The thesis of Yingzhe You was reviewed and approved* by the following:

Ali M. Memari  
Professor of Architectural Engineering and Civil Engineering  
Hankin Chair of Residential Building Construction  
Thesis Advisor  

Aly M. Said  
Associate Professor of Architectural Engineering  

Konstantinos Papakonstantinou  
Assistant Professor of Civil Engineering  

Patrick Fox  
Professor of Civil Engineering  
Head of the Department of Civil Engineering  

*Signatures are on file in the Graduate School
ABSTRACT

Hurricanes can cause extensive damage to the building and the envelope systems of commercial buildings as documented over the past several decades in the United States. This study focuses on improving the performance of commercial buildings and minimizes losses caused by hurricane hazards. For this reason, the study intends to develop a better understanding of the performance of glass panels as building envelope that helps in performance design methodology.

The objective of this study is to make contributions to the Performance-Based Engineering (PBE) design based on fragility information developed from actual hurricane reports. The fragility curves for the failure of glass panels of building envelope caused by wind-borne debris (WBD) give the loss for the exterior of the building, which leads to immediate damage, while the fragility information of wind-driven rain (WDR) through the broken glass panels provides the loss the interior of the building.

The approach that will be followed or developed as appropriate can be used in the more practical application of Performance-Based Hurricane Engineering that can result in mitigating building envelope losses due to hurricane effects.
TABLE OF CONTENTS

List of Figures...........................................................................................................................................vii
List of Tables ...............................................................................................................................................ix
Acknowledgements ....................................................................................................................................x

Chapter 1 Introduction ..........................................................................................................................1
  1.1 Background information .................................................................................................................1
  1.2 Objective ........................................................................................................................................2

Chapter 2 Literature Review ...............................................................................................................4
  2.1 Introduction ....................................................................................................................................4
  2.2 Hurricane damage report ...............................................................................................................4
    Hurricane Katrina ...........................................................................................................................5
    Hurricane Ike ....................................................................................................................................8
  2.3 Impact of shingle missiles on glazing ............................................................................................12
    Experimental Laboratory Test Configuration .............................................................................13
    Test materials ...............................................................................................................................15
    Failure status determination ........................................................................................................16
    Impact procedure ........................................................................................................................16
    Experiment results ........................................................................................................................17
  2.4 Summary ......................................................................................................................................20

Chapter 3 Research approach ..........................................................................................................22
  3.1 Damage caused by WBD ..............................................................................................................23
  3.2 Damage caused by WDR ..............................................................................................................23
  3.3 Performance-based hurricane engineering design and cost estimate of repair .............24

Chapter 4 Fragility function development methodology, PBD approach and WDR study ......25
  4.1 Review of fragility development method .....................................................................................25
  4.2 Development of fragility functions .............................................................................................26
  4.3 Wind-driven rain research ...........................................................................................................29
    WDR definitions and parameters ...............................................................................................30
    Rain Admittance Factors .............................................................................................................31
    WDR intrusion .............................................................................................................................33
4.4 Performance-based engineering (PBE) ................................................................. 34
4.5 PBE methodology ................................................................................................. 35
4.6 Summary ................................................................................................................. 36

Chapter 5 Fragility information for WBD based on lab tests ...................................... 38
  5.1 Fragility functions and curves development ......................................................... 38
  5.2 Limitations of lab experiment .............................................................................. 40
  5.3 Summary ................................................................................................................. 41

Chapter 6 Fragility information for WBD based on actual hurricane damage ............ 43
  6.1 Case study of WBD using hurricane report ......................................................... 43
  6.2 Fragility information of WBD using hurricane report ......................................... 45
      Case 1 ......................................................................................................................... 45
      Case 2 ......................................................................................................................... 46
      Case 3 ......................................................................................................................... 47
      Case 5 ......................................................................................................................... 49
  6.3 Fragility development of WBD using hurricane report ........................................ 51
      Damage state ........................................................................................................... 51
      Assumptions ............................................................................................................ 51
      Development ........................................................................................................... 52
  6.4 Summary ................................................................................................................. 55

Chapter 7 Fragility information for WDR based on actual hurricane damage ............ 57
  7.1 Fragility information of WDR using hurricane report ........................................... 57
      Case 1 ......................................................................................................................... 58
      Case 2 ......................................................................................................................... 58
      Case 3 ......................................................................................................................... 59
      Case 5 ......................................................................................................................... 60
  7.2 Fragility development of WDR using hurricane report ......................................... 62
      Development of breakage information ...................................................................... 62
      Development of water intrusion information ............................................................. 64
  7.3 Summary ................................................................................................................. 66
Chapter 8 Repair Cost........................................................................................................67
  8.1 Repair cost of the exterior of the building.................................................................67
  8.2 Repair cost of the interior of the building.................................................................69
  8.3 Case study using fragility information......................................................................70
Chapter 9 Summary and Conclusions............................................................................72
References.......................................................................................................................77
LIST OF FIGURES

Figure 1. Area sustained glazing damage in downtown New Orleans, Louisiana.............5
Figure 2. View of glazing damage of T1 – T3 and S4.................................................6
Figure 3. Close-up view of façade of S4....................................................................6
Figure 4. Mid-rise building damaged by aggregate from BURs....................................7
Figure 5. JP Morgan Chase Tower and JP Morgan Chase Center...............................8
Figure 6. Northwest façade glazing damage on JP Morgan Chase Center...............9
Figure 7. Office damaged in the JP Morgan Chase Center.......................................10
Figure 8. Glazing damage in Chevron Center Area.................................................11
Figure 9. Chevron Center glazing damage...............................................................12
Figure 10. Wooden box (left) and glazing support frame (right)...............................13
Figure 11. Shingle missile launcher...........................................................................14
Figure 12. Glass breakages during the test...............................................................15
Figure 13. Research plan flowchart...........................................................................22
Figure 14. Wind-driven rain.......................................................................................31
Figure 15. Rain deposition factor of the tall building (>10, HW>>1).........................33
Figure 16. PBEE methodology flowchart..................................................................36
Figure 17. Fragility curves for glass panels..............................................................40
Figure 18. Hyatt hotel damage after Hurricane Katrina............................................43
Figure 19. Hyatt hotel damage condition generated by AutoCAD............................44
Figure 20. 15-story building damage after Hurricane Katrina....................................45
Figure 21. Case 1 generated by AutoCAD.................................................................46
Figure 22. Case 2 generated by AutoCAD.................................................................47
Figure 23. 13-story building damage after Hurricane Katrina....................................48
Figure 24. Case 3 generated by AutoCAD.................................................................48
Figure 25. Medical office building damage after Hurricane Ivan..................................................49

Figure 26. Case 5 generated by AutoCAD. ..................................................................................50

Figure 27. Fragility curves based on case study. .........................................................................54

Figure 28. Damage to different parts of Case 1. ..........................................................................58

Figure 29. Damage to different parts of Case 2. ..........................................................................59

Figure 30. Damage to different parts of Case 3. ..........................................................................60

Figure 31. Damage to different parts of Case 5. ..........................................................................61

Figure 32. Percentage of different parts of building envelope system.................................63
LIST OF TABLES

Table 1. Test specimen matrix ................................................................. 17
Table 2. Threshold momentum for various glass specimens ....................... 18
Table 3. Glass breakage velocity .............................................................. 19
Table 4. Fragility data for selected window glass specimens ...................... 38
Table 5. Probability of failure of different cases ....................................... 51
Table 6. Fragility data for WBD ............................................................... 54
Table 7. Probability of failure for different parts of building facade ............... 62
Table 8. Fragility data for WDR ............................................................... 63
Table 9. Percentage of each part of the building ....................................... 65
Table 10. Repair cost breakdown for the window glass .............................. 68
Table 11. Probability of failure for case study .......................................... 70
Table 12. Repair cost for each predetermined damage degree ..................... 71
Table 13. Damage area for each part of the building envelope .................... 71
Table 14. Water intrusion in each part of the building envelope ................... 71
ACKNOWLEDGEMENTS

