Hurricane Mitigation Procedures to Protect Residential Structures

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The damage incurred following major hurricanes has a negative impact on communities and the nation's social and economic stability. Mitigation of hurricane damage begins with the understanding its impacts and problem areas of residential structures. This paper qualifies key impact areas to provide a means to address mitigation procedures to understand the interconnections between all the factors involved. Identifying key elements of the damage causing agents of a hurricane: hurricane forces, the built environment variables and natural attributes, provide a basis for mitigation of hurricane damage. The implementation of a mitigation program will aid a community by reducing the damage levels, allowing for an expeditious recovery, saving money and providing a safe environment for the residents. This paper provides a procedural format to identify problem areas in residential structures for use in mitigating hurricane damage. The first step in this process is to identify and produce a system to aid in the mitigation process. The identified factors provide a means to evaluate residential structures to mitigate potential damage.

Key Words: hurricane, mitigation, residential, check-sheet, damage

Introduction

Much has been studied concerning quality in construction, and there are of course many levels at which construction quality can be examined (i.e. construction quality in the context of building standards and codes). This research focuses on the evaluation of damage potentials in new and existing structures. The identification and resolve of problem areas in residential structures before the impact of a hurricane will provide a safer structure and community. In recent years various U.S. authorities have modified building codes producing mitigation procedures against damage in the event of future hurricanes. There is therefore a clear link between the mitigation measures that are influenced by building codes and the damage potential of future hurricanes (Huang, 2000). Revisions to existing structures will assist in mitigating probable hurricane damage by bringing the structure up to new code standards. The design of a hurricane damage impact mechanisms check-sheet will aid in mitigation procedures.

As in many parts of the world, the United States (U.S.) continues to experience population growth, with the coastal regions experiencing the highest rate of growth, requiring additional housing. An increase in residential properties means an increase in the hurricane damage potential and the financial consequences of storm events (Bookman, 1999). In a 2003 National Oceanic and Atmospheric Administration (NOAA) report, an estimated 53 percent of the U.S. population resides in coastal counties (Crossett, et.al. 2004). The 2003 NOAA report also identified 673 U.S. coastal counties in the United States. Hurricane damage costs to the nation and insurance companies are immense. In a 2009 NOAA report, the estimated costs of hurricane damage from 2000-2008 is a staggering 131 billion dollars (NOAA Economics, 2009). It is therefore clear that hurricanes are very costly events. There is an obvious and clear connection between cost and the extent of damage and an equally clear connection between damage and structural behavior (e.g. reactions). In turn, the structural behavior or reaction is determined primarily by the quality and maintenance of construction.

Problem Statement

The present research contends that the total damage caused to a residential structure by a hurricane is dependent on a finite number of interdependent and interrelated damage mechanisms which are established when a hurricane makes landfall. The development of a hurricane damage impact mechanisms model will provide coastal communities the tools needed to reduce the damage levels in the hurricane impact area. The model provides a check-sheet for inspecting new and existing structures for probable weaknesses and design problems. Once identified the problem areas are addressed prior to the impact of a hurricane to create a safer structure and subsequently a safer community. Construction contractors and costal residents will benefit from this research by having a greater understanding of the interrelationships between structural components. The results will allow for resolving problems before they occur and to inspect current structures for deficiencies.

Literature Review

The literature review is divided into three categories hurricane forces, the built environment variables and natural attributes. These three categories allow for sorting the derived data into similar groupings for creating mitigation analysis. Once identified, the attributes is expanded through detailed examination of the conditions surrounding the variables' qualities. The following discussion offers explanations to a select few for the total list of possible variables.

Hurricane Forces

Structural research conducted by Thornton and Joseph (1999) has indicated a series of considerations that are required to implement a multi-natural force evaluation of residential structures. They suggest that that the construction of a database with the two main headings of wind and hydrology. Damage from high winds effects such items as roof suction, wall pressures and flying debris. The research subdivided hydrology into two subcategories: flooding and foundation stability. Flooding investigates the impacts of water upon the structures in terms of: buoyancy, wall pressure, latitudinal drag, scour and debris impact. Foundation stability incorporates foundation settlement from structure's weight over time, consolidation of the soil, pile failure and debris impact (Thornton and Joseph, 1999). Preserving the structural envelope to reduce flying debris, requires examining the materials used and the connection methods employed to join the structural members.

