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HURRICANE DAMAGE ASSESSMENT PROCESS FOR RESIDENTIAL BUILDINGS

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

Engineering Science

by
Carol C. Massarra
Bachelor, Tishreen University 1999
August 2012

To the spirit of my father, whom I never forget

To my mother, for being my smile

To Uncle Horace, for being another father for me

ACKNOWLEDGEMENTS

First, I want to thank my advisor, Professor Carol J. Friedland for her direction and guidance throughout my graduate education at Louisiana State University. I would also like to thank my thesis committee members: Professor Emerald Roider, Professor Ayman Okeil, and Professor Barry Keim, for their support. I am grateful to Shandy Ogea Heil, and Elizabeth Matthews, for their continuing help, and for being my best friends. I am forever thankful to my parents, Constantine and Daad, and to my brothers, Tony and Michel for their unwavering love. I also gratefully acknowledge support for this research by (1) the Louisiana Board of Regents (LA BoR) through the Pilot Funding for New Research (Pfund) Program of the National Science Foundation (NSF) Experimental Program to Stimulate Competitive Research (EPSCoR) under Award No. LEQSF (2011)-PFUND-232 and 2) the Industrial Specialty Contractors L.L.C. Professorship in Construction Management

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ABSTRACT

Assessing an affected area immediately after a severe natural hazard event and saving the resulting data are vitally important in any effort to reduce future economic losses from natural hazards. These data are used as a record of buildings performance and as a major component for statistical analysis and damage modeling studies. Since these data are used as input for these studies, the data must be assessed and collected in a scientific and standardized way. Despite this requirement, neither a systematic damage assessment process nor a standardized data collection protocol is currently available in the United States to ensure that the necessary, correct, and accurate damage and attribute data are collected, assessed, managed, and saved for hurricane events. In cases where these data are actually collected and assessed, they are lost soon after the event, rather than kept to longitudinally assess building performance in severe natural hazard events over the long term.

To make building damage assessment more effective and more accurate, a systematic process to standardize assessment data is needed. Additionally, to ensure that data are correctly assessed and collected, a standard protocol implemented in damage assessment activities is vitally needed. This study presents a proposed hurricane damage assessment process for residential buildings subjected to combined hurricane wind and flood loads, as well as a protocol that can be implemented into the process to standardize data collection and damage assessment.

The proposed process and protocol represent the first comprehensive building damage data assessment and collection process in the literature. Implementation of this process will aid in improving building data collection and assessment after hurricane events, which will result in improved data for a better understanding of building performance. Long-term implementation of this process will provide insight about the performance of multiple buildings subjected to various levels of hazard. This knowledge will facilitate reassessment of the level of loss experienced in

hurricane events, and will provide needed data for the development of enhanced performance-based design standards and building codes, which will lead to more reliable building performance.

CHAPTER 1: INTRODUCTION

A natural disaster occurs when an extreme meteorological, hydrological or geological event exceeds the ability of a community to withstand the event (Lindell & Prater, 2003). Extreme events are generally defined as uncommon and unexpected phenomena that exceed a defined scale. The severity of the event and whether the event is considered a disaster depends in large part on the vulnerability of the affected natural environment and human society. Extreme events can be short-term (e.g., temperature, precipitation, flood, and hurricane events) or long-term events (e.g., drought). Studying and analyzing extreme events are important not only to gain knowledge about the underlying physical phenomena, but also to improve our understanding of these events and their effects on comunities and infrastructure (Clark, 1985).

Although not all hurricanes are considered extreme events, recent hurricanes in the United States, especially in the past seven years, may certainly be considered natural disasters. Since Hurricane Katrina's landfall in 2005, the combined forces of wind and storm surge have significantly overwhelmed the capacity of single family residental buildings in Katrina (2005), Rita (2005), and Ike (2008). A better understanding of the effects of hurricanes on residential buildings is vitally important and strongly needed to reassess if the current level of building damage and economic loss are at acceptable levels.

To completely understand the impact of hurricanes on residential buildings, standard data are needed to comprehensively analyze building performance. To standardize the data, damage assessment and data collection must be prescribed through a systematic process and a standardized protocol. The depth of understanding of both the immediate aftermath and longer term impacts of hurricanes is in large part dependent on the amout of data collected. For these reasons, data relevant to individual structures, groups of structures, areas around structures, and the hazard event must be available. Aftermath data should not only be specific to the studied

subject area (e.g., data for an individual structure), but must also include environmental and other relevant data to help understand more global impacts.

One of the first processes that generally takes place after hurricane landfall is assessment. Assessment is conducted immediately after the occurrence of the hurricane to capture perishable data and to get an impression about the degree of damage and loss. “Perishable data” in this context refer to data about the building’s condition that are lost as clean up and reparie are conducted. In the case of buildings, an assessment is conducted either to estimate economic loss (i.e., loss assessment) or to estimate building damage (i.e., damage assessment). Traditionally, hurricane damage assessment is conducted through field reconnaissance, where damage information is visually captured and cataloged (Friedland, 2009). In the case of building damage assessments, assessments are generally conducted using either a rapid or detailed technique.

Data resulting from field assessments, regardless if they are rapid or detailed assessments, are generally not systematically categorized, not consistently evaluated, often cannot be queried, are not typically geo-located, and are not usually tied directly to the intensity of the hazard. The absence of these complete and reliable data on structures after hurricane events results in engineering practices and designs that are based on subjective observations, theoretical models, and trial-and-error, rather than on systematic processes (NIBS, 2007). Rapid, detailed, and accurate building assessments after a hurricane are necessary and very effective in capturing the full and clear picture of the damage. The resulting data not only capture the post-event condition of buildings, but also serve as an invaluable resource to improve understanding of design and construction deficiencies. These data may also help identify potential improvements in building design and construction practices. Additionally, these data are critical in validating increasingly complex damage models for the combined hurricane wind and flood hazard environment.

Inventory data (e.g., number of stories, construction type, foundation type) serve as valuable input for statistical studies and damage models (Friedland, 2009). Assessing community impacts from natural hazards is also important because the resulting information will help in determining the amount of external assistance needed, and will help in developing disaster impact projections (Lindell & Prater, 2003). To capture the most accurate and useful information, hurricane assessment tools must be developed with these end goals in mind.

Delays in collecting data may lead to incomplete information about damage conditions and may result in a failure to capture accurate damage information for buildings (Friedland, 2009). Furthermore, assessing buildings immediately after hurricane events and saving the data are vitally important in saving lives and reducing economic losses (Vatsavai et al., 2011) because capturing perishable data will help in better understanding the impacts of the disaster on the buildings and the community. Further, in most cases, these collected data are essentially lost after the event rather than kept for future use (NIBS, 2007), preventing their use in fully comprehensive outcomes. Preserving these data for future use is important because a record of the events is kept for use in recovery plans, theoretical planning, statistical evaluations, and damage modeling studies.

One of the most significant limitations in assessing these data is the difficulty in assessing multihazard damage. The methods used to assess wind damage are very different from the methods used to assess flood damage. Wind damage in the United States is assessed using different metrics (e.g., FEMA, 2006b; Fujita, 1971) that rely only on evaluation of physical damage (e.g., Hazus wind damage scale shown in Appendix), Table.1. However, flood damage is not measured using descriptions of physical damage, but rather is measured as a function of economic loss (FEMA, 2005; White, 1945). The only scale that is currently available to assess

damage to buildings subjected to combined wind and flood loads is the Wind and Flood Damage Scale, or WF Damage Scale (Friedland, 2009).

1.1 Problem Statement

The manner in which data are collected, assessed, managed, and archived after a natural hazard event builds the foundation for future building design and construction practices through engineering standards and building codes. This foundation is made possible through detailed information and knowledge of the performance of the built environment, which becomes available through the implementation of a systematic damage assessment process. Unfortunately, no existing process in the United States currently addresses the way data should be collected, assessed, managed, and archived after a hurricane event (i.e., a damage assessment process). The absence of a systematic damage assessment process that addresses these needs limits subsequent statistical and theoretical modeling and validation. The lack of data was cited as one of the most significant challenges to model and simulate infrastructure resilience after Hurricane Katrina (Steinberg et al., 2011).

1.2 Goal and Objectives

As a means to address the problems defined above, the goal of this research is to improve the quality and quantity of data that are collected after hurricane events by means of a systematic hurricane building damage assessment process for residential buildings. As a step towards achieving this goal, the following objectives are undertaken in this thesis:

- Examine existing literature to identify post-hurricane assessment practices and determine remaining gaps in existing practices.
- Propose a damage assessment process framework for residential buildings affected by combined hurricane wind and flood hazards.

- Propose a data collection and assessment protocol for single family dwellings as a primary component of the damage assessment process.
- Identify typical Gulf Coast building attributes through review of data previously collected in the aftermath of Hurricanes Katrina and Ike to develop a catalog of building attributes.

The proposed process will improve damage assessment as a whole by segmenting the assessment process into phases. Once implemented, the proposed standard protocol will standardize data collection and damage assessment by implementing a damage scale and a building attribute catalog. The resulting data will be organized, tied to the hazard, able to be queried, and easy to archive and evaluate. The process will also reduce data duplication among different users because the protocol proposes a standard methodology for data collection and assessment, facilitating the sharing of data.

1.3 Study Limitations

This study is specific to rapid damage assessments for wood framed single family residential structures subjected to combined wind and flood hazards in hurricane events. The methodology developed by this research is intended to be applicable to collect data and assess damage to residential buildings in coastal areas after hurricane events. The methodology has been designed specifically to be applied to recorded video and rapid field damage assessments and is based on post-hurricane data collected in the aftermath of Hurricanes Katrina (2005) and Ike (2008). As such, some influence of the construction and environmental properties found in coastal Mississippi (Katrina) and Galveston Island, Texas (Ike), is expected. Refinement of the damage assessment process and protocol is anticipated as more data are collected. In spite of these limitations, the underlying development of the damage assessment process and protocol methodology is applicable to other types of hurricane assessments (e.g., detailed damage

assessments), to other hazards (e.g., flood, earthquake, fire) and to other building types (e.g., commercial, institutional).

1.4 Organization of the Thesis

This thesis is organized into five chapters: (1) Introduction; (2) Literature Review; (3) Methodology; (4) Results; and (5) Summary, Conclusions, and Recommendations. Chapter 2 provides a literature review of the different types of assessments and data collection after disaster events. Chapter 3 outlines the methods used in developing the process phases, as well as methods used to develop the protocol and attribute catalog. Chapter 4 presents results of the study, including a damage assessment process framework, data collection and damage assessment protocol, and building attribute catalog. Chapter 5 presents the overall conclusions and recommendations resulting from this research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Natural hazards such as earthquakes, hurricanes, coastal inundation, and flooding cause thousands of deaths, severe damage, and billions of dollars in loss around the world every year. In the United States alone, approximately 18,000 hurricane deaths occurred between 1900 and 2006 from landfalling Atlantic or Gulf tropical cyclones with an average of 177 deaths per year (Blake et al., 2007). Hurricane Katrina alone caused at least minor damage for nearly 550,000 single family homes along the Gulf Coast, with over 300,000 single family homes destroyed (FEMA, 2006a). During these 106 years, the average annual losses from hurricanes in the United States were approximately $10 billion (Pielke Jr. et al., 2008). Average losses are expected to increase because of the steady increase of population in hurricane prone regions of the U.S. (Ahuja, 2011; Li & Ellingwood, 2006) and the expected increase in intensity and frequency of hurricanes due to climate change (Emanuel, 2005; Mirza, 2003; Webster et al., 2005). In 2003, the population of coastal counties had increased by approximately 33 million since 1980, reaching approximately 153 million people (Crossett, 2004). The population increase in these regions, coupled with the expected increase in storm frequency and intensity, points to an increased risk in potential hurricane losses.

Economic loss resulting from hurricanes events is just one way to quantify hurricane impacts. Understanding the causes, type, and magnitude of the underlying physical damage is also vitally important and needed to enhance the engineering understanding of the response of the built environment to anticipated hurricane events (Friedland & Gall, 2012). Research to improve the building design phases, construction practices, and mitigation strategies with consideration of multiple hazards is needed (Ahuja, 2011). Data resulting from post-hurricane

damage assessment are one of the most important components to improve understanding of the performance of the residential buildings after hurricane events.

This chapter presents a review of damage assessment for residential buildings after hurricane events. Within the context of the overall goal of the thesis, this chapter investigates how damage assessment and data collection are conducted after hurricane events, and investigates aspects that will facilitate a development of a systematic process for damage assessment. The first section of the chapter provides a review of post-hurricane damage assessment and the second section focuses on building damage assessments. The third section outlines documented data collection methodologies after hurricane events, and the fourth discusses components of a damage assessment process. Chapter 3 incorporates the findings of this literature review to develop a methodology for a damage assessment process and protocol for single family residential buildings damaged by hurricane hazards.

2.2 Post-Hurricane Assessment

Post-hurricane assessments are conducted to obtain information as a vital component of decision making about the effects of the hurricane on the area and residents (e.g., public health needs, housing damage). Evaluating hurricane effects on buildings is conducted to determine the damage resulting from the event, as well as to determine the economic loss caused by the event. An assessment conducted to determine the intensity of physical damage caused by the disaster to buildings and other infrastructure (e.g., residential buildings, commercial buildings, roads) is referred to as “damage assessment” (Jha et al., 2010), while an assessment conducted to estimate the economic obligation to return a physical damage condition to its prior undamaged state is referred to as “loss assessment” (Friedland, 2009).

Damage assessment was defined by Blalock (2011, p. 10) as “gathering of information from a defined area following an incident, event or series of events, on life and property.” Until the area

affected by the disaster is assessed, no decision about the impact of the disaster can be made. Complete assessment after a hurricane is extremely important in understanding the effect of the disaster on the affected areas because the assessment helps to establish the level of post-disaster damage, as well as the level of loss. This thesis focuses only on physical building damage that is observable during a field assessment, rather than economic loss, which is determined through economic calculations.