First, I would like to thank my parents for all their support and encouragement that helped me throughout the course of this study. I would also like to thank my advisor, Professor Ali M. Memari for his suggestions. This research could not have been completed without his guidance.
Chapter 1

Introduction

1.1 Background information

Hurricanes have always caused extensive property damage, mainly to the envelope systems of residential and commercial buildings in coastal cities with better documentation of such damages in the past several decades. While damage to residential buildings has usually been more extensive due to the type of construction (i.e., wood-frame structure with siding and shingles as the exterior skin of the envelope) and the much larger number of residential buildings compared to commercial buildings, this study is focused mainly on commercial buildings. Acceptable structural and nonstructural systems performance would mean injury to occupants should be avoided, but it is also desirable to minimize damage with economic consequences. In particular, building envelope components such as glazing system can be very expensive to replace (FEMA 757_ch5). According to recent reports (FEMA 757, FEMA 549), for commercial buildings located in center business areas (downtowns), most of the damage under hurricane conditions is due to non-structural building components damage, such as damage to glazing systems and claddings. Damage types can be divided into two parts, which are immediate damage and long-term damage. For immediate damage, all losses occur instantly due to direct wind pressure, flying debris impact, or rain water intrusion. Physical damages to building envelope including broken glass in windows or curtain walls and building cladding damage may be followed by water intrusion through broken glass, which can cause further damage to building interior. Long-term damage including water absorption by building envelope components will likely cause more serious problems after some time if not repaired properly.
In order to improve the building envelope system performance of commercial buildings and minimize losses due to hurricanes, it is necessary to have a better understanding of fragility information for building envelope systems under hurricane conditions. Since the overall repair cost estimation is to be considered, not only repair cost due to the immediate damage but also the cost due to potential long-term effects should be accounted for.

1.2 Objective

The main objective of this study is to develop a better understanding of the performance of glazing systems as a building envelope system type under real hurricane conditions that will result in prediction and minimization of losses caused by hurricane hazard. By generating fragility data for envelope systems made up of different materials from FEMA report and other resources, it is possible to develop the framework for consideration of building envelope damage that can be used for performance-based hurricane design. In order to measure the damage or loss of the building in hurricane condition, two types of damage, including material breakage and water intrusion in building, need to be determined.

This study presents a review of damage reports due to hurricanes that have occurred in the past few decades in the United States to get a better understanding of the damage first in Chapter 2. Experimental studies related to wind-borne debris (WBD) impact on glass panels are used for fragility curves development, with the testing procedures and data resulting from tests described in Chapter 2. More cases based on FEMA reports related to WBD are described in Chapter 2; these cases are also used for WDR study. Chapter 3 presents the research approach in this study. Chapter 4 presents a review of the methodology of fragility development used in this study; the previous research on WDR and PBE is also discussed in the chapter. The fragility information based on lab tests is developed in Chapter 5, where the limitation of lab test data is
also explained. Chapter 6 and Chapter 7 illustrate the generation of data from actual hurricane reports and the development of fragility information for WBD and WDR, respectively. Chapter 8 discusses the repair cost development using fragility information for WBD and WDR, and ends with a case study.
Chapter 2

Literature Review

2.1 Introduction

In this chapter, review of some literature on past hurricane damage investigations, building envelope materials failure, and relevant tests carried out on envelope components will be presented. The literature review will then help to identify relevant knowledge gaps and obtain the available data for this research.

2.2 Hurricane damage report

Federal Emergency Management Agency (FEMA) Mitigation Assessment Teams (MAT) conducts explicit investigations after significant hurricane events and publishes their reports as FEMA reconnaissance reports on FEMA website. The reports normally include characteristics of hurricanes, photos of typical buildings that failed during hurricane and description of damaged buildings, which are good sources of data for damage analysis.

Coastal regions that have approximately 3 trillion dollars’ worth of infrastructure and about half of the total population of the United States of America usually sustain severe damage each year due to the hurricane impact (Nation Science Board, 2007). Several significant hurricanes have occurred in the United States over the past few decades resulting in extensive damage. For example, Hurricane Andrew (1992), Hurricane Katrina (2005), Hurricane Ike (2008), Hurricane Sandy (2012), Hurricane Matthew (2016) and Hurricane Harvey (2017) have all been powerful hurricanes that not only resulted in damage to buildings and agriculture systems, but also have caused hundreds of injuries or casualties (FEMA 757). As a representative of other
reports, this chapter reviews two of those hurricane reports to give a better understanding of hurricane damage and the loss caused by hurricanes.

**Hurricane Katrina**

Hurricane Katrina that occurred in August 2005 was one of the costliest natural disaster in the history of the United States (Amadeo, 2017). The total damage is estimated to be $108 billion. Defined as Category IV storm, Hurricane Katrina gust speed at landfall reached 140 mph, and the hurricane eye passed 50 miles east of New Orleans (FEMA 549_ch5).

Several buildings in downtown New Orleans, Louisiana had extensive damage on building façade, and the reason was mainly wind-borne debris impact.

![Figure 1. Area sustained glazing damage in downtown New Orleans, Louisiana.](image)

Buildings in the area shown in Figure 1 sustained severe damage to glazing systems. The wind directions in this area were primarily north and west, and the estimated wind speed was 105 mph.
Building S4 in Figure 2 was an office building and experienced significant glazing damage. Close-up view of Building S4 is shown in Figure 3.
The close-up view of the north façade (windward side) of Building S4 shown in Figure 3 (left) and Figure 3 (right) illustrates the west façade (windward side) of S4. Figure 3 (Right) shows the broken glass due to the impact of wind-borne debris, and the plywood was installed inside the office building to prevent further rainwater damage. The main reason for the broken glass was WBD, which came from nearby buildings. The loose aggregate or debris from the roof of the adjacent building was blown by the strong wind and carried towards the façade of Building S4, resulting in the illustrated failure.

Loose aggregates from built-up roofs (BURs) can cause damage to the glazing systems of nearby buildings. Most broken windows of the mid-rise building shown in Figure 4 were due to aggregates from BURs. The loose aggregates from the roof of Building A in Figure 4 that was adjacent to the tower were blown away and became the main source of WBD that caused the damage to lower level windows of the building.

Figure 4. Mid-rise building damaged by aggregate from BURs.
Hurricane Ike

A powerful tropical cyclone, Hurricane Ike, formed in September 2008. The ultimate damage was estimated at $37.5 billion, including losses in infrastructure and agriculture. In this section, the damage report of buildings in center district of Houston (FEMA 757_ch5) is presented, since this area had the most damage in the hurricane compared with other areas.

Figure 5. JP Morgan Chase Tower and JP Morgan Chase Center.

Although the estimated maximum speed for Hurricane Ike in downtown Houston was about 94 mph, which was not as high as the design wind speed of 108 mph according to ASCE 7-05, some commercial building’s exterior envelope still received extensive damage.

The wind speeds and directions measured by Florida Coastal Monitoring Program are shown in Figure 5. The arrows show the primary wind directions of Hurricane Ike, and the numbers are maximum gust speeds.
**Damage in JP Morgan Chase Tower**

The glass panels for JP Morgan Chase Tower are ¼-inch thick tinted and annealed panels. The damage to glazing systems was severe on the southeast side and approximately 463 windows on this side sustained damaged in both the inner and outer panels. All glass panels in the first 11 floors on the southeast side were broken, and the highest damage occurred on the 47th floor. At the same time, the southeast side of the building experienced significant amounts of rain penetration. For the southwest side of the building, there were 23 windows broken, while for the northeast side, only two. Since the damage was not significant in these two sides’ facades, the damage cost due to water intrusion was not expected to be high.

