typically concrete masonry for our studies. The amount of water penetration necessary to cause delamination will need to be investigated, as well as the typical area of delamination as a function of water penetration will need to be determined. The effects of negative wind pressure on a vulnerable delaminated wall portion will also need to be determined.

In order to model glass, an energy approach to the impact breakage must be devised. Currently, sources have been found which express the strength in terms of momentum. One paper provides results universal to the energy or momentum approach (Saxe et. al, 2002). However, more investigation is necessary for other types of glass found in multi-story buildings. It is possible to model two types of glass, impact-resistant or sacrificial ply, and non-impact resistant glass, such as annealed, tempered, or heat-strengthened glass.

Conclusion

This chapter presents a starting point for development of a probabilistic physical damage model of commercial structures. The major components under consideration will be debris impact resistance, cladding system failure modes, water penetration through failed roof membrane or failed or deformed windows and doors, and damage to the façade itself.

A proposed debris impact model has been presented. The impact resistance of exterior insulating finish systems and glass has been investigated. Other aspects of the model which require further investigation include building geometry statistics, distribution of occupancy types from city to city, information about building material statistics, statistics on building heights and stories, and an investigation of surface roughness and the variation of them throughout an urban area and boundaries. Once the building and neighborhood layout has been simulated randomly, it

would be possible to determine the amount of available debris as well as the likelihood of debris impact on the model building.

Similar to the study conducted for the residential model, a study of the land area and its constituents is necessary to compose a successful model of estimating damage on multi-story buildings. This time, a study will need to be done for urban areas, where mid- and high-rise buildings are common and in highest concentration. A study to identify properties of these buildings will reveal statistical parameters that can be used for a Monte Carlo simulation. For example, the relative use of EIFS, glass, and brick cladding systems on condominiums. Variables that could be modeled statistically, given there is sufficient information available, are building heights and stories, building areas, and terrain. There many cities in the Southeast United States that have numerous high-rise structures in a condensed urban area, and may also have some development authority involving the construction and maintenance of these structures: Miami, Ft. Lauderdale, Palm Beach, Atlanta, Charlotte, Houston, New Orleans, Mobile are some examples.

Information can be derived city by city, for a couple cities, and then spot-check the rest to see if there is a startling discrepancy in statistics. Information that could be useful for the commercial FHLM in an urban study can start with obtaining information about the distribution of different building occupancy types, i.e., business, institutional, and residential. The International Building Code (IBC) defines building in terms of their function to the public. Most relevant to a study of high-rise buildings include office buildings, hospitals, condominiums, and hotels. The IBC (and FBC) also provides limits to building heights and building area per floor depending on the fire resistance of particular structural elements. Thus, reviewing information

available about the fire safety of a building or buildings in a locality can provide a detour to obtaining building area and height statistics.

A second motivation for a building study in urban areas is to obtain some information about the material used for curtain wall, history of EIFS installation or maintenance, etc. Materials of a building's curtain wall construction can be glass, concrete masonry, brick veneer, stucco, EIFS, or even timber frame. Characteristics of glass, impact-resistant or not, throughout the building, what size of glass sheets were installed is also of interest. Locations of EIFS and stucco, relative to floor and wall, are also of interest.

Another aspect of building construction that can be included is building floor layout and cross-section shape. The simplest cases are round and rectangular, but architects strive for more abstract shapes and layouts every day, to accommodate for the public's increasing demand for aesthetics. The dimensions of these layouts can be obtained from average area per floor.

Once this information is obtained, a building can be created from an entourage of randomly simulated variables, which can be stratified in the methods described. Properties of the building, such as height in stories, area per floor, and shape (circular or rectangular) can be determined by random simulation. The terrain roughness in the area can be simulated to reduce the simulated windspeed. The building can be created in the middle of 8 adjacent buildings, also of variable height, area, and shape. The simulation of these buildings may assist in determining the amount of debris present. For example, adjacent buildings' gravel ballast at the roof level will make the model building's curtain wall vulnerable.

Once the model building and adjacent high-rises have been simulated, the amount of debris can be modeled as a function of the buildings simulated. Case studies have shown that window breakage from gravel ballast occurred near the initial position of the debris (i.e., from building

roof) (HAZUS, 2000). Other debris starting at the ground floor can be modeled to possibly affect a certain number of stories above ground.

The window configuration on buildings can take two forms – monolithic construction or single-story assembly. In these differing types of construction, the windows can be installed as to span one story at a time, or multiple stories. The impact of the different methods involves the window area subject to breakage. If a multi-story spanning window is broken, that is more damage as a percentage than if a single-story window is broken. There is also a possibility that a window can be impacted more than once. It would be necessary to identify a particle of debris that has impacted to a window that is subject to being impacted. Multiple impacts must be considered, especially if one succeeds in breaking the window and another doesn't. The amount of windows is a function of the building's stories and area. Once a suitable number for windows is determined, their strengths and damage indicators can be vectorized. Some building codes require that impact-resistant windows be installed from the ground floor up to a minimum distance. They may or may not be a desire to identify the floor and wall where the window is located.

Further investigation needs to produce a statistical model for the impact resistance of windows. It would be ideal to obtain some relation about the strength of glass from impact. It would be advantageous to create this model from an energy point of view, consistent with information about the strength of EIFS and impact from missiles.

Another area that was addressed earlier but not discussed is the amount of mechanical equipment damage that may or may not be included in the model. Questions to answer are what are typical configurations or mechanical equipment, what are identifiable limit states of the equipment, and can the mechanical equipment itself become debris and impact nearby windows.

The last aspect of the commercial that needs further development is the estimation of wind on the building. ASCE 7 contains design recommendations for a building of all heights. The wind pressure increases with height, and the code provides factors to multiple the pressure at gradient height with depending on the height considered. These factors are believed to obey some power or logarithmic rule (Simiu, 1996). It may be advantageous to implement these rules, because the pressure coefficients will get very conservative after 200 feet in height. At this point, the coefficients are increased in 50-ft increments. A good approach to modeling wind in the vertical direction would be to simulate constant lateral pressures per floor.



Figure 4-1. EIFS-clad Building Damaged by Frances and Jeanne, Satellite Beach, Florida.