2.3 Building Damage Assessment

Building damage assessment is conducted after the occurrence of a disaster to estimate the degree of damage to building structures. Generally, building assessment is conducted using either a detailed approach (i.e., targeted focused methodology) or a rapid approach (i.e., fast area sweep methodology) (Kwasinski, 2011). Rapid damage assessment is used to capture a general impression of damaged structures, while detailed damage assessment is used to determine the specific detailed damage state for each part of a structure. Conducting a rapid building damage assessment can provide a general estimation of the number of affected homes (Jha, et al., 2010), and if more detailed information is needed, rapid assessments should be followed by detailed assessments. Accurate damage assessment after natural disasters (e.g., hurricanes) is vitally needed because of projected increases in economic losses and fatalities (Vatsavai, et al., 2011), as a result of the predicted increase in intensity and frequency of hurricanes caused by climate change, and because of population increases in hurricane prone regions of the U.S. (Li et al., 2012).

In rapid assessment, timely data assessment takes priority over the collection of detailed data (Jha, et al., 2010). In other words, timely perishable data are captured in rapid assessments, with the degree of accuracy and completeness of the data as principal tradeoffs. This stated limitation of a rapid assessment can be overcome by following with a detailed assessment to

improve the quality of the data. While decreased assessment time is a major advantage of rapid assessment, increased assessment time and delay in data collection are major tradeoffs for detailed assessments.

Figure 2.1 shows a qualitative difference between rapid and detailed building damage assessment. For a given amount of assessment time, application of the detailed damage assessment will result in fewer buildings assessed, but with greater time spent per building documenting a greater number of details. A rapid damage assessment would yield a larger quantity of assessed buildings, with less time collecting fewer details per structure.

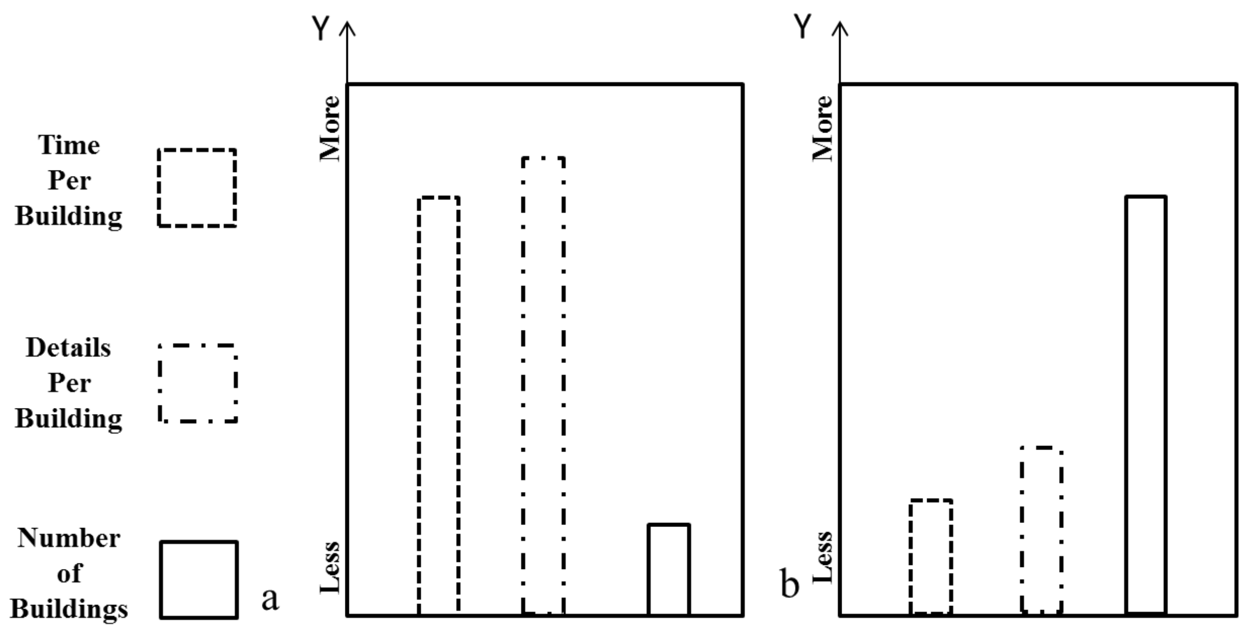

Figure 2.1 Comparison Between (a) Detailed Damage Assessment and (b) Rapid Damage Assessment

2.3.1 Rapid Building Damage Assessment

Rapid assessment takes place as soon as conditions allow survey teams to operate (Jha, et al., 2010).The purpose of a rapid damage assessment is to estimate the nature and magnitude of damage, and to quickly inspect and evaluate building conditions in the damaged areas after the

occurrence of a hurricane. Rapid assessment is the best method to capture perishable data, and to get an overall general understanding of the impacted area. Therefore; the timing of the assessment should ensure that immediate post-event damage conditions are preserved. Rapid building damage assessment is based on the observable conditions of the structure and not on detailed inspection of the structure's condition. Rapid building damage assessment relies on an exterior evaluation of the structure unless the structure's condition cannot be adequately viewed from the exterior. The major observed conditions that are used to evaluate the structure give a general and non-specific description of a structure's condition (e.g., totally collapsed, partially collapsed, minor, moderate). Additionally, the intensity of damage recorded on most damage assessment forms (e.g. ATC, 2004; FEMA, 2008), is generally an estimation of the percentage of damage. However, this percentage is not obtained using a defined scale or accurate measurements, but is based on personal judgment of the damage. Hence, different observers may record entirely different results. An example of the ATC-45 (ATC, 2004) rapid building damage assessment form is provided in Appendix Figure.1.

2.3.2 Detailed Building Damage Assessment

Detailed assessment generally takes place after two to four weeks after the occurrence of a disaster, to gather more detailed and reliable information for the affected area (Jha, et al., 2010).Through detailed damage assessment, estimation of loss value, and determination of the longer-term recovery and development requirements can be achieved (Planitz, 1999). Generally, a detailed assessment follows a rapid assessment to get more detailed reports for the impacted area (Jha, et al., 2010). Detailed building damage assessments are based on a visual inspection of the structure from the exterior and the interior. The assessment includes inspection of certain areas of the structure (e.g., corners, eaves, roof), evidence of wind uplift on the roof, and connection failure (e.g., roof to wall, foundation to wall). In addition, non-structural components

of the building (e.g., damage of balconies, decks, cladding damage) are also assessed as part of a detailed building damage assessment. Detailed assessments are used by ATC (2004) and by the Insurance Institution for Business & Home Safety (IBHS, 2011). This type of assessment includes very detailed assessment procedures for structural and non-structural components. An example of the ATC- 45 (ATC, 2004) detailed building damage assessment form is provided in Appendix, Figure.2.

2.4 Combined Wind and Flood Hurricane Damage Scales

Damage scales are generally used to evaluate the severity of building damage after the occurrence of a hazard event. Since hurricanes are events with coupled hazards (e.g., winds, tornados, storm surge, wave action and heavy rainfall), a combined damage scale should be used to assess damage to ensure all buildings are consistently evaluated. In spite of this, damage assessment methods have relied on hazard-specific wind and flood damage scales until Friedland (2009) developed the Wind and Flood (WF) Damage Scale to assess damage to residential buildings from combined wind and flood loads. This damage scale was developed based on the relationship between wind and flood physical damage and economic loss.

While the WF Damage Scale is the only scale used to assess combined physical damage to residential building, FEMA has recently released the Hazus 2.0 Coastal Surge Model (FEMA, 2011b) to estimate economic losses resulting from combined wind and flood loads. Another recent study also addresses economic losses resulting from the combination of wind and surge after hurricane events (Li, et al., 2012). These recent works do not describe physical damage, nor do they address the concept of an integrated damage scale. However, they indicate a desire within the scientific community for better understanding of the combined hurricane environment and the joint impacts of hurricane events.

2.5 Field Data Collection Approaches after Hurricane Events

After hurricane events, rapid and reliable information describing the nature, severity and magnitude of damage is needed to understand impacts of the event on communities and infrastructure "Data collection" in this document refers to the collection of information in the affected areas to document post-hurricane conditions, with data collection activities generally occurring after the occurrence of the event (Friedland, 2009). Data collection is a documentation procedure, while damage assessment is a decision making procedure, so differentiation between these two terms is needed.

The most commonly used post-hurricane data collection approaches are paper and pen, electronic, and the recorded video approaches. Data collection may be conducted alone or at the same time as the field damage assessment. When combined with damage assessment, data are collected in conjunction with decisions being made about the damage information. Data collection can also be conducted before damage assessment activities. In this case, data are collected by recording videos and pictures for the area, and then damage assessment is conducted in the office by reviewing these pictures and videos. Data are generally collected by following a certain protocol, which is a procedure that guides what to do and when, and how to collect data to ensure the quality of the data.

2.5.1 Paper and Pen Approach

In the paper and pen approach, the surveyor uses a paper and pen to collect data and to assess damage in the field, using either pre-made data collection forms or by taking notes on observations (Chiu & Wadia-Fascetti, 1999; Hecht, 1997). This approach requires double entries if the data are first collected on paper in the field and then transferred to a computer. Data included in an assessment form should cover all possible information that will be collected from the assessed area (Hecht, 1997). Either detailed or rapid assessments can be conducted with the

paper and pen approach. This approach is generally easy and fast to implement, but is time consuming to transfer all the information from paper data collection forms to the computer, and errors can be introduced while entering the data into the computers. Figure.3 in Appendix provides an example of a paper form used for earthquake vulnerability data collection (FEMA, 2002).

2.5.2 Electronic Approach

The electronic approach is more technologically advanced than the paper approach. In this approach, the assessor uses either a personal digital assistant (PDA), which is a small electronic device, or a portable or tablet computer that has assessment forms pre-loaded for the assessor to complete (Crandell & Kochkin, 2005; Hecht, 1997). This approach is faster and more accurate than the paper approach, and it saves time and enhances the quality of data because there is no need to re-enter the data into computer. Some flexibility is required in the electronic data form, as there may not be a means to enter data that may be different than the specific pre-loaded form. Either detailed or rapid assessments can be conducted using this approach.

2.5.3 Recorded Video Approach

The recorded video approach is the newest approach for aftermath data collection. In this approach, videos of the affected area are recorded by linking the videos to a Global Positioning System (GPS) (Figure 2.2) and then integrating the video into a Geographical Information System (GIS). This approach is particularly useful in the post-disaster environment and for recovery assessments. The approach provides long-term visual data storage, which can establish a baseline for later recovery monitoring (Curtis & Mills, 2012; Mills et al., 2010). Additionally, since recorded videos capture both buildings and surroundings, they can be reviewed again to obtain additional data. In the case of photographic records only, this is more difficult unless multiple photographs showing the general location are taken along with specific photographs

documenting building damage and attributes. In this approach, data are collected in the field, and the assessment is then conducted out of the field by watching the recorded videos and the still pictures derived from these videos.

a b

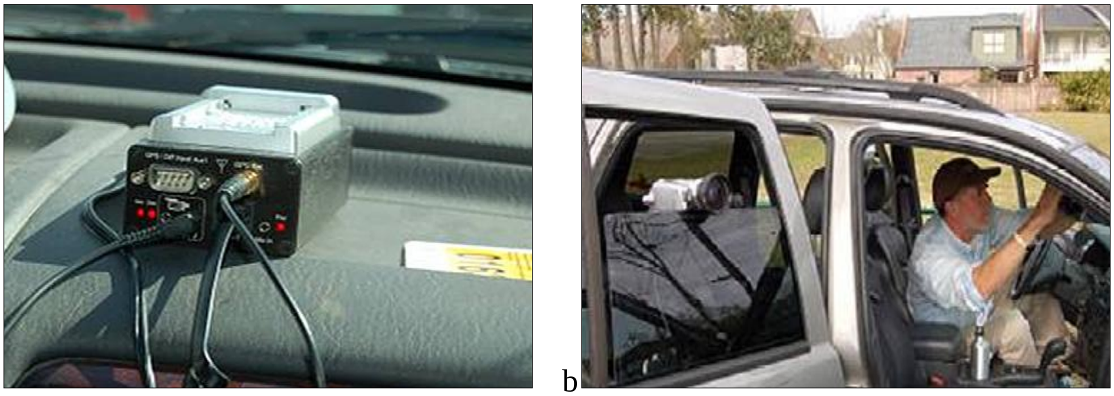

Figure 2.2 Recorded Video Approach (a) GPS Linked to Video Camera, (b) Mounted Video Camera (Mills, et al., 2010).

2.6 Damage Assessment Process

Damage assessment is a continuous process that begins immediately after the occurrence of a disaster and continues into and beyond the post-impact period (Drabek, 1991). A defined building damage assessment process helps in answering principle questions such as *What kind of structures failed and why? What caused the failure? How? What part of the structure experienced significant damage and why*? Kwasinski (2011) presented a process framework for performing systematic field damage assessments after a natural hazard event. Although this work was specific to information and communications technology network infrastructure, it is a relevant process that may be applied to other hazards and infrastructure classifications. The methodology divides the damage assessment process into four main steps – data collection, data examination, analysis, and reporting.

The first step, data collection, consists of two phases: 1) planning and preparation and 2) implementation. Planning and preparation begin when the disaster occurs, or in some cases,

before the occurrence of the disaster when there is a possibility to anticipate the time and location of the disaster (e.g., hurricane landfall). One of the most important aspects of this phase is to determine the sources of data (Kwasinski, 2011). The planning and preparation phase aims to define how to conduct the field investigation, identify specific sites to visit, organize the investigation, identify the type of data to be collected, and the data collection methodology.