The flood risk variable examines the damage levels imposed by flooding upon the community. Flooding risk dictates the piling type, pile depth, foundation settlement and the base flood elevation (BFE) of the floor system. The amount of flooding is directly proportional to the amount of rain that impacts an area. As with the wind data, rain data also provides a single level of rain for a given community. The flood risk data examines the flooding potential using the Flood Insurance Rate Map (FIRM) data from the Federal Emergency Management Agency (FEMA).

The erosion risk potential provides a method to determine the effects of soil erosion upon the coastal community. Soil erosion contributes to the settlement of the foundation and has a relationship to the coastal location. The classification of soils is integral to the resistance of erosion forces. The ability of the foundation to resist the ravages of erosion is dependent upon the design and the seating depth of the pilings. Erosion is a natural state of occurrence that is a dynamic balance between the ability of builders and engineers designing and installing systems to resist the constant depletion of the coastal environment. Erosion occurs when as waves come ashore and the undertow carries the sand back to sea. The measurement of the erosion risk has a profound impact of structures located within the reach of wave action and flooding.

The surge risk examines the hydronic pressures and the combined affects upon the built environment with the impending erosion and flooding that is associated with the wave action. The surge levels are measured in several ways. First, examining the actual physical measurement of the levels and documenting the watermarks from the residual debris and stains measure storm surge. The documentation of the actual high water mark provides the most accurate method of examining the effects of the storm surge. The surge levels will dictate structural concerns such as: the size of framing members and bracing and connection methods.

Built Environment

By maintaining the building envelope and integrity during a hurricane, property losses are minimized (Unanwa, 1997). The basic structural systems consist of the foundation, floor, wall and roof systems all forming the "structural envelope". The structural envelope reacts differently as the various hurricane-induced loads are applied due to the different material components and construction techniques. Properly designed and constructed structures prevent the forces applied by the hurricane from damaging the envelope. With the envelope in place the interior components remain intact and the structures ability to resist both vertical and horizontal loads is maximized.

The examination of the built environment's time line of construction provides an examination of the diversity of construction techniques and materials used throughout the diversity of structures. The year that the structure was built provides the age of the structure in relation to the year of evaluation. The age of the structure provides a myriad of investigative elements. The year built also addressed the varying construction techniques. These techniques changed over time with the advent of new materials. These three pieces of information are measurable by time. The year that the structure was constructed provides a timeline that facilitates this measurement.

The size of the structure is used to examine the relationship between area contained in an affected lot and the amount of debris field that is created. The contention provides that when smaller lots are located in proximity to each other that the amount of damage debris is increased thus exasperating the devastation levels. Thornton (1999) investigated the debris generated by the hurricane and presented a direct relationship to the debris field damage and the density of the community. The proximity of one structure to another effects wind pressures. By funneling the wind between the structures the applied forces are increased. The additional pressures facilitate a greater damage increasing the debris field. The reduction of the debris field is will provide additional safety to the entire community.

Common materials used for sheathing are in two groups, plywood and oriented stranded board (OSB). Plywood performed better of the two materials with less pull through failures. The attachment methods of the sheathing consisted of power driven pneumatic tools or hand driven. The power tools, although they provide the increased production rates, this production rate is often at the expense of the structures quality. When used, overdriving of pneumatic fasteners effectively reduces the thickness of the material and drastically reduces the pullout strength of the fasteners (Phang, 1999). Missing the structural member below with pneumatic fasteners renders the fasteners and their holding capabilities ineffective (Phang, 1999).

Various studies indicate that roof truss attachment using metal strapping to the wall system was inadequate to resist hurricane strength winds. When exposed gable ends of a structure intersect with high winds, the area remised of strapping and bracing leads to a 'domino' effect in the trusses. The qualitative investigation examined the various roof systems in the affected area, indicating that hip roofs out performed gable roofs due to the aerodynamic structure of the roof (Phang, 1999). The Southern Building Code Congress International (SBCCI) building code requires strapping or bonding from the ridge to the ground to properly distribute the hurricane loads. Failure to observe this critical path of load distribution resulted in excessive damage to the structures. Failure to also properly attach garage doors results in their subsequent failure allowing the structure to become pressurized causing internal pressures, jeopardizing the structural envelope (Phang, 1999).