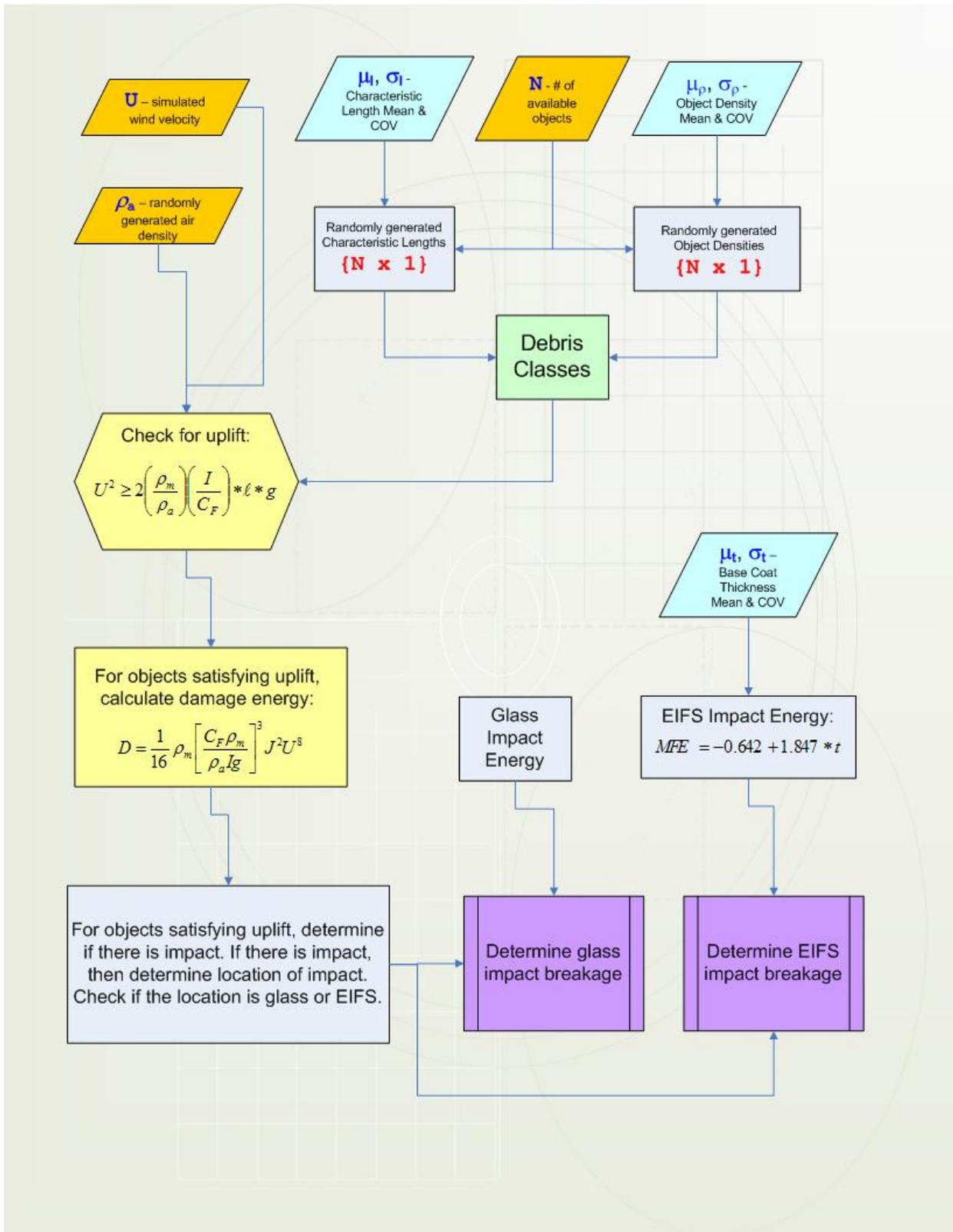


Figure 4-3. Flow Chart for Commercial Hurricane Loss Model Debris Impact Model.

CHAPTER 5 CONCLUSION

Hurricane Damage Mitigation

This thesis presents contributions to several ongoing efforts to mitigate hurricane wind damage to the man-made infrastructure.

Chase software

The collection of in-field extreme wind data will be enhanced through the development of an interactive tool (Chase) that provides a means to visualize alternative equipment deployment scenarios. The program was designed so that nearly anyone can produce a KML file interpretable by Google Earth (GE) software. This will aid significantly in the decision making process in a high-stress environment with a short window of opportunity. The tool allows the user to adapt and develop new strategies based on the most recent information on storm path, intensity and size.

Improvements can be made to the original program to further facilitate the work of the Florida Coastal Monitoring Program. Determining an estimated time of landfall would give the tower deployment team a timetable for deploying all towers before the hurricane's precession reaches land. Information about timestamp of coordinates and translation velocity would facilitate this. Chase should also be able to customize the order of the towers in deployment as seen in Google Earth, as well as provide hyperlink information in the objects' tag box (in GE) leading to the 15-minute summary files posted online. A land use land cover database that contains ground roughness data in GIS format should be interfaced with Chase to allow users to fine-tune tower placement based on surrounding terrain. In this manner a deployment team could conceivably have precise GPS coordinates for instrument deployment location before even getting to the area.

Computational Model of Structural Vulnerability to Hurricane Winds

The residential physical damage prediction component to the Florida Public Hurricane Loss Projection Model was overhauled to create a product that could be used by research assistants in other schools to estimate damages to residential homes. The simulation engine was based on the Monte Carlo methodology, which simulates a residence with random wind loads and component resistances, identifies and records failure from roof to foundation, and compiles the information for statistical analysis.

A correction to the routine calculating roof-to-wall connection failure was introduced and verified. It replaced the original uplift calculation process, which estimates a decrease in damage at high velocities due to excessive sheathing panel loss from uplift. The vulnerability curve produced from the revamped routine exhibited monotonic behavior as desired. A universal damage model file was created that would encompass all simulation variables, including region, roof type, and wall construction material. Finally, a duo of menu functions were designed that could call simulation runs in succession, and eliminate user supervision of the simulation process.

Data points from a damage survey of the 2004 hurricane season were plotted with the Model results of weak and strong mitigation. The strong mitigation simulation results corresponded well to the expected loss for newly-constructed homes. Weak mitigation results were somewhat conservative in comparison to data points from older constructed homes (1994 to 2001 building codes). This is satisfactory because the model's weak mitigation model is meant to emulate a residence of more age, implying weaker performance of the roof components.

The development of a commercial Hurricane Loss Projection Model was initiated with a literature review and methodology formulation. Research produced the characteristics of debris impact, including liftoff and impact energy estimations. Debris was classified into four groups,

and relevant properties of each group were discussed. The information provided is a formulation of statistical values to be used. Component strength of EIFS was also discussed, providing a relation between base coat thickness and mean failure energy. Glass, types of construction, material variations, and impact energy breakage were discussed.