The implementation phase starts after completing the planning and preparation phase. In the implementation phase, the damage assessment is conducted. The outcomes of the implementation phase include written records, photographs and/or videos (Kwasinski, 2011). After the data collection phase, the data are examined to extract relevant information from the field collected data. The data examination step is crucial to draw connections between damage and other important data that may not be available or obvious at the time of the field investigation. After data examination, results are analyzed to find the cause of damage and to understand what failed and what did not fail. The last step of this process is reporting. The report details all collected information and the processes used to collect the information, as well as the results from data analysis (Kwasinski, 2011). Photographs of the studied area (e.g., buildings) are also included in the report.

The process proposed by Kwasinski (2011) is the only process found in the literature review that addresses damage assessment from hurricane events through a defined process. The International Tsunami Survey Team (ITST) has also developed a field survey guide, primarily geared toward conducting international tsunami damage investigations (Dominey-Howes, 2012). The framework of the guide provides post-tsunami survey participants information on how to conduct post-tsunami field surveys by dividing the survey into three parts (before, during, and

after the field survey). These three parts address the logistic and preparation procedures that are needed to be considered before, during, and after deployments into affected areas.

Pre-field survey procedures summarize the needs before conducting the surveys, including coordinating with the host country, providing cultural awareness, incorporating different disciplines within the team that are conducting the survey, providing logistical issues (e.g., scheduling, travel accommodations, meals, currency), and providing translation, guide services, security, first aid, and insurance. Field survey procedures summarize operational issues for the team to consider while working in the affected country. The majority of this part focuses on communication among the survey team members, between the survey team and the host country representatives, and between the survey team and local people. Post-field survey procedures focus on the preparation of a written report in a form that can be used by the host country and the international research community. Although the process of the post-tsunami survey addresses the assessment in three steps (i.e., before, during, and after), the practices in these steps are primarily focused on preparation, and logistical issues, and do not address the practices needed for improved quality of data resulting from the damage.

2.7 Building Damage Assessment Protocol

A protocol is a detailed procedure that provides methods and metrics to measure building performance (Fowler et al., 2005). A primary research need that has been identified is the development of standardized data collection protocols to consistently document and quantify damage from hazard events (Chiu & Wadia-Fascetti, 1999). Data that are consistently collected over multiple events provide a direct insight into the generalized performance of buildings by occupancy. The development of a standard assessment protocol for data collection and damage assessment is consistently needed, regardless of the specific motivation behind a particular field reconnaissance. A consistent hurricane damage assessment protocol is not necessarily location or

event dependent. Therefore, while many pre-assessment activities are relevant to a specific damage assessment, efforts are needed to develop hurricane damage assessment protocols.

Systematic collection and categorization of these data in a secure storage location would serve to retain essential information about building performance in disaster events. A database of this type has been proposed by the National Institute of Standards and Technology (NIST) Disaster and Failure Studies Program through the Disaster and Failure Events Repository. The goal of this repository is to efficiently assess, collect, organize, and store consistent data from multiple disaster events, providing a history of building performance to inform design practices (NIST, 2011; Post, 2012). Implementation of damage assessment processes and protocols, such as the one proposed in this research, is essential to the successful development and implementation of this national repository.

2.8 Chapter Summary

The first objective of this thesis was to examine existing literature to identify post-hurricane assessment practices and determine remaining gaps in aftermath assessment practices. Results of this review revealed that several researchers have called for a standardization of data assessment and collection, practices especially when these data may be used for modeling studies. The absence of standardized data in the aftermath of hurricanes indicates a clear need to develop a defined building damage assessment process that addresses pre-assessment, assessment, and post-assessment practices for assessing hurricane damage data. Two examples of natural disaster damage assessment processes were found in the literature review. Both reviewed process identified that activities are required before, during, and after the assessments, but neither process identifies the data that are needed to be collected or the way to standardize these data. Further, although many studies were reviewed that reported assessment procedures and practices, none of the reviewed studies had implemented a standard protocol for damage

assessment and data collection that would support the development of consistent data after hurricane events. Therefore, the most salient gap identified through the review of the literature is to better define pre-assessment, assessment, and post-assessment activities, including the development of a standardized protocol for hurricane damage.

To address these identified gaps, Chapter 3 explores the methodology behind the development of new techniques for residential buildings damage assessment for combined hurricane wind and flood hazards. Specifically, the remainder of this thesis will focus on 1) proposing a damage assessment process methodology, 2) developing a data collection and assessment protocol, and 3) developing a building attribute catalog for typical Gulf Coast wood-framed single family dwelling.

CHAPTER 3: METHODOLOGY

3.1 Introduction

This chapter focuses on the methodologies used in the development of an overarching damage assessment process, which includes a standardized protocol for collecting and assessing residential building damage, as well as a building attribute catalog to support implementation of the protocol. In the overall context of the thesis, these three areas were identified in the literature review in Chapter 2 as significant gaps in current hurricane damage assessment practices for residential buildings. This chapter begins with definitions and differentiation of basic terms that are used throughout the remainder of the thesis. The chapter then outlines the rationale and methodology behind development of the damage assessment process, standard protocol, and residential building attribute catalog for Gulf Coast dwellings.

3.2 Definitions

Many terms are used to describe the components and activities related to post-hurricane assessments (e.g., damage scale, data collection, data assessment, standard protocol). Generally, "damage assessment" and "data collection" are both used to describe the damage assessment task with no differentiation between the terms, while a "damage scale" is the metric used to assign a degree of damage (e.g., moderate, severe).. Defining these terms is vitally important because they are not synonymous and will facilitate the discussion of required components in the damage assessment process. This chapter proposes the following definitions in the context of this study:

- Damage Scale: a scale that is used to rate the intensity of damage resulting from a natural hazard. In the case of a damaged building, this scale is based on the physical damage description of the structure's components with a range of damage states that are linked to each damage description.

- Data Collection: the recording of data (e.g., written, photographic, video, GIS layers) after a natural hazard, but not including damage evaluation. These data could be for the structure itself, the area surrounding the structure, or the hazard events (e.g., type of roof cover, soil type, wind speed, flood depth). Data should be collected according to a reference that standardizes the action of collection (e.g., attribute catalog)
- Damage Assessment: the decision about a change in a building's condition after a natural hazard according to a defined damage scale.
- Building Damage Assessment Protocol: a standardized procedure to collect data and assess damage to a building after a hurricane event. The protocol has an integrated damage scale to standardize damage assessment and an attribute catalog to standardize data collection.
- Systematic Damage Assessment Process: a defined procedure to guide damage assessment and data collection activities through continuous phases in three stages: pre-assessment, assessment, and post-assessment.

3.3 Proposed Building Damage Assessment Process

The overall goal of the proposed process is to improve building damage assessment in general and the data resulting from the damage assessment in particular by implementing standardized data collection and damage assessment. To achieve this goal, the proposed process is divided into pre-assessment, assessment, and post-assessment stages with a developed protocol to standardize data collection and damage assessment in the pre-assessment stage. As a component of the protocol, a building attribute catalog is also developed. Then the protocol is implemented in the assessment stage (Figure 3.1). Each stage of the proposed process consists of continuous phases that integrate the needs and current state-of-the-art activities identified in the literature review. The methodology for the development of the process was initially based on the

process proposed by Kwasinski (2011) and on the tsunami process (Dominey-Howes, 2012), but with additional phases and much greater definition of activities to support the development of consistent and useful residential hurricane damage datasets. The following bullets define the rationale behind the selection of these three stages and objectives of each of the stages.

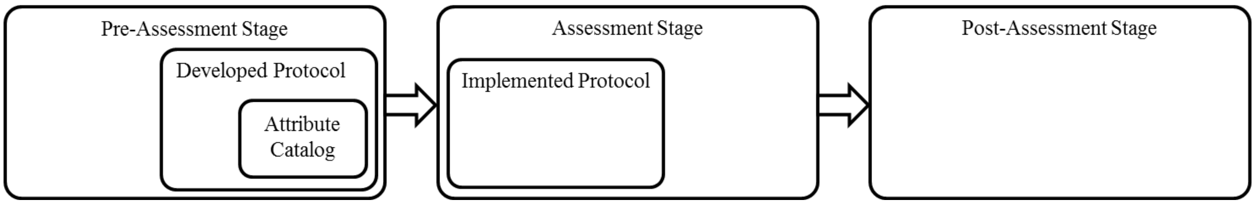

Figure 3.1 Hurricane Damage Assessment Process Theoretical Framework Showing Integration of Damage Assessment Protocol and Attribute Catalog

- Pre-assessment stage: Consistent damage data for buildings after hurricane events are needed (NIBS, 2007) and standardization of these data is vitally important (Chiu & Wadia-Fascetti, 1999). The foundation for consistent data lies in the preparation for the collection of data and assessment. The rationale behind the pre-assessment stage is to logistically prepare for assessment activities and to establish standard procedures to collect representative data.
- Assessment stage: Damage assessments should be conducted using defined methods and approaches (Crandell & Kochkin, 2005; Hecht, 1997). The rationale behind the assessment stage is to collect and assess the required data identified in the pre-assessment stage using a standardized protocol implemented through defined approaches.
- Post-assessment stage: Data developed from damage assessments need to be preserved for future use (NIBS, 2007), and the availability of data is a major challenge in modeling the consequences of disasters (Steinberg, et al., 2011). The rationale behind the post-assessment stage is to prepare the data for use in modeling studies through examination and analysis, and to ensure that data are usable in the future by archiving the assessment data.

3.3.1 Pre-Assessment Stage

To conduct field assessments that will produce meaningful and consistent results, the proposed phases of the pre-assessment stage are: 1) identify the data to be collected, 2) develop a standard assessment protocol for data collection and damage assessment, 3) perform pre-field planning, and 4) evaluate hazard or other data obtained prior to the assessment. Many of these phases are highly dependent both on the specific objectives of the planned assessment, and on the amount of data that are available prior to the field deployment.

3.3.2 Assessment and Post-Assessment Stages

To ensure exact and correct protocol implementation. The objective of the assessment stage is to implement methods to assess and collect data using the pre-defined assessment protocol. As detailed in the literature review, two damage assessment methods (rapid and detailed) and three data collection approaches (i.e., recorded video, paper and pen, electronic) are the most commonly used or documented. The proposed phases of the assessment stage are: 1) conduct the assessment through one of the defined methods and approaches and 2) record assessment results. The state-of-the-art practices identified in the literature review are integrated into the damage assessment process and the results are presented in Chapter 4. Significant improvements in the assessment stage were not identified as a major research need and are therefore not discussed in detail in this thesis.

To address the needs for preserving and sharing data after an assessment is conducted, the objectives of the post-assessment stage are to establish procedures to post-process the collected data. The proposed phases of the post-assessment stage are: 1) examine the resulting data to gain additional knowledge about the data, 2) conduct data analysis to better understand the assessed data, 3) archive the results of data assessment, data examination, and data analysis, and 4) report and share the assessed data among researches, engineers, government and local

agencies. Many of the post-assessment phases were identified based on the post-assessment procedures proposed by Kwasinski (2011). Although these phases have been identified as important components of the post-assessment process activities, much work remains in developing standard post-assessment analysis, archival, and sharing protocols. This topic is an area of significant future research and is therefore also not discussed in detail in this thesis.

3.4 Hurricane Damage Assessment Protocol and Subassembly Framework

This section focuses on the development of a rapid hurricane damage assessment protocol for single family dwellings, and the data and approaches that are used in the development of this protocol. A combined wind and flood damage scale has been identified in the literature review for incorporation into the proposed protocol the WF Damage Scale by Friedland (2009). To ensure standard data collection, a building attribute catalog is also proposed. The deliverable for the assessment protocol objective is a set of data collection forms that can be used in hurricane damage assessments for residential buildings. To develop the damage assessment protocol, the relevant data that will be collected in the assessment phase must be identified. Crandell and Kochkin (2005) suggested that both building attribute and damage data should be collected during an assessment. In addition to these two categories of data, two additional categories are identified for consideration: 1) data that describe surrounding physical (i.e., environmental) conditions and 2) data that describe the magnitude, direction, and duration of the hazards evaluated. Generally, the spatial extents and resolution of the environmental and hazard data will be much greater than the building scale, and much of these data will be collected or aggregated in a geospatial format (e.g., GIS shape file) and can be automatically queried to describe conditions at a specific building location. These data are referred to as “automatic” data, as obtaining information relevant to an individual building will likely be the result of an automatic query process for rapid assessments. Conversely, information relevant to the building itself,

namely the building attribute and damage data, must be assessed manually. Figure 3.3 depicts the four primary types of data identified and segregates them as manual or automatic data.

Figure 3.2 Rapid Residential Damage Assessment Data Categories and Assessment/Collection Methodologies

3.4.1 Subassembly Approach for Building Data

Because loads resulting from wind and flood hazards are not uniformly applied to a building, there is a need to consider the primary location of impact for each hazard (FEMA, 2011b). The wind hazard (i.e., wind pressure) is strongest on the roof, and decreases toward the ground (Figure 3.3). Conversely, flood hazards (i.e., hydrostatic, hydrodynamic, wave loads) primarily affect the lower part of the structure (e.g., foundation or lowest floor) and extend upward through the structure as the depth of flooding increases (FEMA, 2011b). Uncertainty is introduced as these two hazards interact; however, dividing the building into subassemblies aids in the assessment of building performance and also provides a natural segregation in the data assessed and collected in the aftermath of hurricanes.

A subassembly approach was used in the Hazus 2.0 combined hurricane and coastal flood model (FEMA, 2011b) to determine the combined direct economic loss resulting from a defined hurricane event. The subassembly methodology used in Hazus divides a residential building into seven subassemblies (e.g., foundation, below first floor, structure framing, roof covering, roof framing, exterior walls, and interiors). The Hazus methodology was specifically applied to

building loss; however, this same methodology is modified in the present study for implementation in the description of physical damage. The primary approach that is taken in the development of the damage assessment protocol is to identify the relevant subassemblies and the components of each subassembly, as well as the relevant data that will be collected during the assessment phase. This approach contributes to the overall goal of collecting data of improved quality and quantity that can be analyzed in the post-assessment phase to better understand building performance as a function of the subassemblies and as a whole unit.