Investigations of various roof systems determined that the roofing materials were attached using staples. Staples did not provide the holding power to secure the asphalt impregnated felt (tarpaper) or roof shingles. Utilization of plastic capped nails to secure the tarpaper to the sheathing reduces the rate of tarpaper releasing from the sheathing. Complying with the manufactures nailing schedule provides an acceptable performance level, as determined in this investigation. The investigation also determined that when the structure was not incompliance with the building codes, roof damage occurred as the insufficient number or improper location of the nails led to the unveiling of the roof sheathing, allowing water into the structure (Phang, 1999).

Suaris and Kham (1995) determined their own conclusions of the causal factors that were inherent in southern Florida following the impact of Hurricane Andrew. They first examined the shape factors of the structures. Failure to consider the geometries, surface slopes, and natural openings, in terms of the structure itself and the surrounding areas provides for improper planning and for a potential devastating condition. This condition leads to increased horizontal and uplift pressures on the structures and failures (Suaris and Kham, 1995).

The failures in concrete masonry block (CMU) structures had their inherent problems. Omitting reinforcing bars in critical locations in the structure provides no wind and surge load protection. The omission of rebar was noted in missing hooks from the foundations, no tie downs for the wall to foundation connection and missing corner rebar (Suaris and Kham, 1995).

The research noted that in wood framed structures that straps were improperly used between floors and in many cases the straps were bent over the plates with no nails connecting the plate to the framing member. Bracing for lateral loads were also missing. The sheathing investigated proved to have nails of inadequate shank size to resist the lateral loading. In some cases staples were used in place of nails and numerous cases were noted were the nails missed the framing member below. The asphalt shingles proved inadequate for the uplift pressures exerted on the roof system. Underrated shingles for the wind, loads and improper nailing resulted in stripping of the roof covering. In general, the investigation attributed the failures to non-compliance to the standing building code (Suaris and Kham, 1995).

Fang and Okada (1999) conducted a study following Hurricane Andrew and determined that the lack of code enforcement before the hurricane contributed to a higher level of damage. Their study determined that 25% of the damage was preventable with stricter code compliance and enforcement. They recommended two main areas of improvement. The first area of improvement requires initiating educational programs that raise the consciousness of architects, engineers and builders in the latest construction techniques and materials in terms of building codes. The second important influence for a safer community starts with stricter code enforcement. This will direct the building community to provide the safety factors required for the location (Fang and Okada, 1999).

Natural Attributes

The soil type examines the ability of differing soil types to retain foundations and resist erosion. The ability to retain the foundation and the soil will maintain the structural integrity of the structure. The measurement of soil conditions in conjunction with the surge factors examines the soils ability to support the structure and resist the erosive effects of flooding and the surge risk. The built environment impacts include the foundations, pile depths, foundation settlement, and the connection to the soil types. The varying soil conditions in coastal areas provide a differing level of stability to foundations.

The topographical elevations are included for the ability to measure the uplift pressures from the rising wind pressures and the flooding potential. Chiu (1999) presented the model showing the increased pressures upon the structures from the up flow of the winds as the topography increased. The secondary results of Chiu’s research indicated that the uplift pressures upon the structural overhangs. The building’s resistance to damage is dependent upon the materials and the connective devices. The strapping and nails are the focal points to making proper connections in residential structures to resist hurricane forces. These connections were a reoccurring theme in the failure of structures. When properly installed the strapping and nailing patterns provided the structures with the necessary protection.

The ability of the topographical elevations to provide protection from the surge levels is increased as the structure is further away from the coastline. In turn there is an increased chance of flooding with the structure located in the low elevations from the storm surge and the runoff from the higher elevations.

Incremental distances from the coast is evaluated using the established coastline as the baseline for the purpose of providing an evaluation of wind damage in relation to the distance that a structure resides from the beach. The proximity to the coast examines the wind pressures as they move inland, flooding and surge damage potentials. The “buffers” or equal offset zones are determined from the ocean front inwards in set increments. The increments are set at 200’, which are equal to an average city block. The derived variable examines the wind and the surge levels of the community.

Methodology

The aim of this study is to investigate the interrelated causal factors that lead to the partial or total failure of residential structures from a hurricane. The review of literature has shown that there are numerous independent references to hurricane damage reactions and impact points. The research project studied the factors presented in literature and through personal interviews.