Completing the initial version of the commercial model requires further investigation. Building construction statistics for the Southeastern United States would need to be obtained, such as building height distribution, building area per floor, and floor layout geometry. The statistics could be obtained from development authorities in various cities in the Southeast. The objective of conducting these building studies is to obtain some statistical parameters that can be linked to normal-distribution simulation of these properties. Modeling an urban neighborhood effectively will pave the way to creating a successful debris impact model.

APPENDIX CHASE TUTORIAL

This appendix serves to instruct the reader how to use the Chase software to design a deployment layout. It will provide some examples to serve as a walk-through of the program.

Example 1

This example will walk the reader through the procedure to creating the storm path spreadsheet, loading the program, and creating the KML file for use in GE.

Storm Path Spreadsheet File

The process begins when the program calls the file in a format using the storm's name and season. The file name is made by concatenating the hurricane name and hurricane season, without delimiter. For example, Hurricane Jeanne from the 2004 season should be named "Jeanne2004.xls".

Open the spreadsheet file. The spreadsheet is made from scratch, using information available on the NOAA website. Storm center latitude and longitude are posted every six hours on the website. Storm path latitude information should be written into the third column, and longitude information should be written in the fourth column. It is important that the number of latitude and longitude are equal. Information in the other columns will be ignored. See Figure A1 for a screenshot of the contents of a typical spreadsheet ready for utilization.

Initiating Chase Program

Once the spreadsheet program has been created, start the Chase program by clicking on the file "Chase.exe." An additional folder containing system files will be created in the root directory. The Chase GUI window will load up for input. Refer to Figure A2 for a screenshot of the contents of the Chase root directory after decompression. Also, Figure A3 displays the main Chase GUI window.

Loading Hurricane Track

Now that the Chase GUI has been loaded, the program is ready to input the hurricane name and season to load the track. Also, be sure to load the state where you expect the storm to make landfall. Once you have chosen the correct information, click on the “Load Track” button.

A window should be displayed with the states’ contours and the loaded storm path. Notice the x-axis displays the longitude values, and y-axis displays the latitude values, in degrees. Also, notice that a value pops up in the Landfall Heading box, which is the storm’s direction when the eyewall center intersects the coastline. The text window on the bottom left corner should say “Track loaded successfully.” See Figure A4 for this step of the process.

Loading Deployment Layout

The next step is to input how many towers you want to deploy. Suppose our test deployment will include five towers in the Cannonball Run layout. Suppose also you want the towers spaced at 1-mile intervals. Assume that the storm’s radius to maximum winds is 10 miles, and the inland distance we want to deploy is 8 miles. By default, the Cannonball Run is selected at Chase initialization, so you will not need to change that setting. You may use the increment and decrement buttons, or manually input the values. Once Chase is displaying the information you want, click on the “Load Layout” button, and wait for the layout window to display.

You should see the storm’s radius to maximum winds path in red, and the storm cluster centered on the offset path. The cluster center will be indicated by a blue circle, and the towers will be indicated by green stars. All the deployment’s information is repeated in a yellow text box at the top right corner of the figure.

In the Chase GUI window, the tangent heading will indicate the direction that the storm is heading when the storm passes through the tower cluster center. Additionally, a list of the towers’ locations will be seen in the Tower Locations box, in terms of latitude and longitude.

The text window should now say “Layout loaded successfully.” This step can be visualized in the Figure A5.

Creating KML File

If the deployment is consistent with the information you wanted, the next step is to click on the “Write KML” button. You will know the file was written correctly when the text window says “KML file written successfully.” Double-check that the file was created by looking the Chase root directory. There, you should find a file that is called “FCMP-Hurricane Jeanne-2004-Cannonball Run.” Figure A6 displays the Chase GUI window with the satisfactory message. Figure A7 presents the Chase root directory after the KML file has been created.

Loading KML File

Now that the deployment layout has been created, and the KML file written with the deployment details, open up Google Earth. Once loaded, you may locate the KML file just created, then click and hold on the file. With the first mouse button pressed, drag the mouse over into the GE interface, and under the mouse pointer you will see a small gray box appear. Let go of the mouse button, and GE will be instructed to load the KML file just created. When loaded, the camera will zoom out, or in, so that the storm path and max winds path will be maximized in the window. See Figure A8 for the typical view after the Chase KML has been loaded.

The folder structure can be seen in the sidebar to the left. A checkbox should be marked to the left of the folder icon, next to a box with a plus sign. Click on this plus sign to see the contents of this folder. There should be three subfolders: Cannonball Run, Storm Track, and Radius to Maximum Winds. Each can be individually turned off if you wish.

To zoom in closer to where the towers have been deployed, expand the Cannonball Run subfolder. In there you will find a series of tower placemarks and subfolders. The subfolders called “Tower” contain the polygon information used to represent the instrumentation towers.

Click on any one of the tower placemarks, and GE will zoom in to its location. Allow the imagery to update and load completely. You should also see a window appear that contains the name of the placemark and its GPS coordinates. Refer to Figure A9 for a screenshot of GE displaying this information.

Feel free to zoom in closer on any of the towers to observe the land around its proposed deployment position. Be aware of its possible surroundings: residential communities, vegetation, parks, bodies of water, airports, highways, schools, or warehouses. The key to determining an effective layout lies in choosing the inland distance and cluster spacing such that every tower is likely to be placed somewhere within open terrain. Bear in mind that the scale of the tower in GE is grossly exaggerated, but may deceive the user as to the size of the open area in the vicinity of the tower. Refer to Figure A10 to view a close-up of the tower and the vicinity it lies in.

Example 2

The second example will involve integrating a Blue Tarp deployment with a Red Rover deployment. We will load the track for Hurricane Jeanne, and coordinate a tower position for each of two residential homes retrofitted for our pressure sensor instrumentation. The remaining towers will be deployed perpendicular to the storm path.

The Chase program is not designed to create mixed deployments. However, we will accomplish this by creating two KML files, one for the Blue Tarp portion of the deployment, and Red Rover for the second portion.

Loading Hurricane Jeanne Track

Locate the 2004 Jeanne hurricane track in the Chase directory. Make sure that Florida is selected as the state chosen for deployment. Click on the “Load Track” button to verify that the track has been loaded successfully.

Blue Tarp Deployment

Suppose that the deployment for this storm will involve some nearby retrofitted homes. Particularly, the Smith home and Jones home are very close to the projected path of the storm. Suppose that FCMP decides to deploy a tower close to each of these homes.