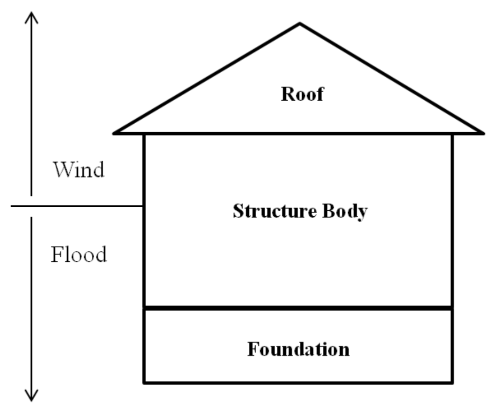

Figure 3.3 Generalized Locations of Primary Effects of Wind and Flood Hazards

To determine the subassemblies, two generalized types of single family dwelling structures are considered. The first structure is built on piles, and the second structure is built on slab or piers. Because the proposed protocol is being developed for rapid damage assessments, the subassemblies defined in the Hazus model are considered to be too detailed, and the building is simplified into more basic subassemblies. The structure on piles is divided into four main subassemblies: roof, structure body, foundation (piles), and below first floor (Figure 3.4a). The below first floor area includes items other than the foundation that are located below the first floor of the structure (e.g., mechanical equipment, stairways, breakaway walls). Structures on

slab or piers are divided into three main subassemblies: roof, structure body, and foundation (Figure 3.4b).

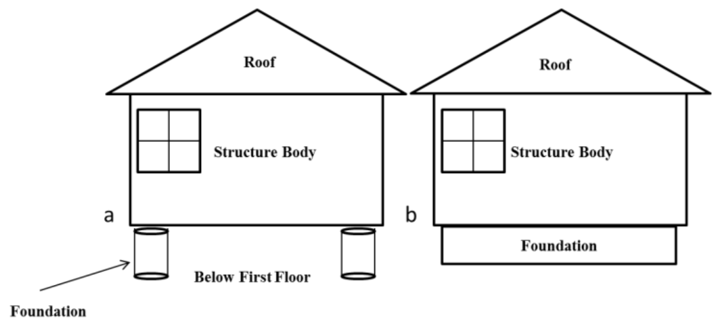

Figure 3.4 Typical Single Family Dwelling Subassemblies for a) Pile Structures and b) Slab or Pier Structures

The components that are considered for each subassembly are also simplified to allow aggregation of data to the primary building components that are likely to be assessed during a rapid assessment (Table 3.1). While these general components will be too coarse for a detailed damage assessment, they are identified as the most relevant components to consider during a rapid damage assessment. Further, they allow categorization of the general type and magnitude of damage to a subassembly and to the constituent components.

Table 3.1 Typical Building Components of Single Family Dwellings Organized by Subassemblies

Roof	**Structure Body**	**Foundation**	**Below First Floor**
Roof Cover Roof Sheathing Roof Structure	Wall Cladding Wall Sheathing Wall Structure Openings	Foundation Type Foundation Material	Mechanical Equipment Stairways Breakaway Walls

Although the identified building subassemblies and their components are simplified, much building attribute and damage data can be collected based on this generalized model. Data that may be collected during rapid assessments are discussed in the next section, including data that are relevant to the building subassemblies and components.

3.5 Building Attribute Data

The loads imparted by hurricane wind and flood hazards are considered environmental loads (ASCE, 2010). These loads may affect a building in the lateral direction, in the direction of gravity, in uplift, or through torsion. The premise behind building design is that a structure will withstand applied loads without failure. Failure is experienced when applied loads exceed a structure's capacity. Many building attribute factors influence the response of buildings subjected to these types of loads. These factors include the dead loads of the buildings themselves (i.e., self-weight), the live loads associated with the use and occupancy of the building (e.g., furniture), building characteristics that either increase or decrease the magnitude of the load that is imparted on the building, and building characteristics that increase or decrease the building's resistance.

An example of building characteristics that impact the load and resistance in wind hazards is roof slop. Flat roof is subject to high uplift forces and a high slope roof is more subject to lateral forces. Higher roof slope is also correlated with larger bending moments on roof members as a result of the perpendicular (i.e., normal force), which requires stronger connections along the full load path. Therefore, roof slope is a component that affects both the load imparted by the hazard, as well as the resistance of the building to the hazard. In the case of flood hazards, the magnitude of the load increases as pile diameter increases. However, larger pile diameters also are correlated with greater structural resistance. Therefore, pile diameter affects both the load imparted by the hazard, as well as the resistance of the building to the hazard. Identification of these attributes and their relevance on building performance will help future research efforts to correlate building attributes and damage for hurricane events.

Building attribute data for the structure as a whole and the four subassemblies identified as the most relevant observed data to be collected during a rapid field assessment are provided in

Table 3.2. A generalized delineation of the primary relevance for hurricane damage is also provided as affecting either the load or resistance side of the failure equation. Although mechanical equipment elevation was identified in Section 3.4, it is excluded from this listing as it is an operational consideration for occupancy of the building.

Table 3.2 Simplified Single Family Dwelling Attributes Segregated by Subassembly and Relevance for Hurricane Damage

Roof Subassembly		**Structure Body Subassembly**	
Load Side	**Resistance Side**	**Load Side**	**Resistance Side**
Roof Geometry	Roof Structure Type		Wall Frame Type
Roof Pitch	Roof Condition		Wall Cladding Type
Mean Roof Height	Roof Sheathing Type		Wall Sheathing Type
	Roof Cover Type		Percentage of Glass Area
	Roof to Body Connection		Type of Window Protection
	Roof Geometry		
	Roof Pitch		
	Mean Roof Height		

Foundation Subassembly		**Below First Floor Subassembly**	
Load Side	**Resistance Side**	**Load Side**	**Resistance Side**
Foundation Type	Foundation Type	Breakaway Wall Orientation	Breakaway Wall Orientation
Pile Shape	Foundation Material		Stairways
Pile Row Orientation (parallel or perpendicular to the shore line)	Foundation to Wall Connection		
Pile Diameter	Pile Row Orientation (parallel or perpendicular to the shore line)		
	Pile Diameter		

General Building Attribute Data			
Structure Type	Structure Condition	Structure Year Built	Exist of Carport or Canopy
Number of Stories	Structure Area and Perimeter	Type of Garage Door	Lowest Floor Height

3.6 Building Damage Data

To develop a standard protocol for residential buildings subjected to combined wind and flood hazards, a combined damage scale is needed to be implemented in the protocol. The WF Damage Scale (Appendix A: Friedland, 2009) has been identified to assess combined damage to residential structures resulting from wind and flood after hurricane events. The scale is chosen to

be implemented in the protocol for two primary reasons. First, it is the only existing scale that addresses physical damage mechanisms from both wind and flood. Second, the structure of the WF Damage Scale segregates damage descriptions into the subassembly components. While the WF Damage Scale does not address all of the components that were identified in Table 3.1, it provides much more delineation of damage by addressing components than at the subassembly level only.

To consider the non-uniformity of wind and flood, data for building damage description categories are determined based on the components of the subassemblies. By segregating damage at the component level, data can be analyzed to identify patterns in damage both from a particular hurricane event and across events. To implement the WF Damage Scale with the subassembly and component approach previously discussed, additional segregation of the damage descriptions in the WF Damage Scale is needed. However, as the intent of the WF Damage Scale is to assess combined damage resulting from wind and flood hazards, this segregation should preserve this intent. For this reason, the segregation was performed only for the damage description data (e.g., roof cover damage, cladding damage), and not for the damage state (e.g., WF-0, WF-1, and WF-2). Segregation of the wind and the flood damage data results in four damage data subcategories:

- Wind damage description data for the upper part of the structure
- Flood damage description data for the lowest part of the structure
- Joint damage description data for the structure body
- WF damage state data (e.g., combined damage scale)

The WF Damage Scale divides roof damage into three primary damage descriptions for the components: roof cover damage, roof deck failure, and roof structure failure. The structure

body is divided into four primary damage descriptions for the components: wall cladding damage, wall sheathing damage, wall structure failure, and opening damage. The foundation is divided into three primary damage descriptions: scouring of slab or pile, cracking of the slab, and racking of an elevated structure. Below first floor area has two damage descriptions: stairway damage and breakaway wall damage.

The description of wind and flood hazards on the structure body may be described either as combined damage or joint damage. Combined damage represents the union of all damage, and includes wind only damage, flood only damage, and the intersection (i.e., joint) damage (Equation 3.1), whereas joint damage represents areas that are affected by both wind and flood (Equation 3.2).

$$Combined\ Damage\ Description\ Data = Flood\ Damage\ Description\ Data \cup Wind\ Damage\ Description\ Data \quad (3.1)$$

$$Joint\ Damage\ Description\ Data = Flood\ Damage\ Description\ Data \cap Wind\ Damage\ Description\ Data \quad (3.2)$$

The foundation and area below first floor will generally not experience any wind damage, while the roof will not generally experience any flood damage. The structure body and below first floor subassemblies will have joint damage resulting from the effects of both wind and flood, in addition to the wind only and flood only damage description. Figure 3.5 shows a Venn diagram depicting the combined damage description, segregated as wind only damage, joint damage, and flood only damage for the joint damage description data. Table 3.3 shows the segregation of damage description data for wind only, flood only, and joint damage for the four subassemblies.

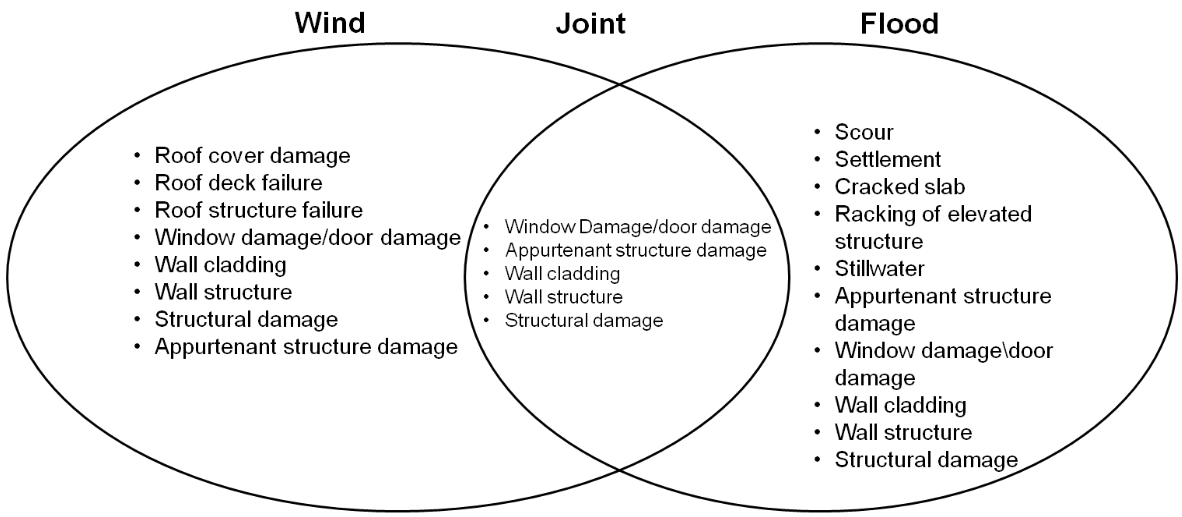

Figure 3.5 Venn Diagram for Wind and Flood Damage Description Data

Table 3.3 Simplified Single Family Dwelling Attributes Segregated by Subassembly and Damage Description Data

Wind Damage Description Data

Roof	Structure Body	Foundation	Below First Floor
Roof Cover Damage Roof Deck Failure Roof Structure Failure	Wall Cladding Damage Wall Sheathing Damage Wall Structure Failure Opening Damage	Not Applicable	Not Applicable

Flood Damage Description Data

Roof	Structure Body	Foundation	Below First Floor
Not Applicable	Wall Cladding Damage Wall Sheathing Damage Wall Structure Failure Opening Damage	Cracking of Slab Scour of Slab or Pile Lateral Movement Foundation Settlement Foundation Collapse Racking of Elevated Structure	Stairway Damage Breakaway Wall Damage

Joint Damage Description Data

Roof	Structure Body	Foundation	Below First Floor
Not Applicable	Wall Cladding Damage Wall Sheathing Damage Wall Structure Failure Opening Damage Appurtenant Structure Damage	Not Applicable	Appurtenant Structure Damage

3.6.1 Integration of WF Damage State Data

The WF Damage Scale divides damage state data into three categories: physical damage state, stillwater (i.e., flood only) damage state, and final combined damage state. The physical

damage state describes the observable damage resulting from wind or flood (including high velocity and wave action) to the following components: roof cover, windows and doors, roof deck, foundation, appurtenant structures, wall cladding, wall structure, roof structure, and overall structural damage. The damage states that describe this physical damage range from WF-0 to WF-6. The stillwater damage state depends only on the depth of flooding for slow rising floodwaters without velocity or wave action to cause physical damage. The damage states that describe stillwater flood damage range from WF-2 to WF-6 the shaded cells in Figure A.4 are used for classification only, whereas non-shaded cells provide typical values. The final combined damage state is the maximum between the physical damage state and the stillwater damage state. This assignment of damage states is preserved in the proposed protocol.