![Image of JP Morgan Chase Tower and Center]

Figure 6. Northwest façade glazing damage on JP Morgan Chase Center.
Damage in JP Morgan Chase Center

The glazing system for JP Morgan Chase Center consists of single-pane, heat-strengthened glass. The damage was severe for this building. All the glazing from the northwest side that was the windward side of the building (blue arrow in Figure 6) was damaged. The yellow arrow in Figure 6 shows that the façade had at least 16 windows broken. There was less damage to the other two sides of the building. Huge damage was also caused by water intrusion. The breached glazing allowed wind-driven rain to penetrate into the building and cause mass damage to the occupants’ properties. The Mitigation Assessment Team (MAT) reported water penetration to offices on Floor 14 through 20 in JP Morgan Chase Center, which caused damage to the floor as well as the interior structures and office supplies. The MAT observed that the water damage extended about 250 feet into the interior of the building, which damaged 150 desktop computers (Figure 7). With about 50 percent of floor area sustained damage in carpet and ceiling boards, the damage in Floors 18 and 19 was extensive. Floors 14 through 17 had approximately 25 percent of the floor area had the same damage.

Figure 7. Office damaged in the JP Morgan Chase Center.
Damage in Chevron Center

Chevron Center was another high-rise building that sustained damage on the building envelope during Hurricane Ike.

The red arrows in Figure 8 show the primary wind directions and maximum speeds in this area. The yellow arrow indicates the side of the Chevron Center that had most windows broken, and the roof membrane blew off from the end of the building is shown by the green arrow.
Figure 9. Chevron Center glazing damage.

Figure 9 shows the detailed photos taken by MAT, who documented about 700 windows broken during the hurricane.

2.3 Impact of shingle missiles on glazing
As discussed earlier, according to previous FEMA report (FEMA 757_ch5, FEMA 549_ch5) review, high-rise buildings with window glass sustain considerable damage during hurricanes mainly due to wind-borne debris impact. Thus, it is necessary to analyze the fragility of window glass under wind-borne debris impact conditions for use in performance-based hurricane design of building envelope systems.
An experimental study conducted at University of Florida (Shah, 2009) shows the effect of the impact of asphalt roof shingles on the window glass. In this experiment (Shah, 2009), a shingle launcher is used to launch shingles with different speeds, and a glazing frame is used to hold the specimen.

**Experimental Laboratory Test Configuration**

![Experimental Laboratory Test Configuration](image)

Figure 10. Wooden box (left) and glazing support frame (right).

In laboratory tests carried out by Shah (2009), the primary test components are a shingle launcher, a specimen box, a wood frame to support the glazing, and a high-speed camera.

The custom-made shingle launcher was used to launch shingles at different speeds to the target glazing being tested. Two vertically oriented rubber tires of 0.19 m (7.5 in) radius contact each other at the reads, and a 0.75 kW (1 hp) Franklin Electric AC induction motor spins the bottom tire, which makes the top tire to contra-rotate. The test shingle specimens go into the tray. The rotation provides the acceleration in the shingle to make the shingle have the desirable velocity. The angular velocity of the tires can be adjusted from 250 to 2400 RPM.
Figure 11. Shingle missile launcher.
The glazing frame holds the testing glazing materials. The wood frame is used to support the top and bottom the testing glazing panels, which are clamped in place between straps of weather-stripping. A 1.42 m (56 in) deep x 1.22 m (48 in) wide x 2.44 m (96 in) tall wood frame box sheathed in 1.27 cm plywood is used, and a 1.03 m (40.5 in) wide x 1.14 m (45 in) high opening was made on the side facing the launcher to let shingles pass.

The high-speed camera used to record shingle impact is Visio Research Phantom V5.2. When using 1152 x 896 pixel frame resolution, the camera is able to get on thousand frames per second. The velocity can be determined by checking the footage of the launched shingle projectile using the high-speed camera.

**Test materials**

All glass specimens were annealed glass with different sizes and thickness, manufactured by Shea’s Glass Company in Gainesville, Florida. New shingles used were 3-tab shingles.
manufactured by Tamko Building Products according to the ASTM S 362 requirements for asphalt shingles. The shingles used were obtained from residential homes in south Florida during re-roofing procedure.

**Failure status determination**

In this lab experiment, visual inspection was used to determine whether or not the specimen was damaged.

Tests were repeated with incrementally increasing impacting speed until the glass broke, which determined the lowest speed for shingles to cause damage to the selected specimen.

To make sure that the unseen damages on the specimen caused by impacts with speeds lower than the failure speed did not contribute to the final failure, repetition of testing was needed. The results of repeating tests have shown that other specimens also fail at about the same shingle speed, which shows that the accumulation of unseen damage is not a factor for the failure speed.

**Impact procedure**

Shingles were placed on a flat plate (tray) on the launcher and then moved to the gap between the tires. If the test specimen did not break after the impact, the speed of motor would increase by 50 RPM to continue the test until a breakage would happen. Once the specimen failure occurred, the next specimen would be tested at that specified RPM and repeated until breakage would occur again.
**Experiment results**

The tables for test specimen data, glass breakage velocity, and momentum at breakage are tabulated in Table 1, Table 2 and Table 3, respectively.

Configurations of seven groups of test specimens are listed in Table 1, and the type of shingle used, as well as the ways shingles were launched, are also shown. The number of specimens for each group indicates the number of specimens that are tested.

In Table 2 and Table 3, effective data that can be used for analysis are presented. Each column of the table shows the impact momentum/velocity of certain test specimen when a failure occurs.

The impact momentum of the shingle was calculated using equation below,

\[
\text{Momentum} = m \times v \quad (1)
\]

where \( m \) = mass of shingle and \( v \) = velocity of shingle when failure happens.

<table>
<thead>
<tr>
<th>Group</th>
<th>Test specimen</th>
<th>Aspect ratio (hXw)</th>
<th>Number of specimens</th>
<th>Type of shingle</th>
<th>Mode of flight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 3.18 mm (1/8 in)</td>
<td>1:1</td>
<td>20</td>
<td>Full weight new shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>2</td>
<td>0.61 m (2 ft) x 1.22 m (4 ft) 3.18 mm (1/8 in)</td>
<td>2:1</td>
<td>11</td>
<td>Full weight new shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>3</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 3.18 mm (1/8 in)</td>
<td>1:1</td>
<td>20</td>
<td>Half weight new shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>4</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 3.18 mm (1/8 in)</td>
<td>1:1</td>
<td>21</td>
<td>Full weight old shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>5</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 3.18 mm (1/8 in)</td>
<td>1:1</td>
<td>09</td>
<td>Half weight old shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>6</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 4.76 mm (3/16 in)</td>
<td>1:1</td>
<td>12</td>
<td>Full weight new shingle</td>
<td>Autorotation</td>
</tr>
<tr>
<td>7</td>
<td>0.61 m (2 ft) x 0.61 m (2 ft) 3.18 mm (1/8 in)</td>
<td>1:1</td>
<td>11</td>
<td>Full weight new shingle</td>
<td>Tumbling</td>
</tr>
</tbody>
</table>
Table 2. Threshold momentum for various glass specimens