First, a little research on Google Earth gives us the GPS coordinates of the Samples and Ridgely home. Putting the street addresses provides us not only with an aerial of the home and neighborhood, but also the precise location as to where the towers may be deployed.

In the Chase GUI window, select the “Blue Tarp” setting. Type in the GPS coordinates for the towers into the Latitude and Longitude edit boxes. When finished, click on the “Update Next” button to append the list. Do this for the Jones and Smith home. When completed, click on the “Load Layout” button to visualize the layout. Then click on the “Write KML” button to complete the design process in Chase. Figure A11 displays the completed Blue Tarp design process.

Red Rover Deployment

To finish the layout design, click on the “Red Rover” button to change the layout setting. Select three towers, 12 statute miles to maximum winds, eight statute miles inland, and a cluster spacing of one statute mile. Click on the “Load Layout” button to verify the tower locations. Finally, create the KML file. Refer to Figure A12 for a visualization of the completed Red Rover layout design process.

Deployment Integration

The final process is to combine the tower deployments, and is begun by loading Google Earth. Drag and drop both KML files located in the Chase root directory. Finally, observe both deployments together in Figure A13.

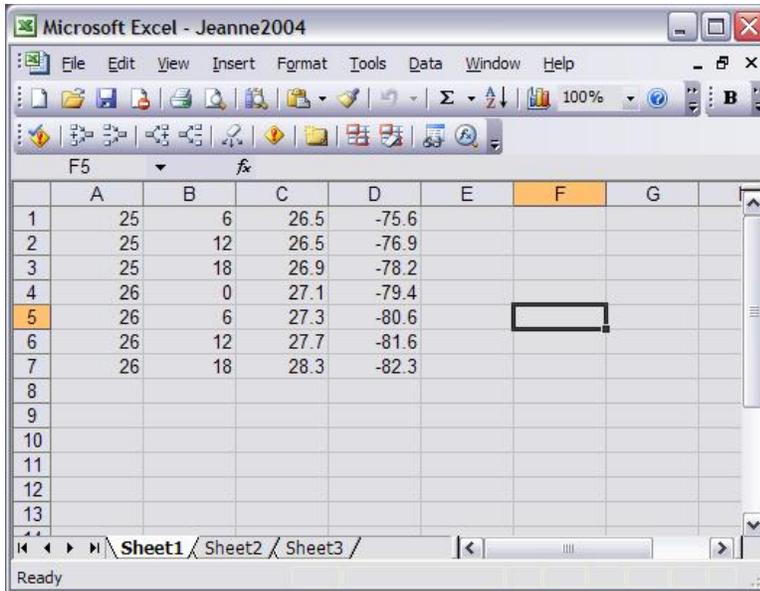


Figure A-1. Projected Path Spreadsheet.

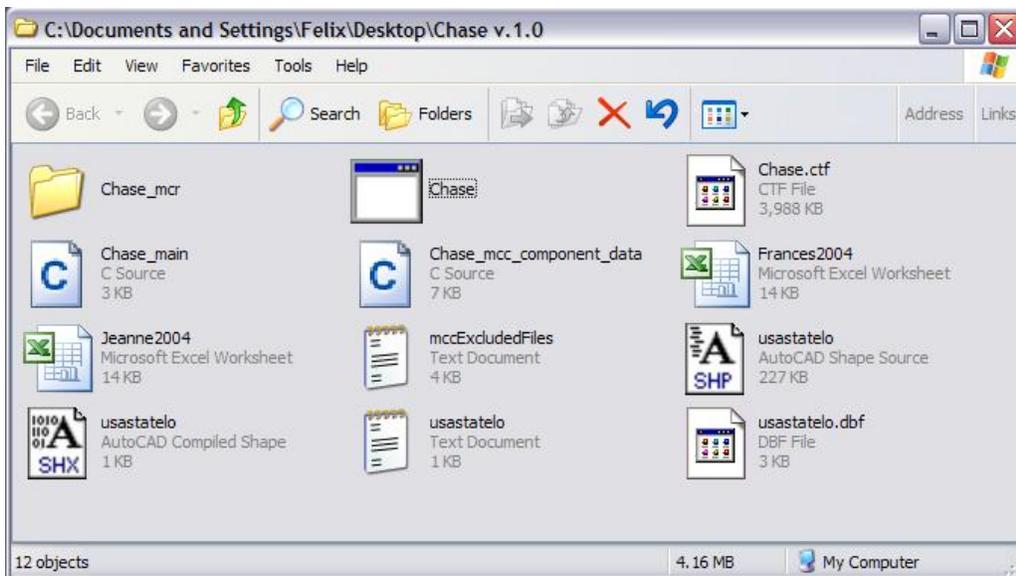


Figure A-2. Chase Root Directory.

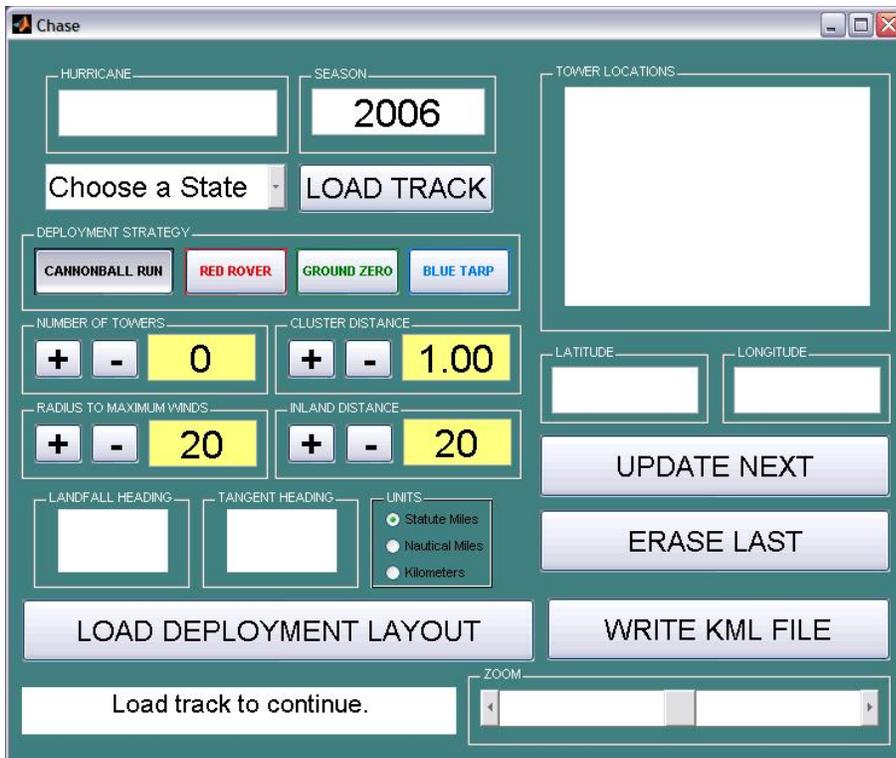


Figure A-3. Initial Chase GUI Window.