3.7 Environmental and Hazard Data

Environmental and hazard data provide specific information about the area surrounding the structure and storm-related data from the hurricane event. This information is invaluable for understanding the type and magnitude of storm damage sustained through examining the location of the site and understanding the recorded storm characteristics. For instance, sites located near the coast are more vulnerable to flooding or joint damage, whereas inland buildings are likely to sustain only wind related damages. Environmental and hazard data along with the attribute and damage data support statistical or engineering damage modeling (Friedland, 2009) Table 3.4 shows the minimum data that are expected to be collected after a hurricane event where damage assessment occurs. Some of these data (e.g.,1-minute wind speed, storm surge elevation, distance from storm track) were identified by Friedland (2009). Wind direction is identified as an important parameters; however, it is noted that the direction will shift during the cause of the hurricane, and the development of a framework to represent the wind direction parameter is recommended for development.

Table 3.4 Minimum Environmental and Hazard Data For Hurricane Events

Environmental Data	Hazard Data
Structure Location	Storm Track
Digital Elevation Model (DEM)	1-Minute Wind Speed
Location of Shore Line	3-Second Gust Wind Speed
Location of Major Debris	Wind Duration
Soil Type	Wind Direction
	Wave Speed
	Significant Wave Height
	Storm Surge Elevation

3.8 Building Attribute Catalog and Data Collection and Assessment Forms

The rationale of the building attribute catalog is to standardize data collection through definitions, descriptions, and photographs for the majority of building attributes. The catalog also details the manner in which some of the attributes are collected (e.g., mean roof height, number of stories). Information contained in the building attribute catalog was developed through review of datasets previously collected by LSU after Hurricanes Katrina and Ike and review of relevant literature for flood and earthquake damage assessments (FEMA, 2002; FEMA, 2011a; FEMA, 2011c). The building attribute catalog directly supports the proposed assessment protocol and is an integral part of data collection activities.

The deliverable output of the protocol development is a set of field forms for data assessment and collection. These forms are designed to capture manual data that must be assessed or collected for every building. Two separate forms are proposed to document the damage and building attribute conditions previously discussed. The forms follow the design suggested by Crandell and Kochkin (2005) and consist of two sheets with data recorded on both sides. Because of the large amount of data to be collected, basic building attributes are collected on one form and the damage assessment data are collected on the second. The forms have been designed to be completed quickly during a rapid field or office assessment.

3.9 Chapter Summary

This chapter presented the methodology of developing a damage assessment process for residential building subjected to wind and flood hazards, a standard protocol to standardize data collection and damage assessment, and a building attribute catalog to be implemented in the protocol to standardize data collection. The proposed process was divided into pre-assessment, assessment, and post assessment stages with multiple phases per stage. The intent of each of the stages and phases is to build upon previous activities to culminate in standardized, consistent, and detailed damage data from rapid assessments that can reliably support damage modeling and validation studies.

The development of a rapid hurricane damage assessment protocol for single family dwellings was presented as an integral component of the proposed damage assessment process. The protocol aims to standardize the damage assessment through the implementation of a damage scale and to standardize data collection through the implementation of a building attribute catalog. To develop the protocol, the WF Damage Scale was implemented into the protocol, and a subassembly approach was developed to better segregate building components and the type and magnitude of building damage. In addition to building attribute and damage data, environmental and hazard data were identified for collection after hurricane events. To standardize data collection, a methodology to create a building attribute catalog was developed. Finally, the damage assessment protocol and building attribute catalog are proposed for synthesis into two field data collection forms for use in rapid damage assessments. Chapter 4 presents the results of this thesis research.

CHAPTER 4: RESULTS

4.1 Introduction

The overall goal of this study was to improve the quality and quantity of data that are collected after hurricane events through development of a systematic and rapid damage assessment process for residential buildings. To accomplish this goal, four main objectives were defined. The first objective, which involved review of existing damage assessment practices, revealed a need for standardization of data assessment and collection. As discussed in Section 2.7, many of the existing practices that were reviewed had not implemented a standard protocol for damage assessment and data collection that would support the development of consistent data after hurricane events. Therefore, the remaining objectives were directed toward meeting these needs: 1) propose a residential damage assessment process to guide the damage assessment after hurricane events; 2) develop a standard protocol to standardize data collection and damage assessment; and 3) develop a building attribute catalog to identify typical Gulf Coast building attributes. The methodology behind these three objectives is presented in Chapter 3, and this chapter presents results of these three objectives.

4.2 Residential Building Damage Assessment Process Framework

The first of these objectives is to develop a residential building damage assessment process. The motivation behind the development of the damage assessment process is to improve the data resulting from post-hurricane damage assessments through standardized data collection and damage assessment. The development of the damage assessment process is presented in detail in Chapter 3 and is defined in three stages: pre-assessment, assessment, and post-assessment. The pre-assessment stage is vital to adequately prepare for assessment activities, identify available and needed data, and to establish standard procedures to collect representative data in the field (i.e., standard protocol). The assessment stage requires data collection through

the use of the standard protocol or through recorded video imagery, to assess hurricane damage sustained by residential buildings. The post-assessment stage includes examining, analyzing, archiving and converting data into digital form.

A detailed framework of the proposed residential building damage assessment process consists of ten major phases (Figure 4.1), which are distributed between the pre-assessment, assessment, and post-assessment stages. Each of the stages is briefly described in the following numbered list. Implementation of the residential building damage assessment process will improve the quality of data obtained from assessment, as well as simplify the assessment process, by organizing the various tasks in the three defined stages.

1. Identify Needed Data: Data identification and selection is performed, considering building attribute, building damage, environmental, and hazard data. Any relevant pre-event or pre-assessment data are identified, as well as data that are expected to be available later in the assessment process (i.e., hindcast model results).
2. Developed Standard Protocol: Standardized criteria for the assessment and collection of data are developed. Section 4.3 presents the proposed residential damage assessment protocol developed in this thesis. The proposed protocol implements the WF Damage Scale and an attribute catalog to aid in the hurricane damage assessment of residential buildings.
3. GIS Data Calculation: Computer-generated calculation is performed to associate relevant environmental and hazard data to study area location.
4. Pre-field Planning: Preparation for the field deployment is conducted. Planning tasks include: identifying impacted geographic locations, identifying and acquiring maps of the area to be assessed, and listing buildings to be assessed.

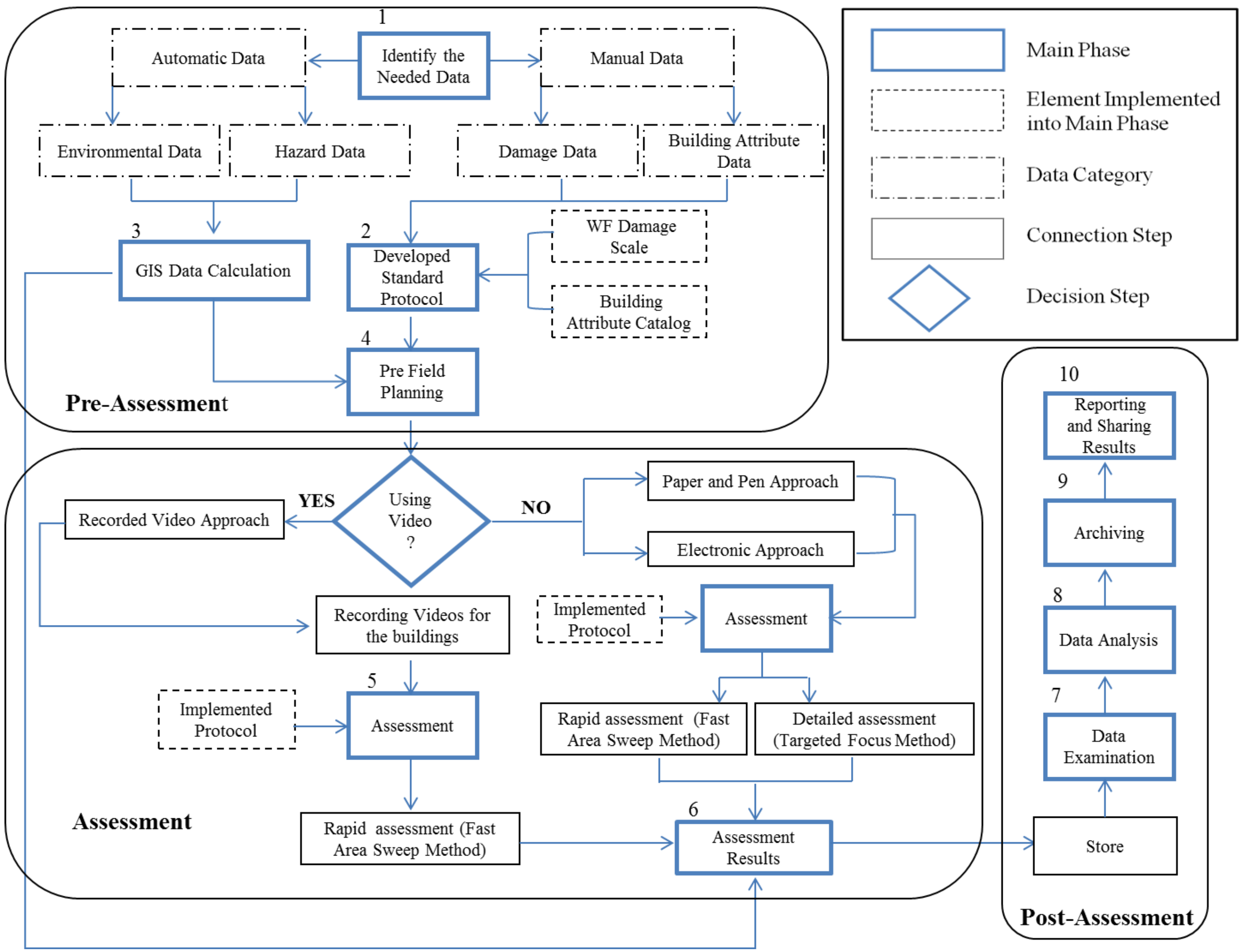

Figure 4.1 Framework of Residential Building Damage Assessment Process

5. Assessment: Assessment is the field activity of collecting data and assessing building performance. The proposed framework considers the recorded video paper and pen, and electronic approaches. If the recorded video approach is used, rapid assessment is conducted in the office. If the paper and pen or electronic approaches are used, rapid or detailed assessment is conducted in the field.
6. Assessment Results: Data resulting from the building assessment phase and the calculation of automatic data using GIS are gathered and compiled.
7. Data Examination: The assessed data are examined to extract relevant information that describes assessment results (e.g., percentage of roof damage, percentage of foundation damage, highest wind speed, significant flood depth).
8. Data Analysis: Data are analyzed to obtain a more comprehensive understanding of the damage conditions, and data are prepared for statistical analysis and validation of predictive damage models.
9. Archiving: Assessment data and data analysis results are saved in an organized database for future use and evaluation.
10. Reporting and Sharing Results: A written report is prepared that includes assessment results, photographs, analytical results, data categories, and methods used in conducting the assessment. Results and data are shared between groups (e.g., engineers, researchers, agencies).

4.3 Residential Damage Assessment Protocol

The second objective of the study was to develop a standard protocol that would standardize data collection during residential building damage assessments. This objective was accomplished by integrating the WF Damage Scale and a newly developed building attribute catalog into an assessment and data collection framework designed to improve the quality of data

resulting from building damage assessments. The rationale behind selection of the building attribute and damage data collected as part of the protocol is presented in detail in Chapter 3, and the results of the protocol are represented in the form of assessment data collection instruments, provided in Figures 4.2 and 4.3.

The Building Attribute Data Form (Figure 4.2) is used during the assessment phase to collect data describing general building attributes and building components by subassembly. The Building Attribute Data Form should be used with the aid of the building attribute catalog to standardize data collection through consistent use of terms. The building attribute catalog is discussed in additional detail in Section 4.4. The Building Damage Description Data Form (Figure 4.3) describes the type and magnitude of damage sustained. The Building Damage Description Data Form is used to record building damage description data and is used with the aid of the WF Damage Scale.

The assessment forms can be used by a structural engineer, an architect, or any individual familiar with building construction and design. The format of the forms is similar to those created by Crandell and Kochkin (2005) and the forms are designed to be filled out quickly during field or office assessments. The paper assessment forms are configured onto one sheet, with assessment criteria on both sides. Because of the large amount of data needed for both the building and damage assessments, two forms were created for each category. When using the paper forms, the data can be checked off or written directly onto the paper during the field assessment.