<table>
<thead>
<tr>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
<th>Group 5</th>
<th>Group 6</th>
<th>Group 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.18mm</td>
<td>3.18mm</td>
<td>3.18mm</td>
<td>3.18mm</td>
<td>3.18mm</td>
<td>4.76mm</td>
<td>3.18mm</td>
</tr>
<tr>
<td>(1/8 in)</td>
<td>(1/8 in)</td>
<td>(1/8 in)</td>
<td>(1/8 in)</td>
<td>(1/8 in)</td>
<td>(3/16 in)</td>
<td>(1/8 in)</td>
</tr>
<tr>
<td>Annealed</td>
<td>Annealed</td>
<td>Annealed</td>
<td>Annealed</td>
<td>Annealed</td>
<td>Annealed</td>
<td>Annealed</td>
</tr>
<tr>
<td>glass(2x2)</td>
<td>glass(2x4)</td>
<td>glass(2x2)</td>
<td>glass(2x2)</td>
<td>glass(2x2)</td>
<td>glass(2x2)</td>
<td>glass(2x2)</td>
</tr>
<tr>
<td>Full weight</td>
<td>Full weight</td>
<td>Half weight</td>
<td>Full weight</td>
<td>Half weight</td>
<td>Full weight</td>
<td>Full weight</td>
</tr>
<tr>
<td>new shingle</td>
<td>new shingle</td>
<td>new shingle</td>
<td>old shingle</td>
<td>old shingle</td>
<td>new shingle</td>
<td>new shingle</td>
</tr>
<tr>
<td>2.90</td>
<td>3.59</td>
<td>2.35</td>
<td>3.02</td>
<td>2.48</td>
<td>5.96</td>
<td>3.35</td>
</tr>
<tr>
<td>3.59</td>
<td>4.56</td>
<td>2.29</td>
<td>3.14</td>
<td>3.13</td>
<td>6.28</td>
<td>3.90</td>
</tr>
<tr>
<td>3.86</td>
<td>4.83</td>
<td>3.06</td>
<td>3.36</td>
<td>3.25</td>
<td>6.52</td>
<td>4.47</td>
</tr>
<tr>
<td>4.51</td>
<td>4.83</td>
<td>3.33</td>
<td>4.28</td>
<td>3.44</td>
<td>6.68</td>
<td>4.36</td>
</tr>
<tr>
<td>4.51</td>
<td>4.83</td>
<td>3.25</td>
<td>4.89</td>
<td>4.10</td>
<td>6.59</td>
<td>4.81</td>
</tr>
<tr>
<td>4.51</td>
<td>5.09</td>
<td>3.63</td>
<td>5.13</td>
<td>4.58</td>
<td>6.59</td>
<td>4.99</td>
</tr>
<tr>
<td>4.71</td>
<td>5.54</td>
<td>4.21</td>
<td>5.54</td>
<td>4.66</td>
<td>6.99</td>
<td></td>
</tr>
<tr>
<td>5.15</td>
<td>5.72</td>
<td>4.20</td>
<td>5.20</td>
<td>7.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.54</td>
<td>4.07</td>
<td>6.20</td>
<td>8.27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.41</td>
<td>4.70</td>
<td>6.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.72</td>
<td>4.58</td>
<td>6.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.12</td>
<td>4.25</td>
<td>6.42</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.43</td>
<td>7.04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Glass breakage velocity

<table>
<thead>
<tr>
<th>Mode of flight</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
<th>Group 4</th>
<th>Group 5</th>
<th>Group 6</th>
<th>Group 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autorotation</td>
<td>3.18 mm</td>
<td>3.18 mm</td>
<td>3.18 mm</td>
<td>3.18 mm</td>
<td>4.76 mm</td>
<td>3.18 mm</td>
<td></td>
</tr>
<tr>
<td>Tumbling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1/8 in)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annealed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass(2x2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>new shingle</td>
<td>7.25</td>
<td>8.85</td>
<td>11.18</td>
<td>8.05</td>
<td>12.11</td>
<td>15.29</td>
<td>8.38</td>
</tr>
<tr>
<td>new shingle</td>
<td>8.85</td>
<td>11.18</td>
<td>11.18</td>
<td>8.05</td>
<td>14.91</td>
<td>16.10</td>
<td>9.08</td>
</tr>
<tr>
<td>11.27</td>
<td>12.07</td>
<td>15.84</td>
<td>11.27</td>
<td>16.77</td>
<td>16.91</td>
<td>11.17</td>
<td></td>
</tr>
<tr>
<td>11.27</td>
<td>12.07</td>
<td>15.84</td>
<td>12.88</td>
<td>20.49</td>
<td>16.91</td>
<td>11.87</td>
<td></td>
</tr>
<tr>
<td>11.27</td>
<td>12.88</td>
<td>17.70</td>
<td>13.69</td>
<td>22.36</td>
<td>16.91</td>
<td>11.87</td>
<td></td>
</tr>
<tr>
<td>12.07</td>
<td>13.69</td>
<td>19.57</td>
<td>13.69</td>
<td>23.29</td>
<td>17.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.88</td>
<td>14.49</td>
<td>20.49</td>
<td>13.69</td>
<td>19.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.69</td>
<td>21.43</td>
<td>16.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.69</td>
<td>22.36</td>
<td>16.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.49</td>
<td>22.36</td>
<td>16.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15.29</td>
<td>22.36</td>
<td>16.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>23.29</td>
<td>18.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>24.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this study, the damage state is assumed to be glass breakage, which depending on the type of glass may occur at different impact velocities.

Considering specimen Group 1 as an example, the test specimen dimension is 2 ft x 2 ft with a thickness is 1/8 in. A total number of 20 specimens were tested using full weight new shingles. The glass breakage velocity in the tests varied from 7.25 to 15.29 m/sec.
As an example of how the data presented in the above tables may be used to generate fragilities, Group 1, 2, 6 in Table 1 that show some variation in aspect ratio and thickness are chosen. This helps to develop a better understanding of the performance of glass with such parameter variation, including window glass types, type of shingles (including weight and condition) and different impact flying mode. By comparing Group 1 vs. Group 2 and Group 1 vs. Group 6, the performance of specimens with different aspect ratios and different thicknesses of the window glass under the same conditions can also be presented.

2.4 Summary

Hurricanes have caused damage to coastal areas, and commercial buildings located in the central area of the cities have sustained massive building envelope system damage. FEMA has conducted explicit damage reports for the hurricanes that formed and landed in coastal regions in the past several decades. Through the review of Hurricane Katrina (FEMA 549) and Hurricane Ike (FEMA 757) damage reports, two kinds of damage, which are WBD damage and WDR damage, are determined to be the primary damage types to the commercial building during hurricane conditions. The WBD damage usually leads to the glass breakage of the exterior of the building and causes the immediate losses. The WDR usually leads to the water penetration into the interior of the building through the breakage due to the WBD, and it can cause long-term damage. Therefore, this study focuses on these two types of damage in order to have a better understanding of the building envelope performance.

Lab tests have been carried out on WBD impacting on glass panels, but very few of these tests have been used to develop the fragility information for building envelope system under hurricane conditions. The results of lab tests conducted by Shah (2009) were reviewed in this chapter. Three sets of experiment data from Shah’s tests are used in this research to study the
fragility information for glass panels under different impacting speed. The specimens for different groups had different sizes and thicknesses, but the weights and types of impacting missiles were the same. The data is then used to develop fragility information for glass panels in this study.
Chapter 3

Research approach

The objective of this study is to gather data from tests and reconnaissance reports and to develop fragility information for glass panels used in building envelope system of commercial buildings under hurricane situations. To be able to study the performance of glass panels under hurricane situations, two sources should be considered. The first part is the damage caused by WBD, and the second part is the damage caused by WDR. With the fragility information for WBD and WDR available, the evaluation can be conducted based on PBD methodology shown in Figure 13.

Figure 13. Research plan flowchart
3.1 Damage caused by WBD

For this study, performing original testing is not feasible, and existing lab tests are not necessarily useful for the objective of the study, so in order to develop the fragility for glass panels caused by WBD, data available and obtainable from other methods may be used. Limited existing test data can be found that is related to the glass damage due to WBD impact. Lab test conditions do not match to the actual cases so the data obtained from lab test cannot be conveniently used in the development of fragility information. The FEMA reports give actual cases, which can be converted into useful data and then used to develop fragility information.

Four sets of actual building damage data and two sets of assumed data are used to develop the fragility information for glass panels under WBD impact condition. Although in this study, the main objective is to develop an approach for fragility information, which means data accuracy is not of vital importance as would be necessary for a case study and evaluation, rather the appropriateness and relevance of data are more important to make this approach more reasonable. Therefore, hurricane reports that are related to damage to commercial buildings under hurricane conditions are the main sources of data in the study. Meanwhile, the available lab experiments are designed for single glass panels under the impact of WBD, which are quite different from actual situations. In this study, efforts will be made to explore available methods that may be used for the conversion of the probability of failure between these two different situations.