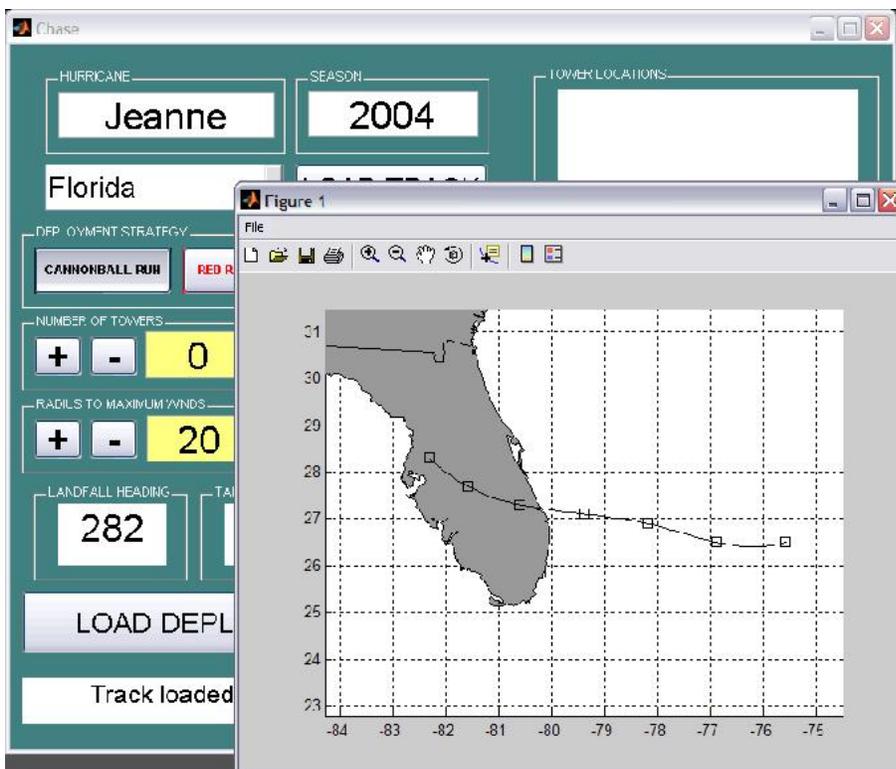


Figure A-4. Loaded Hurricane Track.



Figure A-5. Loaded Deployment Layout.

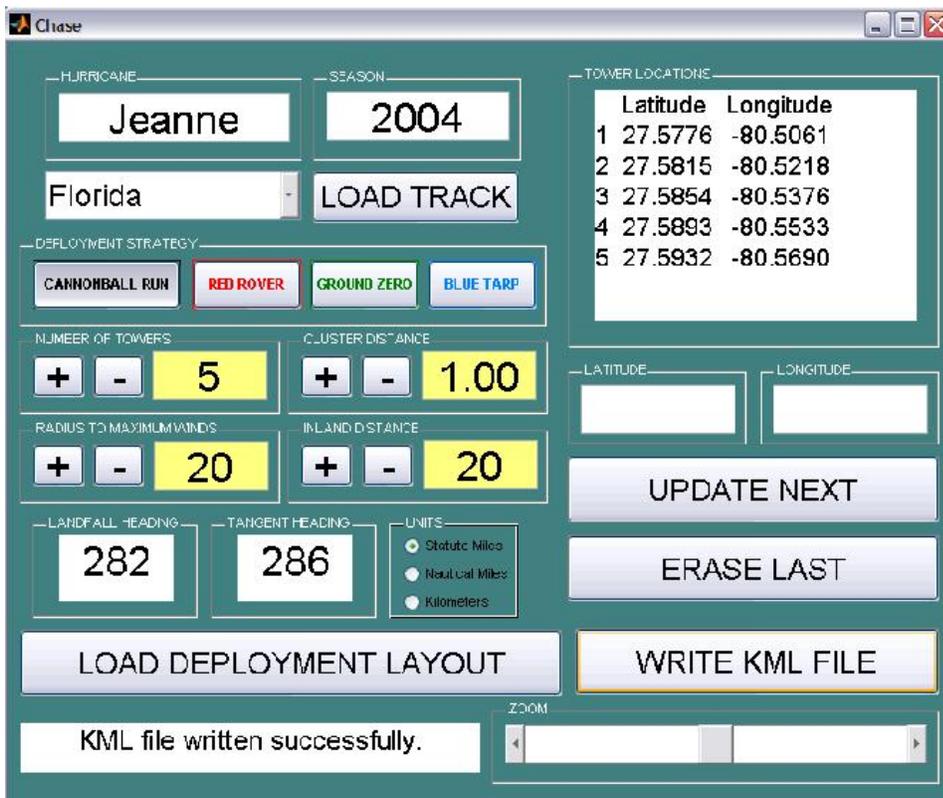


Figure A-6. Written KML File.

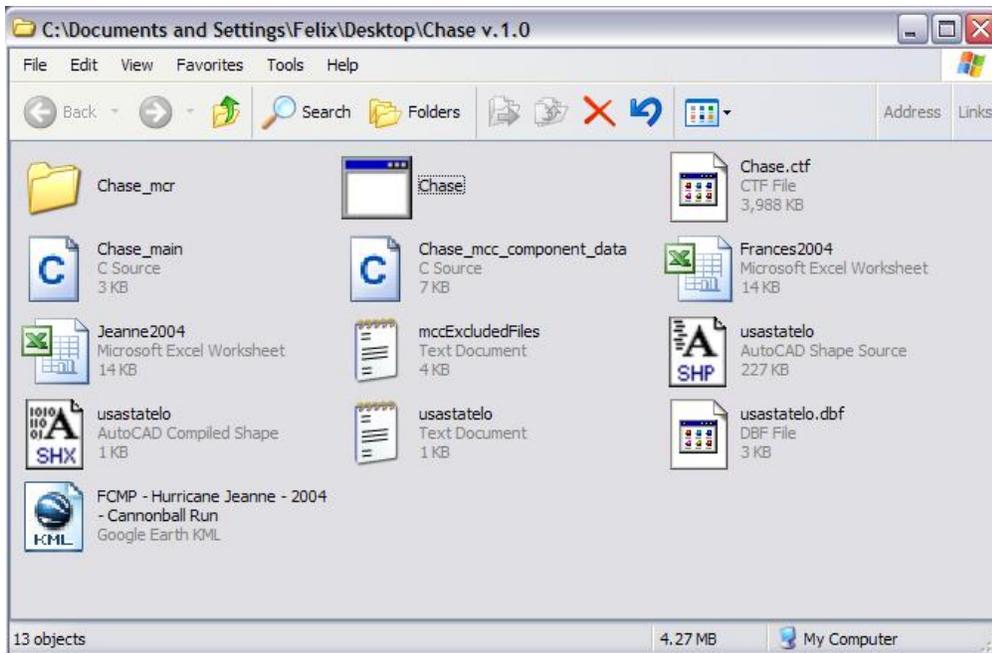


Figure A-7. Chase Root Directory after Completion.