The forms were designed for implementation using the paper and pen approach. However, the data collection fields could be programmed onto a tablet computer for implementation with the electronic approach. An electronic implementation would allow the

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Louisiana State University
Combined Wind and Flood Hazards
Residential Buildings

Building Attribute Data Form

Assessor Name: ____________________
Event: ____________________ Date: __________
Location: ____________________ Zip: __________

Structure Number: ____________________

Photo Range: ____________________

Longitude: __________ | Latitude: __________

Building Type:
☐ Single Family ☐ Manufactured Home
☐ Duplex ☐ Multi Family/Hotel
☐ Non-Residential ☐ Other __________

Photograph of Building

Building Attributes

General	Structure Body
Number of Stories: ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ > 5	**Wall Frame/Construction Type:** ☐ Wood ☐ Masonry (Reinforced/Unreinforced) ☐ Steel ☐ Reinforced Concrete ☐ Cast-In-Place Concrete ☐ Unknown
Structure Condition: ☐ Excellent ☐ Good ☐ Fair ☐ Poor ☐ Unknown	**Cladding Type:** ☐ Siding (Wood/Vinyl) ☐ Brick Veneer ☐ Combined ☐ Unknown
Approx. Building Age: ☐ < 5 yrs. ☐ 5-10 yrs. ☐ 10-20 yrs. ☐ 20-40 yrs. ☐ 40-60 yrs. ☐ > 60 yrs.	**Wall Sheathing:** ☐ Plywood ☐ OSB ☐ Wood Plank ☐ Other ☐ Unknown
Garage: ☐ Yes ☐ No ☐ Detached ☐ Unknown	**Glass Area:** ☐ <5% ☐ 5-20% ☐ 20-40% ☐ 40-60% ☐ >60% ☐ Unknown
Garage Door Type: ☐ Single ☐ Double ☐ Unknown	**Window Protection :** ☐ Shutters ☐ Screens ☐ Laminated Glass ☐ Other ☐ Unknown
Carports/Canopies: ☐ Yes ☐ No ☐ Detached ☐ Unknown	

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Figure 4.2 Building Attribute Form

Continue Figure 4.2

Building Attributes

Foundation & Levels Below First Floor

Foundation Type:	☐ Slab on Grade	☐ Post and Beam	☐ Pile	☐ Stem Wall	☐ Unknown
Foundation Material:	☐ Wood	☐ Concrete	☐ CMU	☐ Brick	☐ Unknown

Lowest Floor Elevation (ft.): __________ **OR** **Height of Lowest Floor above Local Ground (ft.):** __________

Wall to Floor Connection Type:	☐ Anchor Bolts	☐ No connection (Pier and Beam only)		
	☐ Straps nailed	☐ Toe-Nail	☐ Unknown	
Breakaway Wall Orientation :	☐ Perpendicular	☐ Parallel	☐ Unknown	☐ None
Mechanical Equipment:	☐ On Ground	☐ Elevated	☐ Unknown	☐ None

Pile Supported Foundation Only

Pile Shape:

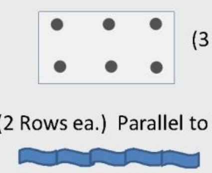
☐ Round

☐ Square

Pile Rows (Count #)

Parallel to Shore: __________

Perpendicular to Shore: __________



(3 Rows ea.) Perpendicular to Shore

(2 Rows ea.) Parallel to Shore

Roof Attribute

Roof Geometry:	☐ Gable	☐ Hip	☐ Flat	☐ Complex	☐ Unknown
Roof Cover Type:	☐ Asphalt Shingle		☐ Metal Panel		☐ Clay Tile
	☐ Wooden Shingle		☐ Built-Up Membrane		☐ Unknown
Roof Deck:	☐ Plywood		☐OSB		☐ Unknown
Roof Condition:	☐ Excellent	☐ Good	☐ Average	☐ Below Average	☐ Unknown
Roof to Body Connection Type:	☐ Clips	☐ Single Strap	☐ Double Strap	☐ Toe Nail	☐ Unknown
Roof Pitch:	☐ < 1:1	☐ 1:1	☐ > 1:1		

Mean Roof Height (ft.): ____________________

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Hurricane Damage Assessment
Louisiana State University
Combined Wind and Flood Hazards
Residential Buildings

Building Damage Description Data Form

Assessor Name: ____________________
Event: ____________________ Date: __________
Location: ____________________ Zip: __________

Structure Number: ____________________	
Photo Range: ____________________	
Longitude: __________	Latitude: __________

Photograph of Building

Building Damage Data

Wind Damage Description Data

Roof Cover:	☐ <2%	☐ 2-15%	☐ 15-25%	☐ 25-50%	☐ > 50%
Roof Structure:	☐ < 2%	☐ >2 - ≤15%	☐ >15 - ≤15%	☐ >50%	
Roof Deck:	☐ < 2%	☐ 1-3 panels	☐ >3 and ≤ 25%	☐ >25%	

Wall Cladding:
☐ Minor cladding damage with building wrap intact
☐ Moderate cladding damage that does not expose structure interior
☐ Wall cladding removed from building structure

Wall Sheathing Damage: ☐ Yes ☐ No | **Wall Structure Damage:** ☐ Yes ☐ No

Wall Opening Damage:
☐ < 2%
☐ one window, door, or garage door failure
☐ >one and ≤the larger of 20% and 3
☐ > the larger of 20% & 3 and ≤50%
☐ >50%

Damage State:
☐ WF-0 ☐ WF-1 ☐ WF-2
☐ WF-3 ☐ WF-4 ☐ WF-5
☐ WF-6

Wind Damage Comments:

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Figure 4.3 Damage Data Description Form

Continue Figure 4.3

Building Damage Data

Flood Damage Description Data

Wall Cladding:
- ☐ Minor cladding damage with building wrap in tact
- ☐ Moderate cladding damage that does not expose structure interior
- ☐ "Wash through" damage (wall cladding removed from building structure)

Wall Sheathing Damage: ☐ Yes ☐ No

Wall Structure Damage: ☐ Yes ☐ No

Wall Opening Damage:
- ☐ < 2%
- ☐ one window, door, or garage door failure
- ☐ >one and ≤the larger of 20% and 3
- ☐ > the larger of 20% & 3 and ≤50%
- ☐ >50%

Damage State: ☐ WF-0 ☐ WF-1 ☐ WF-2 ☐ WF-3 ☐ WF-4 ☐ WF-5 ☐ WF-6

Foundation Damage:
- ☐ None
- ☐ Scour with no apparent building damage
- ☐ Settlement
- ☐ Lateral Movement
- ☐ Overturning
- ☐ Cracked slab with visible deformation
- ☐ Racking of elevated structure
- ☐ Collapse

Flood Damage Comments:

Joint Damage Description Data

Wall Cladding:
- ☐ Minor cladding damage with building wrap intact
- ☐ Moderate cladding damage that does not expose structure interior
- ☐ Wall cladding removed from building structure

Wall Sheathing Damage: ☐ Yes ☐ No

Wall Structure Damage: ☐ Yes ☐ No

Wall Opening Damage:
- ☐ < 2%
- ☐ one window, door, or garage door failure
- ☐ >one and ≤the larger of 20% and 3
- ☐ > the larger of 20% & 3 and ≤50%
- ☐ >50%

Joint Damage Comments:

Damage State: ☐ WF-0 ☐ WF-1 ☐ WF-2 ☐ WF-3 ☐ WF-4 ☐ WF-5 ☐ WF-6

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assessor to enter or select the assessment criteria directly on the tablet screen. Development of an electronic data collection procedure that integrates the identified fields would result in reduced effort required in the post-assessment phase to convert the data to electronic format.

4.4 Building Attribute Catalog

The fourth objective of the study was to develop a building attribute catalog for residential buildings to standardize data collection during the building assessment. The building attribute catalog is an integral part of the damage assessment protocol and ensures consistent data collection for building attributes. The developed building attribute catalog provides descriptions, keys to identification, and photographic examples of the most common coastal residential building attributes. The catalog was developed by reviewing data from Hurricanes Katrina (2005) and Ike (2008) to determine the most common components and attributes. The implementation of the building attribute catalog ensures consistent identification and collection of building attribute data. The catalog is organized into four parts: roof attribute data, structure body attribute data, foundation attribute data, and general attribute data. Each part of the catalog includes a general definition supported with pictures for each of the attributes.

4.4.1 Roof Attribute Data

Roof Cover (Figure 4.4): The exposed exterior roof skin consisting of panels or sheets, attachments and joint sealants (NAWIC, 1996).

Figure 4.4 Example Photographs of Roof Cover Types

Roof Geometry (Figure 4.5): The primary roof shape or configuration

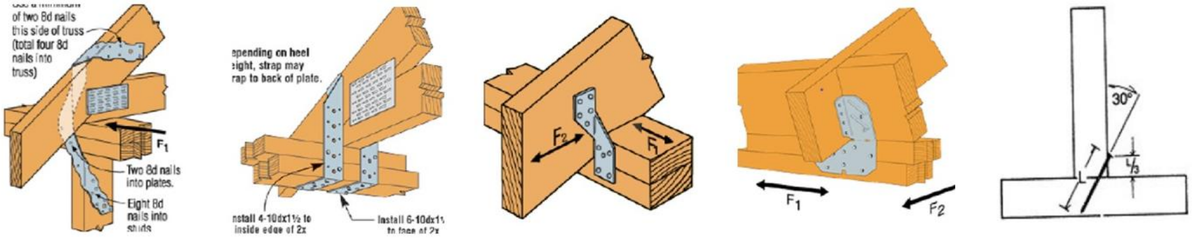
- Hip Roof: Type of roof where all sides slope downwards to the walls. Therefore, it is a roof with no gables or vertical sides
- Gable Roof: Type of roof with a vertical triangular portion of a wall between the edges of a sloping roof. This triangular portion is generally called a gable.
- Flat Roof: Type of roof that is horizontal or nearly horizontal.
- Complex Roof: Type of roof that has more than one part and each part has its own geometry (e.g., gable with hip).

Figure 4.5 Example Photographs of Roof Geometry

Roof Structure (Roof Truss): The structural support for a roof consisting, of braces, timbers or structural iron fastened together for strength and stiffness. (NAWIC, 1996)

Roof Condition: The condition of the roof is a subjective assessment of the pre-event condition of the roof and should be assessed independent of the hurricane.

Roof to Structure Body Connection (Roof to wall connection) (Figure 4.6): Connection between roof and wall elements. The connections are difficult to determine from an exterior view. To identify these connections, an inspection from the attic is needed unless they have been exposed by hurricane damage.



Single Wrap Double Wrap Single Clip Double Clip Toe Nails

Figure 4.6 Example Photographs of Roof to Wall Connection (IBHS, 2011)

Roof Sheathing (Figure 4.7): The boards or sheet material fastened to the roof rafters on which the roof covering is placed (NAWIC, 1996)

Plywood OSB Plank

Figure 4.7 Example Photographs of Roof Sheathing Types

Roof Pitch (Slope) (Figure 4.8): The angle that the roof surface makes with the horizontal plane (NAWIC, 1996). Roof pitch is measured as the vertical rise divided by the measured horizontal span.

<1:1 1:1 >1:1

Figure 4.8 Example Photographs of Roof Pitch

Mean Roof Height (Figure 4.9): The average of the roof eave height and the height to the highest point on the roof surface. For roof angles less than or equal to 10 degrees, the mean roof height is the roof eave height (ASCE, 2010).

Slopes greater than 10 degrees: Mean Roof Height = (A + B) / 2, but A = B + C, therefore; Mean Roof Height = B + (C / 2). Slopes less than 10 degrees: Mean Roof Height = B

Where
A=The height to the highest point on the roof surface; B= Roof eave height; C= Distance between the roof eave and highest point on the roof

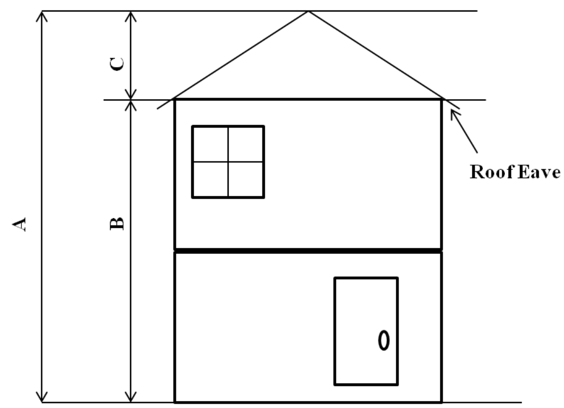


Figure 4.9 Illustration of Mean Roof Height Variables

4.4.2 Structure Body Attributes

Cladding Type (Figure 4.10): The surface material of a exterior walls (NAWIC, 1996).

Siding (Wood/Vinyl) Brick Veneer Combined (CMU/Vinyl)

Figure 4.10 Example Photographs of Cladding Types

Wall Sheathing (Figure 4.11): The innermost layer of the exterior wall covering connected to the structural frame (NAWIC, 1996).

Plywood | Oriented Strand Board (OSB) | Wood Plank

Figure 4.11 Example Photographs of Wall Sheathing

Opening Protection (Figure 4.12): The use of either laminated glass, shutters, screens, or structural wood panels to protect openings (e.g., windows, glazed doors) that are vulnerable to impact from wind borne debris (FEMA, 2009).

Shutters | Wood Panels | Screen | Laminated Glass

Figure 4.12 Example Photographs of Window Protection

Wall Structure Type (Figure 4.13): The primary materials used in wall structure construction (e.g., wood frame, reinforced or unreinforced masonry, steel frame, cast-in-place or pre-cast reinforced concrete. Wall structure type maybe difficult to assess if the structure is not exposed.

4.4.3 Foundation Attributes

Foundation Type: Type of substructure below the first floor or frame of the building.

Slab on Grade | Post and Beam | Pile | Elevated Floor

Figure 4.13 Example Photographs of Foundation Type

Foundation Materials (Figure 4.14): Type of materials used in the substructure below the first floor or the frame of the building.

Wood | Concrete | Concrete Masonry Units (CMU) | Brick

Figure 4.14 Example Photographs of Foundation Materials

Pile shape (Figure 4.15): The shape of pile foundation members.