A review of existing literature resources and interviews was conducted to generate a general inspection check-sheet of casual factors and key inspection points to assist in determining mitigation procedures. Items that commonly impact residential structures during a hurricane, indicated in the literature review, were combined into a general inspection check-sheet. Only findings that fit the three general headings of the hurricane forces, the built environment variables and natural attributes are compiled and presented in this paper. Items included in the check-sheet indicate the common hurricane damage reactions and impact points considered important for residential contractors.

Results

The main damage mechanisms that are produced when hurricanes make landfall are wind, storm surge, flooding, flying debris and rip tides. These various damage mechanisms interact with the topography upon which a coastal community is built and with the construction styles and methods that have been adopted by the structures in that area, together with the standards to which they have been maintained, to produce the final total damage result (Pilkey, 1983). The processes by which each of the identified damage mechanisms produce damage to various elements of the structure, from its foundations to its roof vary with differing materials (McDonald, 1994). The total level of damage sustained by a residential structure will be a function of the interaction between the set of hurricane damage mechanisms that are known. A set of natural environment variables that are specific to the given geographical area examined, and a set of built environment factors that ultimately attempt to resist the forces that are inflicted upon them (Hanna, 2002).

The rationale is straightforward insofar as it is understood that hurricanes will inflict wind loads, flood loads, scour loads and surge loads upon a coastal community. These variables represent the set of hurricane damage mechanisms. These damage mechanisms or variables will be amplified or suppressed by the topography of the coastline they hit and its geological composition (Bryant, 1991). The topography and geology of the land represents the set of natural environment variables and includes factors such as the elevation of the land and its gradient away from the shoreline, the makeup and condition of the soil, the extent to which vegetation, including trees and shrubs are present and the degree of water inlets or river mouths that may be present. The damage level is based on an assumption that these variables will worsen or lessen the impact of hurricane forces prior to their transmission to the built environment (NAHB, 1993).

In the case of a coastline having a low elevation and gradient relative to the shoreline, a poor non-cohesive soil structure, and vegetation that could be easily uprooted by strong winds, it would be considered likely that the natural environment would offer little resistance to the hurricane forces and may even amplify them. It may be considered that the natural environment may act as a significant barrier between the hurricane forces and the built environment and as such may 'intervene' to lessen the final level of damage done to structures in the area. The example is perhaps exaggerated; however, is serves as an indication of the position of the natural environment as a 'buffer' zone between the hurricane forces described above and the built environment, which will be addressed shortly (Bryant, 1991).

Lastly, there is the set of built environment variables. This set of variables captures the ability of the built environment to resist the loads imposed by the hurricane and transmitted to the built environment via the natural environment which may have amplified or suppressed the damage potential. The first issue concerning the built environment has to do with the density of building stock. If residential structures are located close together on dense plots, there is greater potential for wind borne debris to transmit damage from one structure to the next. If plot sizes are large and houses are constructed further apart, this potential is reduced; however, the potential for dampening of the wind forces (since one structure may 'shield' another) is also reduced (Hartman, 2002). The second set of built environment criteria concern the actual constructed state of a structure. It is clear that the better constructed a structure is and the better it has been maintained, the greater its resistance will be to the forces of the hurricane and therefore the better its chance of survival and the total level of damage it will sustain should be lessened, all things being equal. Therefore, in total, the built environment set of variables will include factors such as plot density, the date of construction together with the building codes that have been enforced, the level of maintenance and the quality of construction workmanship (Burleson, 1994).

Damage mitigation of existing structures revolves around the three interconnected categories. This explains the basic rationale that underpins the conditions that affect the total damage level produced by the interactions between a clearly identifiable set of hurricane damage mechanisms, natural environment variables and built environment variables. This basic rationale is presented graphically in Figure 1.