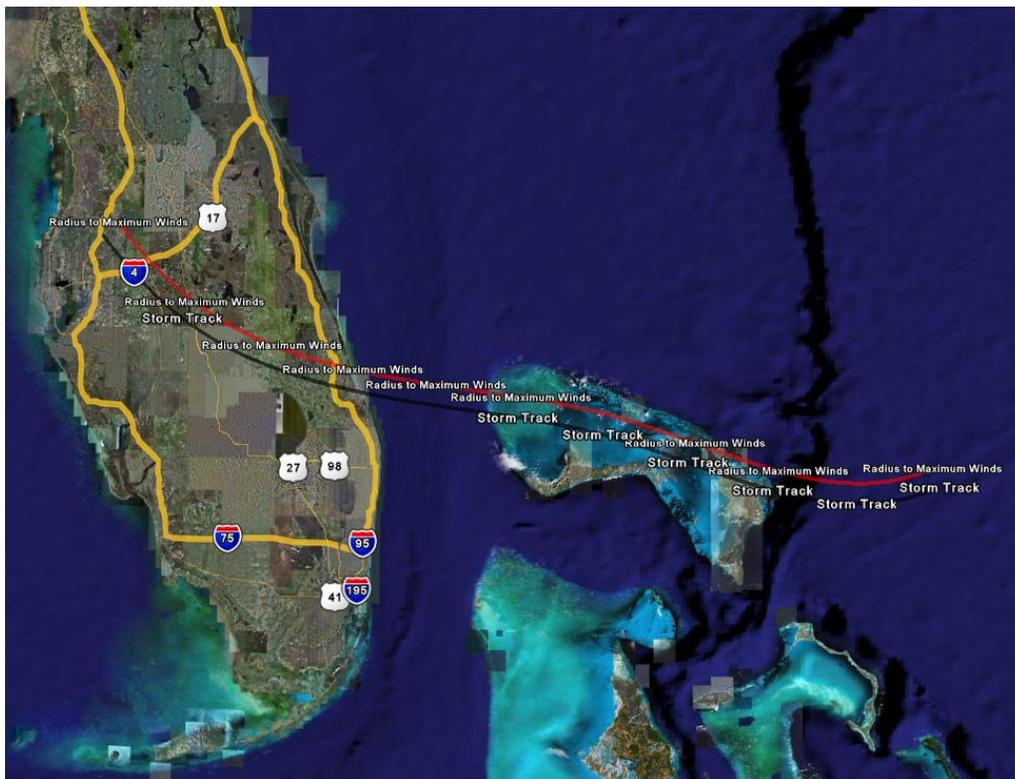


Figure A-8. Loaded KML in Google Earth.

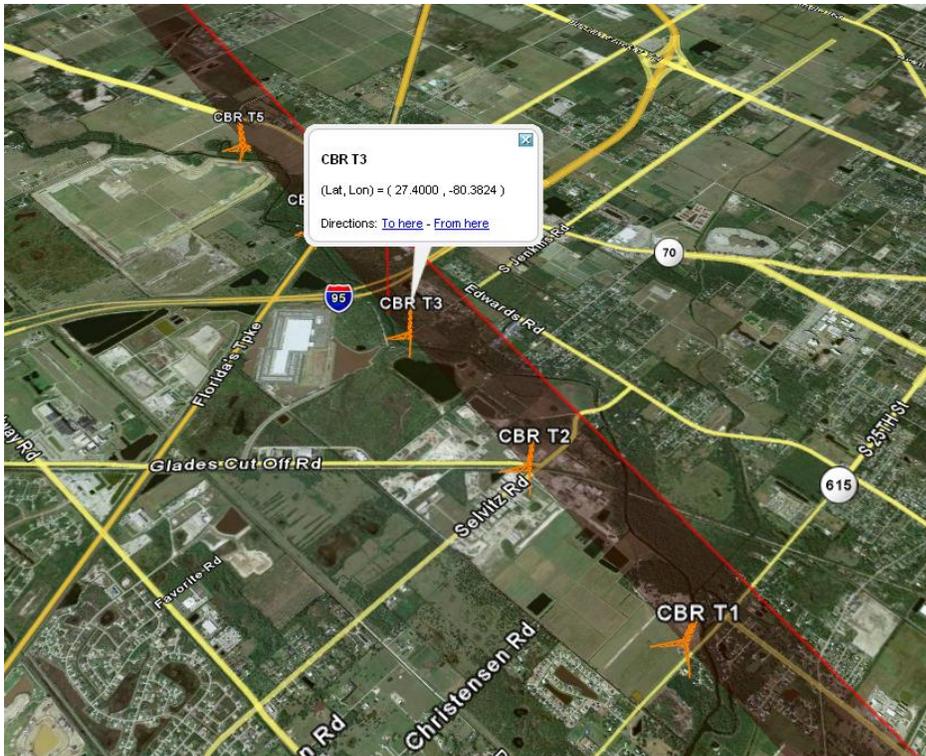


Figure A-9. Info Box of Selected Tower.