3.2 Damage caused by WDR

Because of significant challenge to calculate the damage caused by WDR through modeling, this study develops a simplified method that can be used for estimation of such damage. The fragility information can be developed using actual cases obtained from hurricane reconnaissance reports. Percentage of different parts of building envelope system can be
developed based on six sets of data developed from actual hurricane reports and one set of data obtained from lab experiments. Since different parts of the building have different rain admittance factor (RAF) based on Straube’s approach (Straube et al., 2000), this can lead to the amount of water intrusion through broken glass panels of building envelope systems. The proposed study will focus on the conversion from the percentage of broken glass panels to the rain accumulation (WDR intrusion).

3.3 Performance-based hurricane engineering design and cost estimate of repair

In this study, the cost of the repair and replace due to the hurricane damage is estimated after the fragility information for building envelope system is obtained. Costs are estimated from the building damage states using empirical cost estimation techniques for building repair and replacement. RS Means provides data for the cost of construction, including the building envelope materials, which can be used to estimate the loss of the direct physical damage to the glass panels. The repair and replacement cost can also be obtained from industry through direct contact and/or survey of selected companies. For the rough estimation of loss due to the water intrusion, different scenarios should be defined to better understand the evaluation of the damage condition to the inside of the building.
Chapter 4

Fragility function development methodology, PBD approach and WDR study

4.1 Review of fragility development method

Research on fragility development for different aspects of buildings has been of great interest over the past couple of decades. According to Seismic Performance Assessment of Buildings-Methodology by FEMA, “Fragility functions are statistical distributions used to indicate the probability that a component, element, or system will be damaged as a function of a single predictive demand parameter, such as story drift or floor acceleration” (FEMA P-58-1, 2012a).

The basic definition of fragility for application to the performance-based design of buildings was initially suggested by Ellingwood et al. (2004). The probability of the limit states, defined as $G(X)<0$, can be expressed as (Dao et al, 2010)

$$P[G(X) < 0] = \sum_y P[G(X) < 0 | D = y]P[D = y]$$  \hspace{1cm} (2)

where $X$ is the vector of basic uncertain variables that describe the limit state, $P[D = y]$ is the probability of natural hazard intensity, and $D$=demand of a certain hazard such as wind speed, rainfall intensity or other variables when applied with hurricane design and PGA (peak ground acceleration), spectral acceleration when applied with the seismic design. The conditional probability, $\sum P[G(X) < 0 | D = y] = F_r$, which means the probability of failure of the given structure or system under a certain condition, is defined as the fragility.

Fragility development is crucial to the performance-based design of structures. As the probability of failure, the fragility of a system can provide the needed information on the capacity
of the system under a given condition. This can help engineers better design buildings according to desirable performance criteria that the owners set.

According to the expression for fragility development given above, the function for fragility of water intrusion can be written as

\[ P((s - S) < 0) = \sum_h P((s - S) < 0 | H = h)P[H = h] \]  

where \( s \) = predetermined rate of water intrusion (limit state); \( S \) = rate of water intrusion; and \( H \) = hazard vector. According to ASCE7-05, \( H = [IV]^T \) where \( I \) is the rainfall intensity, \( V \) is the basic wind speed, and \( P[H = h] \) is the joint probability of \( I \) (rainfall intensity) and \( V \) (basic wind speed). Similarly, the fragility of water intrusion \( F_r \) is \( F_r = P((s - S) < 0 | H = h) \), which means the probability of the amount of intruded water exceeds the predetermined amount when certain hurricane happens.

4.2 Development of fragility functions

Although the definition of fragility function (FEMA P-58-1, 2012a) is quoted from the seismic design document, the definition and methodology of developing fragility function still remain the same. For hurricane resistant design, the single predictive demand parameter can be wind speed or the momentum of impacting missile.

The theory and methodology in developing fragility curves and functions for use in performance-based seismic design as introduced by FEMA have been widely used in research undertaking. However, the efforts for application to the hurricane design area are still not well developed, and there is a need for increasing development in this area using the experience gained in performance-based seismic design.
Porter et al. (2007) have conducted much of the early studies related to developing fragility functions for performance-based earthquake engineering study. The experience of generating fragility curve for seismic design can certainly be useful in developing such fragilities for performance-based hurricane design studies as well.

Porter et al. (2007) suggest six methods to develop fragility functions depending on the extent and quality of data available. Accordingly, these approaches are Method A (Actual failure engineering demand parameters), Method B (Bounding engineering demand parameters), Method C (Capable engineering demand parameters), Method D (Derived fragility), Method E (Expert opinion) and Method U (Updating). In this study, Method A seems to be more appropriate for hurricane condition since the data used is when a specimen failed at observed values of engineering demand parameters (Actual failure engineering demand parameters).

\( F_{dm}(edp) \) is denoted as a function of fragility for damage state \( dm \), and it is defined as the probability of failure (components reach or exceed damage state \( dm \)) shown in Equation (4).

\[
F_{dm}(edp) = P[DM \geq dm | EDP = edp]
\]

A lognormal distribution equation (Equation 5) can be used as an idealized equation for Equation (4) (Porter et al., 2007)

\[
F_{dm}(edp) = \Phi\left(\frac{\ln(edp / x_m)}{\beta}\right)
\]

where \( \Phi \) is the standard normal (Gaussian) cumulative distribution function (CDF), \( x_m \) is the median value of the distribution and \( \beta \) is the logarithmic standard deviation.

According to Porter et al., (2007), method A can be used for generating fragility curves for those experiments that had sets of data. For architectural glass curtain wall systems, the
damage state can be defined as the condition when glass breaks, which can be observed by inspecting buildings after the hurricane event. The EDP can be defined as the speed of the flying debris. In this study, Method A is adopted.

From the definitions of \( x_m \) and \( \beta \) (Porter et al. 2007),

\[
 x_m = \exp\left(\frac{1}{M} \sum_{i=1}^{M} \ln r_i \right) \quad (6)
\]

\[
 \beta = \sqrt{\frac{1}{M-1} \sum_{i=1}^{M} \left( \ln \left( \frac{r_i}{x_m} \right) \right)^2} \quad (7)
\]

where \( M \) = number of specimens tested to failure, \( i = \) index of specimens, \( i \in \{1, 2, \ldots, M\} \), and \( r_i \) = EDP at which damage was to occur in specimen \( i \).

To generate a full fragility function/curve, the following four requirements are necessary (Porter et al., 2007):

1. **Description of specimens.** The number of specimens tested or observed should be listed, as well as the way they are counted. Specimen material, material properties, and specimen configuration should also be mentioned.

2. **Engineering design parameters.** In this study, the way to calculate Engineering Design Parameters (EDP) should be defined and the damage state should be stated according to method A (Actual failure engineering demand parameters).

3. **Damage evidence.** Physical damage should be described in this study. A clear definition of damage stage in the experiment can be helpful for the definition of EDP based on observation of specimens.

4. **Summary of observation and results.** A tabular form can be used to show the results of the test
along with a summary of fragility function parameters $x_m$ and $\beta$. Fragility curves can be generated and presented as graphs.

4.3 Wind-driven rain research

Wind-driven rain (WDR) is rain that is given a horizontal velocity component by the wind. It refers to the amount of rain that passes through a vertical plane in the atmosphere (Straube, 2000). The intrusion of WDR through building envelopes is a source of significant loss during hurricanes. The immediate losses include damage to furniture and other occupants’ properties. Examples of long time losses are water penetration into exterior walls, possibly rotting of wood in the wall if the moisture is trapped efflorescence, freeze-thaw damage, which are not easy to quantify. WDR is the most important source that affects the hydrothermal performance and durability of building envelope system, which leads to different damage forms, including frost damage to building facades, discoloration by efflorescence. Surface soiling on exterior façade of buildings that happens commonly in urban areas is also due to WDR.

There are three pathways for intrusion of WDR, which are (1) defects of building envelope system, including poorly sealed openings, wall cracks after a long time and unfitted plumbing and electrical units (Mullen, 2006); (2) building envelope openings such as vents and roof (Jesteadt, 2007); and (3) openings as a result of glass breakage caused by external forces, such as wind-borne debris impact or over-pressurization (Cope, 2004).