Round Piles | Square Piles

Figure 4.15 Example Photographs of Pile Shape

Breakaway wall (Figure 4.16): “A wall that is not part of the structural support of the building and is intended through its design and construction to collapse under specific lateral

loading forces, without causing damage to the elevated portion of the building or supporting foundation system.” (FEMA, 2011a)

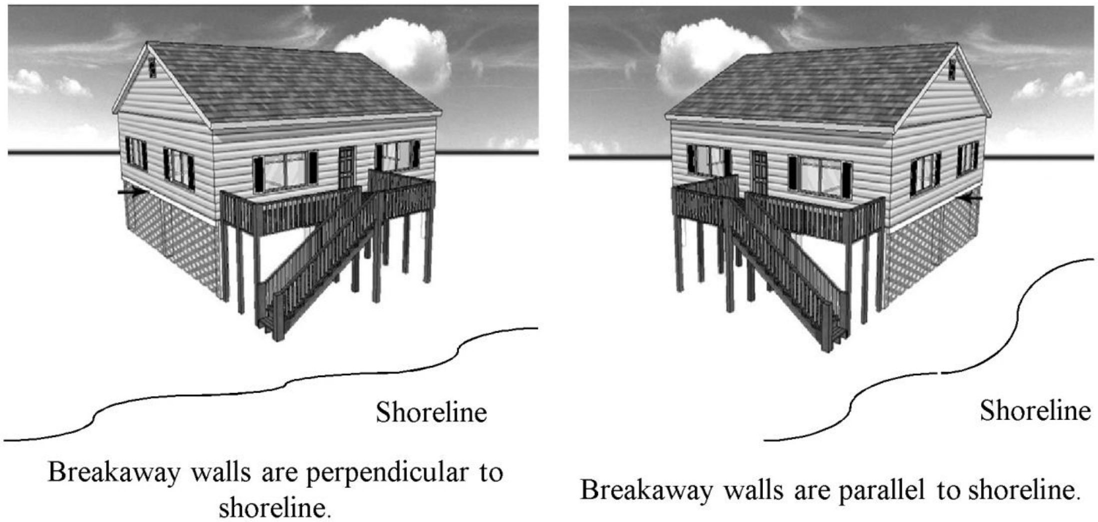


Figure 4.16 Example Photographs of Breakaway Wall Orientation (FEMA, 2011a)

4.4.4 General Attributes

Number of stories (Figure 4.17): A story is defined as a part of a building between any floor and the next floor or roof above. Counting the number of floors starts from the lowest elevation upward toward the roof. In a case where the building has several different roof levels or is constructed on a hill, as a rule, the largest number of floors is used, which is the number of floors counted on the downhill side to the roof (FEMA, 2002).

Figure 4.17 Example Photographs of Number of Stories

Garage Type (Figure 4.18): Single, double or detached garage

Detached Single Door Double Door

Figure 4.18 Example Photographs of Garage Types

Carports/Canopies (Figure 4.19): A carport is shelter for the automobile in conjunction with a dwelling, usually roofed, but not fully enclosed (NAWIC, 1996).

Carport Canopy

Figure 4.19 Example Photographs of Carports and Canopies

Wind- and Flood-Borne Debris (Figure 4.20): Commonly referred to as missiles that can be generated after hurricane.

Minor Debris Moderate Debris Severe Debris

Figure 4.20 Example Photographs of Wind- and Flood-Borne Debris Amount

Structure Condition: The condition of the structure is a subjective assessment of the pre-event condition of the roof and should be assessed independent of the hurricane.

Building Age: Identifying the age of the building is subjective and it is tied directly to design and construction type. The best source to determine the structure year built can be found in the drawings.

Lowest Floor Elevation (Figures 4.21, 4.22): The lowest floor elevation of the lowest enclosed area including a basement if present. An unfinished or flood-resistant enclosure, usable solely for parking vehicles, building access, or storage in an area other than a basement area, is not considered an enclosed area (FEMA, 2011a).

- 1 floor
- Slab-on-grade foundation

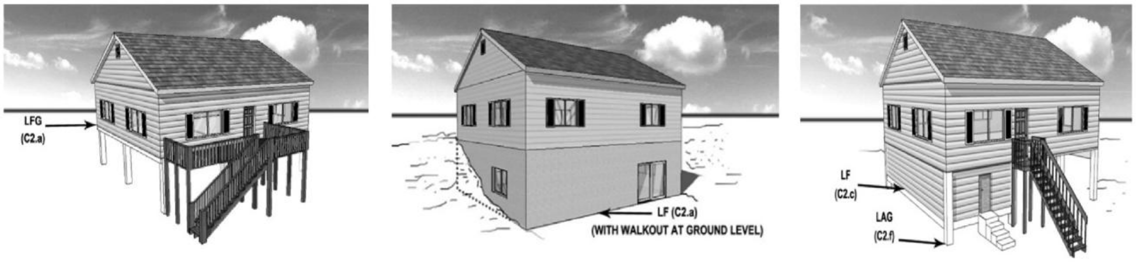
The lowest floor elevation is the top of the bottom floor

- 1 or 2 floors with attached garage
- Slab-on-grade foundation
- Garage is at lower elevation than the structure

The lowest floor elevation for a structures with a garage located at a lower elevation than the main is:

- Top of the bottom floor of the garage if garage does not have required openings and contains machinery or equipment.
- Top of finished floor or the structure otherwise.

Figure 4.21 Example Photographs of Lowest Floor Elevation for Un-Elevated Structure (FEMA, 2011a)



- 1- floor
- Elevated on piers, posts, piles, or columns

The lowest floor elevation is the top of the lowest elevated floor.

- 2 floors
- Lower floor is not below grade on all sides
- Principal use of the building is on the elevated floor

The lowest floor elevation is the top of the lowest floor.

- 2 floors (Bottom floor is considered as hanging floor)
- Elevated on piers, posts, piles, or columns

The lowest floor elevation is the top of the lowest floor.

Figure 4.22 Example Photographs of Lowest Floor Elevation for Elevated Structure (FEMA, 2011a)

Mechanical Equipment Elevation (Figure 4.23): The height of the equipment from the ground (e.g., HVAC system).

Ground Level Elevated

Figure 4.23 Example Photographs of Mechanical Equipment Elevation

4.5 Chapter Summary

The overall goal of the study was to improve the quality and quantity of data that are collected after hurricane events. A literature review of published damage assessment practices was presented in Chapter 2, and results and recommendations from this literature review are provided in Section 2.8. The second objective of this study was to develop a residential building

hurricane damage assessment process framework to describe the continuum of activities in the pre-assessment, assessment, and post-assessment phases that would lead to the development of consistent datasets. Overall, results of the final three objectives are designed to work in concert, as shown in Figure 3.1. The assessment process framework establishes the stages of the pre-assessment, assessment, and post-assessment phases. Within the pre-assessment phase, a standard protocol is identified for implementation in the assessment phase to ensure consistent damage assessment and data collection. The building attribute catalog is a key component of the protocol to ensure consistent collection of building attribute data. The standardized data that will result from a clearly defined process and protocol will eliminate data duplication and provide consistent data that can be used for damage model development and validation. The process and protocol are especially beneficial when there are multiple building assessors or teams of assessors by ensuring that all assessors follow the same procedures while conducting the assessment, producing consistent and reliable results. Ten key phases were identified, and are recommended for significant future research in the full development of a comprehensive damage assessment process.

The third objective was to develop a standard protocol to standardize data collection and damage assessment. This was achieved by the implementation of the WF Damage Scale to standardize damage assessment and the development of a building attribute catalog to standardize data collection. The tangible result of this objective was the development of two data collection instruments for building attribute and damage data. The developed forms are intended to be implemented using the paper and pen approach, but can also be integrated into an electronic data collection platform.

The fourth objective was to develop a building attribute catalog appropriate for Gulf Coast building characteristics. The building attribute catalog is an integral component of the proposed standard protocol and was developed through review of relevant literature and previous hurricane data. The catalog contains descriptions, photographs, and keys for successful identification of roof, structure body, foundation, and general attributes. The attribute catalog is intended for use with the protocol data collection forms to standardize building attribute results during an assessment, especially when multiple assessors participate. The attribute catalog is divided into four categories.

CHAPTER 5: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

The overall goal of this thesis was to improve the quality and quantity of assessed data after hurricane events by means of a systematic hurricane building damage assessment process for residential buildings with the implementation of a standard protocol. Four objectives were outlined to accomplish this goal: 1) to examine existing literature to identify post-hurricane assessment practices and determine remaining gaps in existing practices, 2) to propose a damage assessment process framework for residential buildings affected by combined hurricane wind and flood hazards, 3) to propose a data collection and assessment protocol for single family dwellings as a primary component of the damage assessment process, and 4) to identify typical Gulf Coast building attributes through review of data previously collected in the aftermath of Hurricanes Katrina and Ike in order to develop a catalog of building attributes. Chapter 2 presented the findings of the literature review and Chapters 3 and 4 presented the methodology and results, respectively, for the remaining three objectives. This chapter presents the conclusions of the study, as well as recommendations for future work in this topic.

The first objective of this thesis was to examine existing literature to identify post-hurricane assessment practices, and determine remaining gaps in aftermath assessment practices. A major finding of this review was that several researchers have called for a standardization of data assessment and collection, especially when these data may be used for modeling studies. The absence of standardized data in the aftermath of hurricanes indicated a clear need to develop a defined building damage assessment process that addresses pre-assessment, assessment, and post-assessment stages of the assessment. Further, although many studies were reviewed that reported assessment procedures, none of the methods found in the literature presented a systematic procedure that encompasses all of the reviewed building damage assessments

activities. Additionally, none of the published methods have considered the physical damage resulting from flood hazards, nor the combined effects of wind and flood hazards. A standard protocol for the assessment and collection of data after hurricane events has yet to be published that would support the development of consistent data after hurricane events.

Two damage assessment processes after natural disasters were found in the literature review. The first process was defined to assess damage for information and communication technology network infrastructures. Although the damage assessment was presented within a four-step process, no protocol to standardize the assessed data was implemented into the process, and the majority of the process dealt with the post-assessment stage. The second process was defined for tsunami field surveys. While this process did address the pre-assessment, assessment, and post-assessment stages, the emphasis in this document was on logistics and preparation practices within these stages.

Based on this review of the literature, it was determined that no existing methodologies are available to describe a systematic damage assessment process for residential buildings after hurricane events. Additionally, a standard protocol for data collection and damage assessment has yet to be published for hurricane events.

The second objective was to develop a building damage assessment process for residential buildings affected by combined wind and flood hazards that divided the assessment into the stages pre-assessment, assessment, and post-assessment stages, with the implementation of a standard protocol. The process was developed considering the desired qualities of a standardized dataset that could support building damage modeling and validation efforts after hurricane events. Chapter 3 presented the methodology upon which the process was built, and Chapter 4 presented the process framework.

The third objective of this thesis was to develop a protocol to standardize data collection and damage assessment through the implementation of a damage scale and attribute catalog. Chapter 3 presented the methodology upon which the protocol was built, and Chapter 4 presented the resulting protocol in the form of two data assessment and collection instruments. Implementation of the protocol into the process standardizes the assessment and collected data, which results in consistent data in the post-assessment stage.

The fourth objective of the study was to develop a building attribute catalog. Chapter 3 presented the methodology upon which the catalog was developed, and Chapter 4 presented the resulting catalog. The building attribute catalog includes definitions of building components, procedures for data collection, and supporting photographs, where applicable. Catalog utilization along with the assessment protocol forms will aid in the collection of more consistent data..

5.2 Conclusions

This study has resulted in the development of a detailed damage assessment process for single family residential buildings subjected to combined wind and flood hazard events. The study has allowed the implementation of the previously developed Wind and Flood (WF) Damage Scale in a damage assessment process to consistently document the combined effects of wind and flood damage for residential structures. Specific contributions include the development of an assessment protocol to standardize data collection and damage assessment; segregation of wind and flood damage in a way that the assessment could be applied to assess physical damage caused by wind only, flood only, and joint wind and flood; and identification of the relationship between the required phases in pre-assessment, assessment, and post- assessment stages that support the improvement of data quality.

The specific conclusions of this study are:

- A defined damage assessment process for combined hazards events enhances the efforts of government agencies, universities, and organizations to collect post-event data that will improve building design and construction, saving lives and reducing economic loss. The application of the damage assessment process will provide consistent assessment results even if the data are collected by different assessors, or in different locations or events.
- The application of the damage assessment process provides data that are useful in developing damage models and validating existing models.
- The process provides accessibility of more standardized data among groups (e.g., engineers, researchers) through the reporting and sharing phase.
- Application of the protocol reduces data duplication, because multiple assessors will follow a standard strategy in assessment, with the goal of more consistent assessment results.
- Application of the protocol provides data that can be automatically queried using GIS to describe the conditions at a specific building location, can be consistently documented and categorized, and easily retained to obtain essential information about building performance.
- Applying the building attribute catalog along with the building attribute form make the protocol applicable not only to an individual with a construction or engineering background, but also by any trained individual.

5.3 Recommendations and Future Research

Damage resulting from flood hazards has traditionally been expressed only as a function of economic loss, preventing the establishment of performance standards using existing data. Therefore, for hurricane events, significant research effort is needed in the post-assessment stage to examine and analyze assessment data to support the development of performance based standards, comprehensive hurricane building damage models, and changes in building codes.

While the information to support these decisions will come directly from the post-assessment stage, the damage assessment process builds upon each of the stages and phases identified. Without additional research in the pre-assessment, assessment, and post-assessment stages, information on the performance of buildings in the combined hurricane environment will not be available to support improvements in engineering and construction standards. This thesis presented the overall framework for a damage assessment process and the development of a standard protocol for residential buildings. Within this thesis, the assessment stage and the post-assessment stage were not discussed in detail and much work remains to develop a comprehensive damage assessment process that will result in the desired outcomes.

The major contribution of this research lies in the methodology that has been developed in the damage assessment process, protocol and building attribute catalog. Through the developed methodology, the results of this research are applicable to other occupancies and hazards.. Overall, the intent of the methodology is to lay out a research roadmap to fully develop standard processes and protocols for damage assessment and data collection. In this roadmap, much work remains to enhance the pre-assessment, assessment, and assessment stages.

Research in the pre-assessment stage will improve the protocol by defining additional subassemblies, which will enable integration between the newly defined subassemblies and the existing protocol subassemblies, resulting in additional data. Development of protocols for occupancies other than residential will require changes in the data needed for the building attribute categories and the damage description categories. Hazard and environmental data generally will not change based on occupancy, as the scale of these data is much larger than the building scale. Research on developing similar protocols for detailed damage assessment is also

needed In this case, additional attributes and damage description data that address interior and exterior attributes must be included in the protocol

Research on the use of technology for building assessments is also needed, which will serve to increase the ease and accuracy of the assessment stage. Research on hurricane joint hazard damage models is vitally needed, and the resulting assessment data will serve as invaluable input and validation data for these efforts. Research on developing shared archival data structures is perhaps one of the areas of most impact, as these types of data storage will provide data across multiple disciplines and groups.