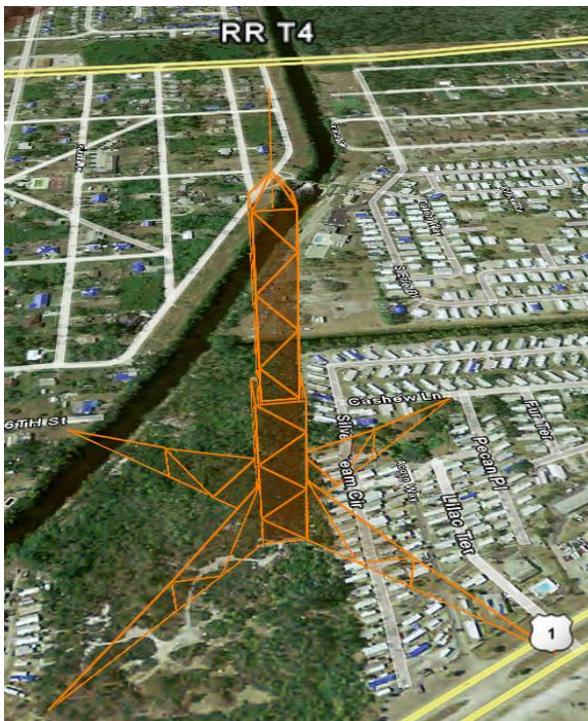


Figure A-10. Google Earth Close-up of FCMP Tower.

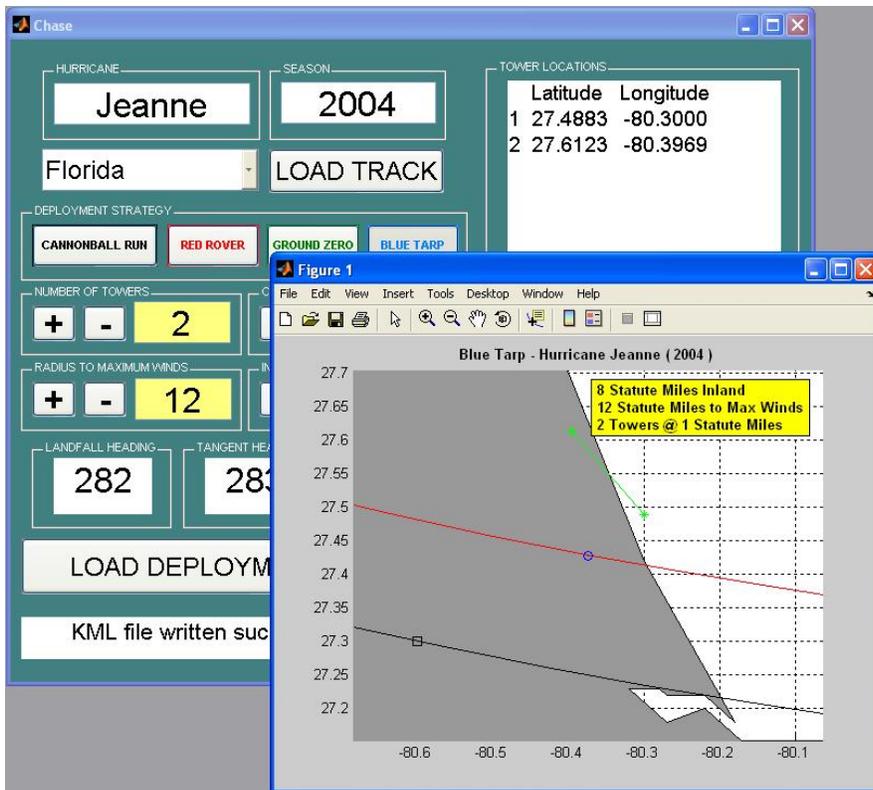


Figure A-11. Completed Blue Tarp Process and Chase GUI.

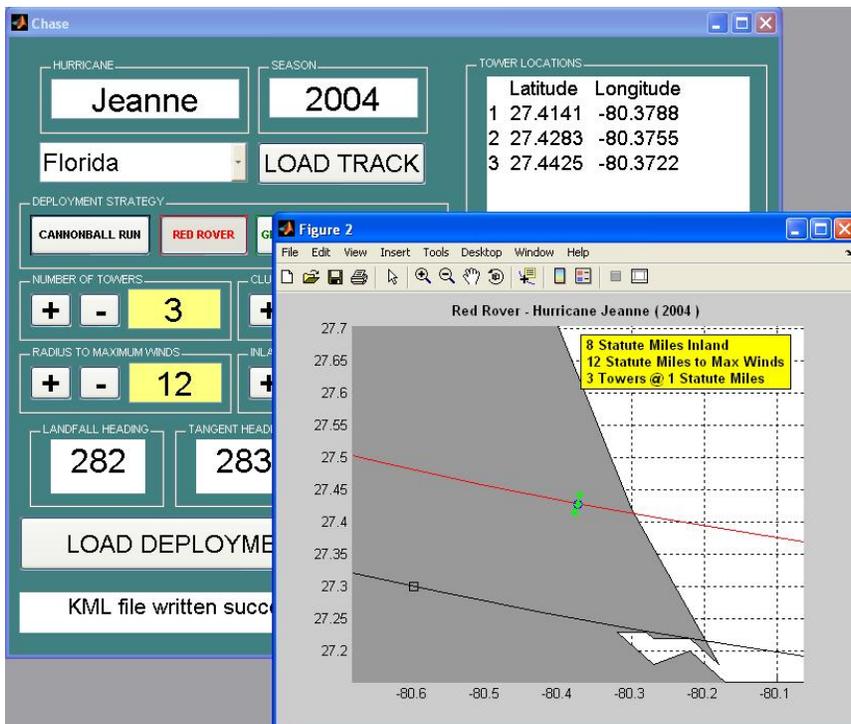


Figure A-12. Completed Red Rover Process and Chase GUI.