The WDR problem has always been around, and although some solutions have been developed, buildings still experience damage due to this moisture source, which increases the total repair cost due to hurricanes. The reason for the vulnerability of buildings to such WDR damage consists of two parts: the first one is that the performance of newly used building
technologies and materials has not been fully understood, and the second one is that appropriate quantitative design data for WDR is not sufficient.

To better understand WDR, both quantification of WDR loads and the corresponding response of building envelope would have to be considered. Quantification of WDR is controlled by several parameters including wind speed and direction, rain intensity, rain duration and position on the building envelope. These parameters include weather (hurricane) data and building envelope properties, whose uncertainty and variation makes quantification and consideration of WDR in the design of envelope systems challenging.

Although the study of WDR on buildings has been going on for decades, much work still remains to be done. The studies that have been carried out can be divided into three parts according to the methods used (Blocken et al., 2004): (1) experimental methods, (2) semi-empirical methods and (3) numerical methods.

**WDR definitions and parameters**

The wind-driven rain (WDR) or driving rain is the oblique rain, and the “WDR intensity” refers to the oblique rain vector or, as defined by CIB (International Council for Building Research), “component of the rain intensity vector causing rain flux through a vertical plane”. The horizontal rainfall intensity, which causes rain flux through a horizontal plane, is the other component of rain intensity vector.
The horizontal velocity of WDR drops will equal to the wind speed within a short distance (Beard, 1976), so the falling rain that will pass through a vertical plane can be written as:

\[ r_v = r_h \cdot \frac{V}{V_t} \]  

(8)

where \( r_v \) = the rate of rain passing through a vertical plane (mm/m²/h), \( r_h \) = the average rainfall rate on the ground (mm/m²/h), \( V \) = average wind velocity (m/s), \( V_t \) = terminal velocity of a raindrop (Straube, 2000).

A simple equation proposed by Lacy (1965) that describes the relationship between WDR \( r_v \) and wind speed \( V \) and rainfall intensity \( r_h \) is as follows:

\[ r_v = 0.208 \cdot V \cdot r_h = DRF \cdot V \cdot r_h \]  

(9)

The driving rain factor (DRF) in Equation (9) is a constant relating rain on a vertical plane (WDR) to rain on horizontal plane (falling rain). Field studies and literature review have found that the value of DRF is 0.20 to 0.25 for average conditions (Straube, 2000).

Rain Admittance Factors

The rain admittance factor (RAF) is related to factors such as building’s shape, wind speed, and wind angle. When the wind encounters buildings, the WDR is usually redirected since
the stream lines and pressure gradient are formed around the building. Since it would be too time-consuming to predict the rain deposition on buildings through modeling, the RAF is introduced to simplify the calculation (Straube, 2000).

The RAF is used to transform WDR at a horizontal distance to deposited rain on buildings. Hence, the WDR deposition on the vertical face of building envelope can be written as an extension form of Equation (9) using RAF (Lacy, 1965)

\[ r_{br} = RAF \cdot DRF(r_h) \cdot \cos(\theta) \cdot V(h) \cdot r_h = RAF \cdot \cos(\theta) \cdot r_v \] (10)

where \( V(h) \) = wind speed at the height of interest, and \( \theta \) = the angle between the normal to the wall and the wind direction.

The RAF can be calculated from the literature if information such as wind speed and wind direction are given. Study on the RAF using this method has been conducted for many years (Lacy, 1965), and the value of RAF is less than 1.0 in most cases.

After comparing past studies on DRF and RAF, Straube et al. (2000) summarized typical measured RAF for tall buildings (Figure 15) using their own measurements and computer modeling (Karagiozis, 1995), which shows that the amount of WDR deposited on the tall building. Figure 15 shows that almost all parts of the tall building (>10m) have an RAF less than 1.0 which means that the amount of WDR deposition on the tall building is usually less than the amount in the free wind.
Figure 15. Rain deposition factor of the tall building (>10, HW>>1).

WDR intrusion

Semi-empirical models are used to help the development of interior damage models. However, several parameters of the semi-empirical models are determined by estimation, including rain admittance factor (RAF), which is for distribution of the rain, and surface runoff coefficients (SRC) which is for the accumulation of surface runoff rainwater. This may cause inaccuracy and uncertainty of the model based on the assumed parameters.

Dao and Lindt (2010) proposed a mechanistic framework for WDR damage estimation. The model considers the impact of raindrops and surface runoff rainwater, which are two parts of WDR intrusion, but the model still has many restrictions, which makes it only applicable to certain conditions.

The total volume of WDR intrusion through an opening on building façade can be calculated using
\[ V_{\text{tot}} = V_{DI} + V_{SR} \quad (11) \]

where \( V_{\text{tot}} \) = total volume of water intrusion through a given opening, \( V_{DI} \) = WDR intrusion resulting from direct impinging raindrop and \( V_{SR} \) = WDR intrusion resulting from surface runoff rainwater.

One way the WDR intrusion can be considered is through building envelope openings or breaches. Because of the large opening, the pressure remains equal on both sides of the opening. Therefore, the total volume of water intrusion can be expressed as:

\[ V_{\text{tot}} = RAF \cdot IR \cdot A_{b} + SRC \cdot IR \cdot A_{SR} \quad (12) \]

where \( IR \) is the total amount of free-field impinging rain (WDR), \( A_{b} \) is the area of the opening, and \( A_{SR} \) is the surface runoff area.

The other path of WDR intrusion is through building envelope defects. The building envelope defect is defined as small openings which can be anywhere over the entire building envelope. The main difference between WDR intrusion through defects and openings is the driving pressure. The pressure difference between the two sides of defects can drive the rainwater into the building envelope. During hurricane or rainy weather, the continuous rainwater can have a significant contribution of the total amount to rainwater intrusion.

### 4.4 Performance-based engineering (PBE)

The Load and Resistance Factor Design (LRFD) method as well as other methods based on probabilistic foundation, which is widely used for the design of structures, are prescriptive in nature and not suitable to satisfy specific levels of damage (Borges et al., 2009). PBE that aims at designing for different levels of performance is recognized to be the most rational method for structural design considering risk due to natural phenomena (Augusti et al., 2008). PBE approach
is intended to result in a structure with only a small probability of damage exceeding the limit states describing the failure, serviceability, and/or other performance measures (Bertero et al., 2002). In PBE, Engineering Demand Parameters (EDP) is defined as a measurable quantity that describes the response of a structure, such as maximum deformation or maximum force applied on a member. The Intensity measure (IM) gives an evaluation parameter with different levels, such as peak ground acceleration in earthquake engineering, and mean wind speed in hurricane engineering (Petrini, 2009). In PBE, the performance of the structure is determined by comparing the actual behavior with the predetermined Damage Measure (DM). The Decision Variable (DV) shows the cost of the structure under the certain condition for the owner and PBE provides the estimation of structural risk by determining the probability of exceeding predetermined DV. DVs for different design options can be compared in PBE analysis and provide the most desirable selection for the final design (Barbato et al., 2011).

Performance-Based Earthquake Engineering (PBEE) method is currently a general and widely accepted approach proposed by The Pacific Earthquake Engineering Research (PEER) Center (Cornell, 2003). It focuses on evaluating performance at both component and system level in terms of DVs such as repair cost and casualties. An extension of PEER PBEE methodology, a Performance-Based Hurricane Engineering (PBHE) design was developed by Barbato et al (Barbato et al., 2011), which mainly accounts for the different hazards such as WBD and rainfall.

4.5 PBE methodology

The PBEE method provides a way to calculate the frequency of exceeding a predetermined degree of DV, g[DV], as:

\[
g[DV] = \int \int p[DV \mid DM] \cdot p[DM \mid EDP] \cdot p[EDP \mid IM] \cdot p(IM \mid D) \cdot dIM \cdot dEDP \cdot dDM (13)
\]

where \( g[DV] \) = frequency of exceeding variable DV, \( p[A\mid B] \) = probability density function (PDF)
of variable A conditional on a specified value of variable B. A flowchart is used to illustrate the methodology of PBEE in Figure 14 (Barbato et al., 2011)

![Flowchart](image)

Figure 16. PBEE methodology flowchart.