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APPENDIX

Table.1 Hazus-MH Hurricane Model Residential Damage Scale (FEMA, 2006b)

Damage State	Qualitative Damage Description	Roof Cover Failure	Window/ Door Failures	Roof Deck	Missile Impacts on Walls	Roof Structure Failure	Wall Structure Failure
0	No Damage or Very Minor Damage Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	≤2%	No	No	No	No	No
1	Minor Damage Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	<5 impacts	No	No
2	Moderate Damage Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 20% & 3	1 to 3 panels	Typically 5 to 10 impacts	No	No
3	Severe Damage Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	Typically 10 to 20 impacts	No	No
4	Destruction Complete roof failure and/or, failure of wall frame. Loss of more than 25% of roof sheathing.	Typically >50%	>50%	>25%	Typically >20 impacts	Yes	Yes

Note: The shaded cells are used for classification, whereas non-shaded cells provide typical values.

ATC-45 Rapid Evaluation Safety Assessment Form

Inspection

Inspector ID: ______________________ Inspection date: ______________________

Affiliation: ______________________ Inspection time: ______________ ☐ AM ☐ PM

Areas inspected: ☐ Exterior only ☐ Exterior and interior

Building Description

Building name: ______________________

Address: ______________________

____

Building contact/phone: ______________________

Number of stories: ______________________

"Footprint area" (square feet): ______________________

Number of residential units: ______________________

Type of Building

☐ Mid-rise or high-rise ☐ Pre-fabricated

☐ Low-rise multi-family ☐ One- or two-family dwelling

☐ Low-rise commercial

Primary Occupancy

☐ Dwelling ☐ Commercial ☐ Government

☐ Other residential ☐ Offices ☐ Historic

☐ Public assembly ☐ Industrial ☐ School

☐ Emergency services ☐ Other: ______________

Evaluation

Investigate the building for the conditions below and check the appropriate column.

Observed Conditions:	Minor/None	Moderate	Severe
Collapse, partial collapse, or building off foundation	☐	☐	☐
Building significantly out of plumb or in danger	☐	☐	☐
Damage to primary structural members, racking of walls	☐	☐	☐
Falling hazard due to nonstructural damage	☐	☐	☐
Geotechnical hazard, scour, erosion, slope failure, etc.	☐	☐	☐
Electrical lines / fixtures submerged / leaning trees	☐	☐	☐
Other (specify) ______________	☐	☐	☐

☐ See back of form for further comments.

Estimated Building Damage (excluding contents)

☐ None

☐ >0 to <1%

☐ 1 to <10%

☐ 10 to <30%

☐ 30 to <70%

☐ 70 to <100%

☐ 100%

Posting

Choose a posting based on the evaluation and team judgment. Severe conditions endangering the overall building are grounds for an Unsafe posting. Localized Severe and overall Moderate conditions may allow a Restricted Use posting.

☐ **INSPECTED** (Green placard) ☐ **RESTRICTED USE** (Yellow placard) ☐ **UNSAFE** (Red placard)

Record any use and entry restrictions exactly as written on placard: ______________________

____

____

Number of residential units vacated: ______________________

Further Actions Check the boxes below only if further actions are needed.

☐ Barricades needed in the following areas: ______________________

____

☐ Detailed Evaluation recommended: ☐ Structural ☐ Geotechnical ☐ Other: ______________

☐ Substantial Damage determination recommended

☐ Other recommendations: ______________________

____

☐ See back of form for further comments.

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Figure.1 Rapid Damage Assessment Form (ATC, 2004)

ATC-45 Detailed Evaluation Safety Assessment Form

Inspection

Inspector ID: ______________ Inspection date: ______________

Affiliation: ______________ Inspection time: __________ ☐ AM ☐ PM

Final Posting
from page 2

☐ Inspected
☐ Restricted Use
☐ Unsafe

Building Description

Building name: ______________

Address: ______________

____

Building contact/phone: ______________

Number of stories: ______________

"Footprint area" (square feet): ______________

Number of residential units: ______________

Type of Building

☐ Mid-rise or High-rise
☐ Low-rise multi-family
☐ Low-rise commercial
☐ Pre-fabricated
☐ One- or two-family dwelling
☐ Other: ______________

Primary Occupancy

☐ Dwelling
☐ Other residential
☐ Public assembly
☐ Emergency services
☐ Commercial
☐ Offices
☐ Industrial
☐ Other: ______________
☐ Government
☐ Historic
☐ School

Evaluation

Investigate the building for the conditions below and check the appropriate column. There is room on the second page for a sketch.

	Minor/None	Moderate	Severe	Comments
Overall hazards:				
Collapse or partial collapse	☐	☐	☐	______
Building or story lean or drift	☐	☐	☐	______
Fractured or displaced foundation	☐	☐	☐	______
Structural hazards:				
Failure of significant element/connection	☐	☐	☐	______
Column, pier, or bearing wall	☐	☐	☐	______
Roof/floor framing or connection	☐	☐	☐	______
Superstructure/foundation connection	☐	☐	☐	______
Moment frame	☐	☐	☐	______
Diaphragm/horizontal bracing	☐	☐	☐	______
Vertical bracing	☐	☐	☐	______
Shear wall	☐	☐	☐	______
Nonstructural hazards:				
Parapets, ornamentation	☐	☐	☐	______
Canopy	☐	☐	☐	______
Cladding, glazing	☐	☐	☐	______
Ceilings, light fixtures	☐	☐	☐	______
Stairs, exits, access walkways, gratings	☐	☐	☐	______
Interior walls, partitions	☐	☐	☐	______
Mechanical & electrical equipment	☐	☐	☐	______
Elevators	☐	☐	☐	______
Building contents, other ______	☐	☐	☐	______
Geotechnical hazards:				
Slope failure, debris impact	☐	☐	☐	______
Ground movement, erosion, sedimentation	☐	☐	☐	______
Differential settlement	☐	☐	☐	______

Continue on page 2

Figure.2 Detailed Damaged Assessment Form (ATC, 2004)

Continue Figure.2

ATC-45 Detailed Evaluation Safety Assessment Form — Page 2

Building name: ______________________ Inspector ID: ______________________

Sketch

Make a sketch of the damaged building in the space provided. Indicate damage points.

Estimated Building Damage
(excluding contents)

- ☐ None
- ☐ >0 to <1%
- ☐ 1 to <10%
- ☐ 10 to <30%
- ☐ 30 to <70%
- ☐ 70 to <100%
- ☐ 100%

Posting

If there is an existing posting from a previous evaluation, check the appropriate box.

Previous posting: ☐ INSPECTED ☐ RESTRICTED USE ☐ UNSAFE Inspector ID: __________ Date: ______

If necessary, revise the posting based on the new evaluation and team judgment. *Severe* conditions endangering the overall building are grounds for an Unsafe posting. Local *Severe* and overall *Moderate* conditions may allow a Restricted Use posting. Indicate the current posting below and at the top of page one, whether the posting has been revised or not.

☐ **INSPECTED** (Green placard) ☐ **RESTRICTED USE** (Yellow placard) ☐ **UNSAFE** (Red placard)

Record any use and entry restrictions exactly as written on placard: ______________________

Number of residential units vacated: ______________________

Further Actions

Check the boxes below only if further actions are needed.

☐ Barricades needed in the following areas: ______________________

☐ Engineering Evaluation recommended: ☐ Structural ☐ Geotechnical ☐ Other __________

☐ Substantial Damage determination recommended

☐ Other recommendations: ______________________

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Rapid Visual Screening of Buildings for Potential Seismic Hazards

FEMA-154 Data Collection Form

HIGH Seismicity

Address: ____________________

____________________ Zip ____________

Other Identifiers ____________________

No. Stories ____________ Year Built ________

Screener ____________ Date ____________

Total Floor Area (sq. ft.) ____________________

Building Name ____________________

Use ____________________

Scale:

PHOTOGRAPH

OCCUPANCY			SOIL	TYPE						FALLING HAZARDS			
Assembly Commercial Emer. Services	Govt Historic Industrial	Office Residential School	Number of Persons 0 – 10 11 – 100 101-1000 1000+	A Hard Rock	B Avg. Rock	C Dense Soil	D Stiff Soil	E Soft Soil	F Poor Soil	☐ Unreinforced Chimneys	☐ Parapets	☐ Cladding	☐ Other: ______

BASIC SCORE, MODIFIERS, AND FINAL SCORE, S

BUILDING TYPE	W1	W2	S1 (MRF)	S2 (BR)	S3 (LM)	S4 (RC SW)	S5 (URM INF)	C1 (MRF)	C2 (SW)	C3 (URM INF)	PC1 (TU)	PC2	RM1 (FD)	RM2 (RD)	URM
Basic Score	**4.4**	**3.8**	**2.8**	**3.0**	**3.2**	**2.8**	**2.0**	**2.5**	**2.8**	**1.6**	**2.6**	**2.4**	**2.8**	**2.8**	**1.8**
Mid Rise (4 to 7 stories)	N/A	N/A	+0.2	+0.4	N/A	+0.4	+0.4	+0.4	+0.4	+0.2	N/A	+0.2	+0.4	+0.4	0.0
High Rise (> 7 stories)	N/A	N/A	+0.6	+0.8	N/A	+0.8	+0.8	+0.6	+0.8	+0.3	N/A	+0.4	N/A	+0.6	N/A
Vertical Irregularity	-2.5	-2.0	-1.0	-1.5	N/A	-1.0	-1.0	-1.5	-1.0	-1.0	N/A	-1.0	-1.0	-1.0	-1.0
Plan irregularity	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
Pre-Code	0.0	-1.0	-1.0	-0.8	-0.6	-0.8	-0.2	-1.2	-1.0	-0.2	-0.8	-0.8	-1.0	-0.8	-0.2
Post-Benchmark	+2.4	+2.4	+1.4	+1.4	N/A	+1.6	N/A	+1.4	+2.4	N/A	+2.4	N/A	+2.8	+2.6	N/A
Soil Type C	0.0	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4
Soil Type D	0.0	-0.8	-0.6	-0.6	-0.6	-0.6	-0.4	-0.6	-0.6	-0.4	-0.6	-0.6	-0.6	-0.6	-0.6
Soil Type E	0.0	-0.8	-1.2	-1.2	-1.0	-1.2	-0.8	-1.2	-0.8	-0.8	-0.4	-1.2	-0.4	-0.6	-0.8

FINAL SCORE, S

COMMENTS

Detailed Evaluation Required

YES NO

* = Estimated, subjective, or unreliable data
DNK = Do Not Know

BR = Braced frame
FD = Flexible diaphragm
LM = Light metal

MRF = Moment-resisting frame
RC = Reinforced concrete
RD = Rigid diaphragm

SW = Shear wall
TU = Tilt up
URM INF = Unreinforced masonry infill

Figure.3 Paper Form Data Collection (FEMA, 2002)

Damage State	Qualitative Wind Damage Description	Qualitative Surge/Flood Damage Description	Roof Cover Damage	Window/ Door Damage	Roof Deck Failure	Foundation Damage	Appurtenant Structure Damage	Wall Cladding Damage	Wall Structure Failure	Roof Structure Failure	Structural Damage	"Stillwater" Flood Depth
WF-0	No Damage or Very Minor Damage Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof cover, with no or very limited water penetration.	No Damage or Very Minor Damage No floodwater impacts the building.	≤2%	No	No	No	No	No	No	No	No	None
WF-1	Minor Damage Maximum of one broken window, door or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	Minor Damage Breakaway walls or appurtenant structures (staircases carports, etc.) damaged or removed without physical damage to remaining structure. No floodwater impacts the building.	>2% and ≤15%	One window, door, or garage door failure	No	Slab, pile scour with no apparent building damage	Yes, without damage to building	Minor cladding damage with building wrap intact	No	No	No	None
WF-2	Moderate Damage Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	Moderate Damage Some wall cladding damage from floodborne debris or high velocity floodwater. Breakaway walls or appurtenant structures (staircases carports, etc.) damaged or removed with physical damage to remaining structure.	>15% and ≤50%	> one and ≤ the larger of 20% & 3	1 to 3 panels	Yes	Yes, with damage to building	Moderate cladding damage that does not expose structure interior, building wrap not intact	No	No	No	> 0 ft and <2 ft (one story) or <5 ft (two+ stories)
WF-3	Severe Damage Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	Severe Damage Removal of cladding from "wash through" of surge without wall structural damage.	>50%	> the larger of 20% & 3 and ≤50%	>3 and ≤25%	Yes	Yes	"Wash through" damage	No	No	No	>2 ft (one story) or >5 ft (two+ stories)
WF-4	Very Severe Damage Complete roof failure and/or, failure of wall frame. Loss of more than 25% of roof sheathing.	Very Severe Damage Failure of wall frame, repairable structural damage to any portion of the building or cases of unrepairable structural damage, not to exceed 25% of the building plan area.	Typically >50%	>50%	>25%	Cracked slab with visible deformation	Yes	Yes	Yes	Yes	Any repairable structural damage or ≤25% unrepairable damage	>10 ft
WF-5	Partial Collapse House shifted off foundation, overall structure racking, unrepairable structural damage (structure still partly intact).	Partial Collapse House shifted off foundation, overall structure racking, unrepairable structural damage to > 25% of the building plan area. Structure is still partly intact.	Typically >50%	>50%	>25%	Racking of elevated structure	Yes	Yes	Yes	Yes	Unrepairable structural damage (>25%)	>10 ft
WF-6	Collapse Total structural failure (no intact structure).	Collapse Total structural failure (no intact structure).	Typically >50%	>50%	>25%	Yes	Yes	Yes	Yes	Yes	Total structural failure	>10 ft

Note: The shaded cells are used for classification, whereas non-shaded cells provide typical values.

Figure.4 Combined Wind and Flood Damage Scale (Friedland, 2009Friedland, 2009)

VITA

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