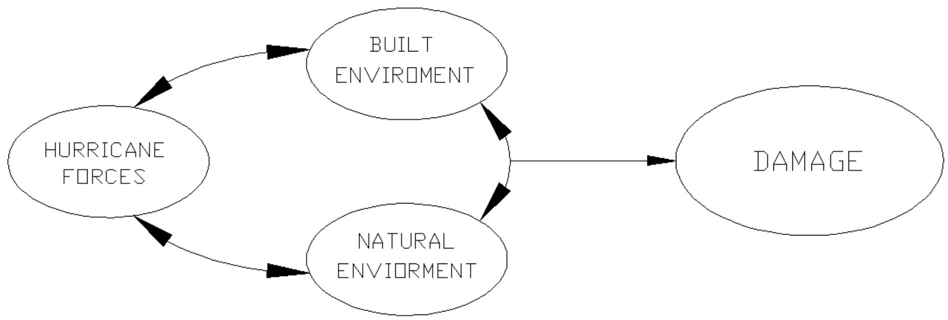

Figure 1: Basic Damage Interactions Model

Conclusion

The conditions and effects that produce damage to residential structures from hurricanes are varied and severe. The severity of the damage is determined by the interactions of the conditions reacting upon each other. The analysis of the literature has produced numerous models that predict the probable damage levels and document the actual devastation. The interactions were presented and compared showing the relationships between the identified conditions and the desired attributes. The sample evaluation presented show the extent of the comparisons between the available attributes. The detailed analysis of the identified mechanisms provides a detailed explanation to direct the mitigation efforts of a community. Circumventing damage prior to it occurring protects not only the owner's residences, but those surrounding the structure.

Damage does not necessarily occur from one factor, but an accumulation of factors that interact. The utilization of the one variable to explain another function or functions becomes necessary when examining data in retrospect to the occurrence of the hurricane. The extraction of information from available data provides an opportunity to determine the causal factors from a hurricane that impacts structures. The detailing of the mechanisms directs the mitigation process by identifying the interconnectivity of all parts and their subsets in a manner to create a holistic view of a structure.

The final results were assembled into a check-sheet that contractors can apply for planning and inspections of new and existing residential structures. The check-sheet is a composite list of the variables investigated through the literature review. The compiled check list of individual components for each of the three elements that interact to cause damage during a hurricane is provided in Appendix A.

Future research will employ the mitigation variables as a basis for the statistical analysis of hurricane damage. The quantification of the variables measured against the structural damage costs provides a means to determine which forces caused what type of damage. The proposed new model will evaluate a single event for significant damage variables. This data will provide planners with focal points for improving building codes and mitigation procedures.

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Appendix 1

Possible Hurricane Damage Impact Mechanisms

Hurricane Forces			
Erosion	Wind pressure	Storm surge	Tornados
Flooding	Flying debris	Riptides	Storm landfall
Scour	Dunes	Rain	Hydronic pressures
Hail	Category of storm	Wind speed – MPH	
Built Environment			
EIFS systems	Decking loss	Materials	Plywood
2x4 studs	2x6 studs	CMU wall	CDX sheathing
OSB sheathing	Sheetrock	Roof leaks	Moisture damage
Wood decay	Continual load path	Connections	Fastening devices
Pre-existing conditions	Deteriorating conditions	Corrosive deterioration	Continuous flow of strapping
Nailing patterns	Construction type	Nail shank size	Pneumatic fasteners
Construction practices	Nails missing members	Contractor education	Construction inspections
Nail shear	Structural envelope	Lateral loads	Lateral support
Uplift loads	Airborne debris	Building codes	
Proper design	Planning	Engineering (PE)	Builder’s quality
Installation procedures	Height of the structure	Value of the structure	Pile foundation depth
Foundation	Proximity to coast	Building condition	Sitting
Envelope breach	Redundant systems	Inline framing	Structural age
Building inventory change	Number of stories high	Upgrades to structure	Elevated mechanical equipment
Elevated electrical equipment	Base Flood Elevation	Structural reinforcing bars	Masonry wall damage
Wash at piles	Breakaway walls	Structural elevation	Foundation type
Pile	Crawl	SOG	Adding free board
Foundation settlement	Window and door openings	Wood under structure	Concrete under structure
Monolithic slab	Stem wall footing	Woodpile	Concrete pile
Wall system	Structural weight	Storm shutters	Storm sheathing
Shear walls	Wall cladding	Vinyl siding	Omission of rebar
Stucco exterior finish	Roof to wall connections	Impact resistant glazing	Loss of roof sheathing
3-Tab shingles	Inline framing	Roof system	Roof diaphragm
Roof pitch	Ridge vents	Clay tile roof	Metal roof
Gable ends	Hip roof	Engineered trusses	Commercial rafters
Breakage of openings	Architectural shingles	Stick built roof system	Loss of gable end sheathing
Roof drainage	Loss of shingles	Roof span	
Natural Attribute			
Tidal conditions	Community density	Ocean floor topography	Topography
Soil type	Foliage	Land cover	