The analysis procedure can be divided into several phases from left to right in Figure 14. The first phase is $g(IM)$, which is the hazard analysis part, defined by the hazard curve or function for the location of the structure. The hazard curve or function provides the probability of certain level of intensity of the hazard that can happen in a given time frame. For the second phase, a PDF of EDP conditional to knowledge of IM ($p[EDP|IM]$) can be determined. The third phase is the damage analysis, which is used to determine the fragility information to show the probability of exceeding a predetermined limit state DM conditional to knowledge of EDP ($p[DM|EDP]$).

The last phase is the DV conditional to knowledge of DM ($p[DV|DM]$), which stands for the loss analysis.

### 4.6 Summary

Fragility function is defined as a statistical distribution used to indicate the probability that a component, element, or system will be damaged as a function of a single predictive demand parameter (FEMA P-58-1, 2012a). The research on fragility development has been going on for decades and its application is widely used in the performance-based engineering approach. Porter
et al. (2007) suggest six methods to develop fragility information based on different scenarios and the quality of data available. In this study, Method A is used for developing fragility information for glass panels.

WDR is rain that is given a horizontal velocity component by the wind. WDR usually causes not only immediate losses but also long-term losses. The water intrusion path during hurricane mainly is due to the breakage of the exterior of the building envelope. Lacy (1965) proposed a simple equation to relate wind speed and rainfall intensity to WDR using DRF, which for the average condition is 0.20 to 0.25 according to mass field studies (Best, 1950; Laws and Parsons, 1943; Marshall and Palmer, 1948). The RAF is used to transform WDR at a horizontal distance to deposited rain on buildings. Lacy (1965) is credited for contribution to converting WDR to WDR deposition on the vertical face of the building envelope. Analysis on the RAF using this method has been discussed by Lacy, 1965; Sandin, 1988, 1991; and Henriques, 1992, among others, while a simplified method has been proposed by Straube et al. (2000) using Figure 15.

PBE that aims at designing for different levels of performance is recognized to be the most rational method for structural design (Augusti et al., 2008). In PBE approach, EDP is defined as a measurable quantity that describes the response of a structure, and IM gives an evaluation parameter with different levels. Studies in PBEE have been conducted for several decades (FEMA, 2012a), but PBHE has been discussed more recently (e.g., Barbato et al, 2011). In this study, the focus is mainly on doing the cost estimate of repair based on the damage scenario and RS Means cost data.
Chapter 5

Fragility information for WBD based on lab tests

According to the FEMA report P-58-1 (FEMA, 2012a), fragility functions can be defined as statistical distributions that indicate the conditional probability of incurring damage at a given value of demand. In this study, fragility curves have been developed for selected damaged building envelope systems.

The methodology and results of impact experiments were discussed in the previous chapter. In this chapter, the development of fragility functions and curves will be presented.

5.1 Fragility functions and curves development

According to the results of experiments carried out by Shah (2009) presented in Table 1 and Table 3, and based on Method A (Actual failure engineering demand parameters) mentioned previously, the fragility data can be calculated. Table 4 summarizes the fragility data for the selected group of window glass specimens mentioned earlier.

Table 4. Fragility data for selected window glass specimens

<table>
<thead>
<tr>
<th>Group number</th>
<th>Specimen description</th>
<th>$x_m$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1/8” Annealed glass (2x2)</td>
<td>11.57</td>
<td>0.218</td>
</tr>
<tr>
<td>2</td>
<td>1/8” Annealed glass (2x4)</td>
<td>12.06</td>
<td>0.149</td>
</tr>
<tr>
<td>6</td>
<td>3/16” Annealed glass (2x2)</td>
<td>17.28</td>
<td>0.098</td>
</tr>
</tbody>
</table>
The fragility curve can be plotted using Excel as shown in Figure 17, which presents the probability of failure for each size of the glass window. The figure indicates that specimens in Group 1 (1/8’’ Annealed glass 2x2) start to fail at the impacting speed of 8 m/s (17.89mph), and there is almost 100% certainty for the glass to break at the impacting speed of 16 m/s (35.79mph). Compared with Group 1 (1/8’’ Annealed glass 2x2), specimens of Group 2 (1/8’’ Annealed glass 2x4) have similar performance. The failure happens at the impacting speed of 6 m/s (13.42 mph), and the probability of failure reaches 100% at the impacting of 18 m/s (40.26 mph). The Curve 3 in Figure 17 indicates Group 6 (3/16’’ Annealed glass 2x2) specimens have a better performance under impact condition compared with other two groups. The failure rates of Group 6 are approximately 67.14% at the impact speed of 18 m/s (40.26 mph) when both Group 1 and 2 specimens are certain to fail. Figure 17 also shows the glass thickness is a dominant factor in failure caused by missile impact. For example, the probability of breakage of 3/16’’ Annealed glass (2x2) from missile impact at wind speed 17 m/s (38.03 mph) is 42.95%, which is much smaller than that for 1/8’’ Annealed glass (2x2) and 1/8’’ Annealed glass (2x4). The minimum breaking velocity of glass panels is also related to the thickness. The minimum breaking velocities for Group 1 and Group 2 are 7m/s (15.66mph) and 8.5m/s (20.13mph), respectively, and it is 16m/s (19.01 mph) for Group 6 which is twice as thick as that for first two groups.
5.2 Limitations of lab experiment

Although some lab experiments have been carried out and fragility functions and curves are obtained in Section 3.1, there are still significant differences between lab tests and actual building façade failures, so the lab test results cannot be used when discussing actual hurricane condition failure.

Study on fragility development of building envelope systems under seismic condition (Zhu, 2016) has been conducted based on lab tests (Terentiuk and Memari, 2012; Kermani and Hairstans, 2006). In the study focused on the building envelope system under earthquake hazards, the predictive demand parameter is defined as drift ratio. When a building sustains damage during an earthquake, the drift ratios for each brick veneer panel/glass panel/SIP in building envelope system are the same, which means the condition (predictive demand parameter) that are assumed
in lab tests reasonably match the actual condition. Therefore, the lab test results can be used for evaluation of actual real-life cases. However, in the hurricane condition, there are some significant differences between lab test conditions and actual cases. In Shah’s lab experiment, all glass panels are tested by continuing missile impact until the failure happens, which means all specimens are 100% hit by the missile. Since in the actual cases, the WBD is generated because the loose aggregate or gravel from the roofs of nearby buildings become air-borne and turn into a missile by the wind, the trajectory is usually unpredictable, so not all glass panels on the face of the building are hit by the WBD. Hence, in the actual case, the reason for a glass panel not reaching damage state, i.e., the glass panel remains undamaged, can be that it sustains an impact but the impact speed (predictive demand parameter) is not large enough to break the panel or it does not sustain an impact, i.e., debris does not hit the glass. It is then unreasonable to use the fragility curve generated based on lab tests (debris impacting glass) to develop the fragility information for buildings in hurricane condition unless some modification factors are developed to be applied to lab test results.

5.3 Summary

In this chapter, the fragility information based on lab tests conducted by Shah (2009) was developed. Three sets of data in Table 4 were used to illustrate the performance of different sizes and thickness glass panels in the same impact conditions. An Excel spreadsheet (Figure 17) was used to plot the fragility curves based on Equation (5). The median value of the distribution $X_m$ and the logarithmic standard deviation $\beta$ was calculated using Equation (6) and Equation (7) based on Method A (Porter et al. 2007). The fragility curves developed from the results show the performance of three types of glass panels under different impact speeds, which gives us a clear comparison of the performance of different glass panels under the same wind speed condition.
(e.g., the thicker glass panels perform better during the lab tests with a lower probability of damage).