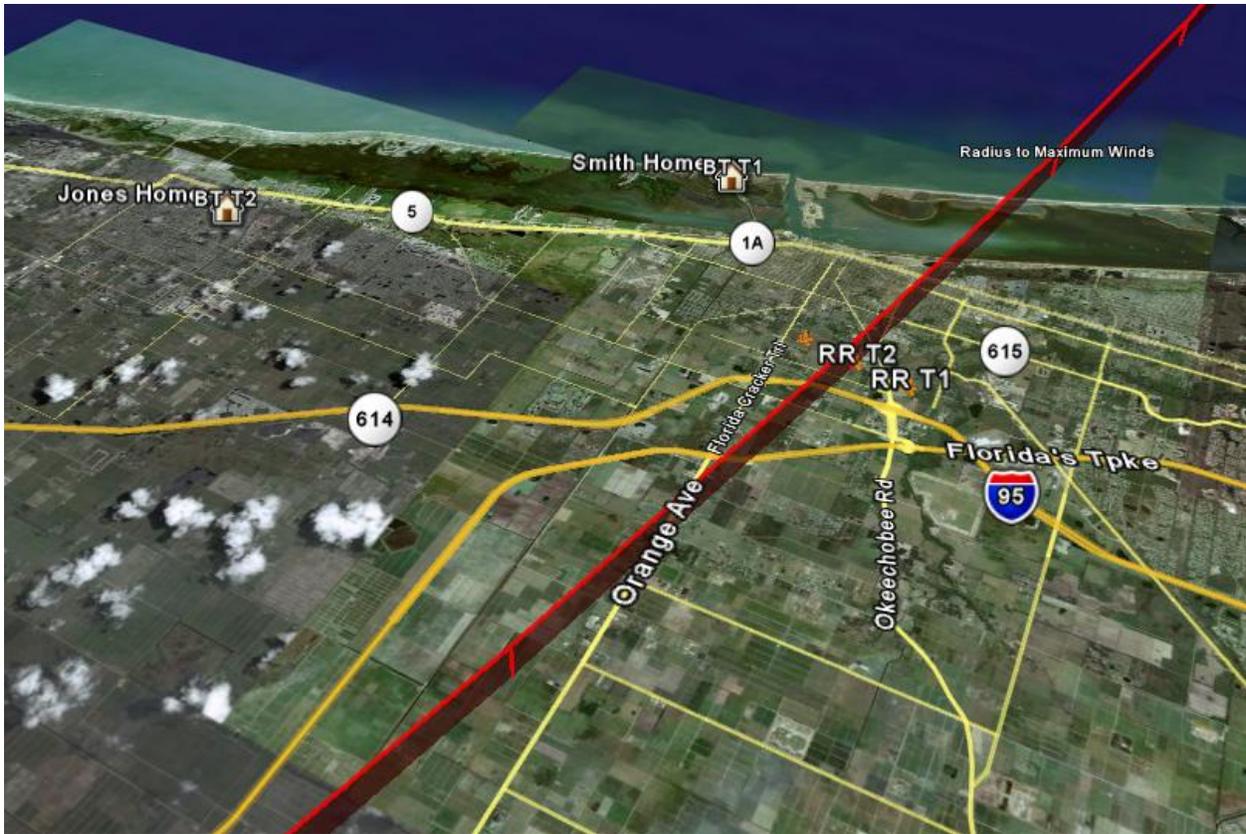


Figure A-13. Google Earth Screenshot of Mixed Deployment.

LIST OF REFERENCES

- American Forest & Paper Association, Inc. National Design Specification: Design Values for Wood Construction - Supplement. Washington, D.C.: American Forest & Paper Association, 2005.
- Applied Research Associates. HAZUS Wind Loss Estimation Methodology. Raleigh, North Carolina: Applied Research Associates, 2000.
- American Society of Civil Engineers. Minimum Design Loads for Buildings and other Structures (ASCE 7-02). Reston Virginia: American Society of Civil Engineers, 2002.
- Cheple, Marilou, and Patrick H. Huelman. "Literature Review of Exterior Insulation Finish Systems and Stucco Finishes." University of Minnesota Cold Climate Housing Program 15 February 2000. 1 February 2007
http://www.state.mn.us/mn/externalDocs/Commerce/Stucco_Study_111302112348_Stucco.pdf
- Cope, Anne D. "Predicting the Vulnerability of Typical Residential Buildings to Hurricane Damage." Ph. D. Dissertation, Gainesville, Florida: University of Florida Press, 2004.
- Gurley, Kurt. "Post 2004 Hurricane Field Survey—an Evaluation of the Relative Performance of the Standard Building Code and the Florida Building Code." Florida Building Commission April 2006. 1 February 2007
http://www.dca.state.fl.us/FBC/commission/FBC_0606/Summary_Briefing.pdf.
- Lampo, Richard G., and Jonathon Trovillion. "Use of Exterior Insulation and Finish Systems on U.S. Army Facilities." Exterior Insulation Finish Systems: Materials, Properties and Performance (STP 1269). Ed. Peter E. Nelson and Richard E. Kroll. Philadelphia, Pennsylvania: American Society for Testing and Materials, 1996.
- Lampo, Richard G., and Jonathon Trovillion. "Performance of Class PB and Class PM Exterior Insulation and Finish Systems under Various Impact Loadings." Development, Use, and Performance of Exterior Insulation and Finish Systems (STP 1187). Philadelphia, Pennsylvania: American Society for Testing and Materials, 1995.
- Lee, Brian E., and John Willis. "Vulnerability of Fully Glazed High-Rise Buildings in Tropical Cyclones." *Journal of Architectural Engineering* June 2002. 1 February 2007
<http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JAEIED00000800002000042000001&idtype=cvips&prog=normal>
- Minor, Joseph E., and H. Scott Norville. "Design of Window Glass for Lateral Pressures." *Journal of Architectural Engineering* September 2006. 1 February 2007
<http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JAEIED00001200003000116000001&idtype=cvips&prog=normal>

- Saxe, Timothy J., Richard A. Behr, Joseph E. Minor, Paul A. Kremer, and Lokeswarappa R. Dharani. "Effects of Missile Size and Glass Type on Impact Resistance of "Sacrificial Ply" Laminated Glass." *Journal of Architectural Engineering* March 2002. 1 February 2007
<http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JAEIED00000800001000024000001&idtype=cvips&prog=normal>
- Simiu, Emil, and Robert H. Scanlan. Wind Effects on Structures. New York, New York: John Wiley & Sons, 1996.
- Suiker, Akke S., Ernest T. Selig, and Raymond Frenkel. "Static and Cyclic Tri-axial Testing of Ballast and Sub-ballast." *Journal of Geotechnical and Geo-environmental Engineering* June 2005. 1 February 2007
<http://scitation.aip.org/getpdf/servlet/GetPDFServlet?filetype=pdf&id=JAEIED00000800001000024000001&idtype=cvips&prog=normal>

BIOGRAPHICAL SKETCH

Felix was born and raised in Miami, Florida. In high school, he enrolled in various Advanced Placement courses, represented his high school in numerous mathematics competitions, and played saxophone in his school jazz, symphonic, and marching band. He graduated in the top 3 percent of his high school class at G. Holmes Braddock Senior High as an AP Scholar with Distinction. A recipient of the Florida Bright Futures Scholarship, Felix attended Florida International University before transferring to University of Florida. As an undergraduate student, he participated in many engineering organizations and competitions, including the American Society of Civil Engineering Conference. He completed a double major in December 2005, earning a bachelor's degree in civil and coastal engineering and in mathematics. For his graduate studies, Felix studied under the direction of Dr. Kurt Gurley, and assisted in various hurricane deployments, including wind observation tower setup and pressure instrumentation projects the Florida Coastal Monitoring Program. His primary interests lie in hurricane damage mitigation, and structural mechanics.