However, limitations exist for the lab experiments since in the lab tests, all impacting missiles hit the glass panel specimen every time (100% of the time), while in the actual case, not all glass panels are hit by the WBD. This difference makes the test results not directly usable for the analysis of actual hurricane case and design. The alternative way of obtaining valid data for building envelope under real hurricane condition analysis is presented in the next chapter.
Chapter 6

Fragility information for WBD based on actual hurricane damage

6.1 Case study of WBD using hurricane report

A case study (Kaskel, 2017) was conducted by Wiss, Janney, Elstner Associates, Inc. (WJE) in determining fragility of curtain wall under Hurricane Katrina. The photos taken at the affected site after hurricanes can be of great value for fragility development, as they help identify the type and extent of the damage. The building photos reveal the condition of the building envelope after hurricane occurrence.

In this case, Hyatt hotel experienced extensive damage on its north side of the building (Figure 18), including breakage of glass and damage to the interior content (e.g., furniture, carpet).

Figure 18. Hyatt hotel damage after Hurricane Katrina.

The probability of failure can be determined by considering the percentage of broken windows. The number of glass panels that experienced breakage during the hurricane can be
obtained through inspection of the building prior to repair or from photos taken after the hurricane. The total number of windows can be obtained from post hurricane survey reports that show buildings with broken glass. The probability of failure can be determined using the following equation,

\[
\text{Percentage of failure} = \frac{\text{Number of broken windows}}{\text{Total windows}}
\]  

(14)

and a north elevation drawing of the building (Figure 19) can be used as an example to illustrate the damage more directly. The wind speed can also be found in the report, which when paired with the percentage of glass damage will provide a data point for fragility curve development. By finding more hurricane damage reports, more data related to the probability of failure under certain wind velocity can be obtained, and thus, more refined fragility curve/function can be developed.

Figure 19. Hyatt hotel damage condition generated by AutoCAD.
6.2 Fragility information of WBD using hurricane report

A similar method can be used in developing fragilities for building envelope.

Case 1

Figure 20 shows damage to the south façade of a building in the report of damage by Hurricane Katrina (FEMA 549_ch5). The damage was caused by aggregate from roof A, and likely from roofs and C (Figure 4). The estimated wind speed was 130mph (FEMA 549_ch5).

Figure 20. 15-story building damage after Hurricane Katrina.
Figure 21. Case 1 generated by AutoCAD.

The drawing (Figure 21) was generated using AutoCAD according to photos from FEMA report (Figure 20) (FEMA 549_ch5), which showed the damage condition of the building right after the hurricane. The drawing only reveals the top 11 floors of the building, which used glass strip windows as part of building envelope. The number of damaged glass panels and a total number of glass panels were 114 and 396, respectively. Using Equation (14), the probability of failure (fragility) is 114/396=28.78% at a wind speed of 130 mph, which is one fragility curve data point.

**Case 2**

Based on Figures 2 and 3, the drawing shown in Figure 22 can be generated using AutoCAD that shows damage to the glazing system that clads Building S4. The drawing shows a total number of 1120 glass panels, from which 308 are broken. According to Equation (14), the probability of failure (fragility) is 308/1120=27.50%, at a wind speed of 105 mph.
Case 3

Figure 23 shows a building damaged in Hurricane Katrina (FEMA 549_ch5), and the red circle indicates the temporary repair of the damaged glass panels. Similarly, generated by AutoCAD, the drawing (Figure 24) shows a total number of 390 glass panels, with 88 of them shown broken, so the probability of failure at a wind speed of 105 mph is 88/390=22.56%.
Figure 23. 13-story building damage after Hurricane Katrina.

Figure 24. Case 3 generated by AutoCAD.
Case 5

Figure 25 shows a medical office building damaged in Pensacola, Florida during Hurricane Ivan (FEMA 489_ch5), and wood studs and gypsum board had been temporarily installed after the hurricane to prevent further losses to the interior building and occupants. Similarly, generated by AutoCAD, the drawing (Figure 26) shows a total number of 270 glass panels, with 50 of them shown broken. Therefore, the probability of failure at a wind speed of 90 mph is 50/270=18.51%.

Figure 25. Medical office building damage after Hurricane Ivan.
Results based on hurricane reports

In this study, fragility information is primarily developed based on the data obtained from the actual hurricane reports. Since the limited source of damaged commercial building information is readily available in open literature, collecting the extensive amount of data becomes a challenging task, which may be outside the scope of this work. Theoretically, the method used to develop accurate fragility information works best when selected usable data is more than 25 (Porter, 2007). For a better understanding and development of the fragility data approach, some assumptions for data need to be made until additional data from literature or development of modification factors for lab test results become available. Based on the failure
information of Case 2 and Case 3 at 105 mph wind speed, a set of data related to the probability of failure at a wind speed of 130 mph is assumed as shown in Table 5 Case 4.

Table 5. Probability of failure of different cases

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind speed (mph)</th>
<th>Probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>28.78%</td>
</tr>
<tr>
<td>2</td>
<td>105</td>
<td>27.50%</td>
</tr>
<tr>
<td>3</td>
<td>105</td>
<td>22.56%</td>
</tr>
<tr>
<td>4*</td>
<td>130</td>
<td>33.72%</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>18.51%</td>
</tr>
<tr>
<td>6*</td>
<td>90</td>
<td>23.45%</td>
</tr>
</tbody>
</table>

* Case 4 and Case 6 are assumed cases

6.3 Fragility development of WBD using hurricane report

Damage state

The damage state (damage measurement) used in the previous lab test is the breakage of the glass panel. In actual cases, the loss in a building due to hurricane damage can be glass breakage and water intrusion. In order to better estimate the loss in the actual case study, the damage state is defined as the possibility to reach certain damage degree.

Assumptions

Because the approaches to obtain effective lab data or find actual cases are limited, several assumptions are necessary at this stage to make some simplifications for the development of fragility information.
1. Although the configurations, thicknesses, and types of glass panels affect the probability of failure of the building envelope system, in this study, these parameters are considered fixed and assumed to be the same as those in the case study buildings. The variation in properties of glass panels in actual cases is assumed not to affect the probability of failure.

2. It is recognized that different surrounding conditions may have different contributions to the damage percentage of the building envelope systems. Moreover, different locations and heights of the nearby buildings may cause differences in the generation of WBD, which is usually the gravel and shingle from the roof of the building. However, as a simplification, the surrounding conditions for each case in hurricane reports are assumed the same as those in the case study buildings.

**Development**

In PBEE, IM (intensity measure) is the link between hazards and structure response. However, in this study, the wind acts directly on the surface of the building and causes the damage that this study is interested in. Therefore, the EDP (engineering demand parameter) in this study can be referred to the IM in PBEE. In the PBEE design, IM should be identified in a sufficient and efficient way (Petrini, 2009; Luco N, 2007), so in this study, the chosen EDP should be appropriate as well.

At this stage of the study, limited data can be obtained from actual hurricane case studies, so the fragility information presented is only generated to illustrate an appropriate approach chosen for the study.

Since data from lab tests do not perfectly fit the actual hurricane condition and until an approach for correlation of lab test data and actual hurricane damage can be developed, in this
study, development of fragility information for glass panels is mainly based on Section 3.5. According to the predetermined damage state, the probability of failure can be calculated.

The probability of total glass panel breakage at a wind speed of 105 mph for Case 2 and Case 3 is 27.50% and 22.56%, respectively. Taking 25% of the total glass panels damage as a predetermined damage degree, the probability of reaching such damage degree is 1 out of 2 total samples, which is 50%. Cases 1 and 4 denote the damage condition at a wind speed of 130 mph. Since the probability of failure is 28.78% and 33.72%, respectively, both of these two cases have damage greater than 25%. In this way, the probability of reaching 25% of the total glass damage is 100%.

Similarly, if we take 30% as another predetermined damage degree (state). For Cases 1 and 4 at 130 mph, the probability of reaching 30% damage is 50%, and for Cases 2 and 3 at 105 mph, neither of these two cases has damage greater than 30%, so the probability of reaching 30% damage state is 0.

Similarly, let’s define 30% as another predetermined damage degree (state). For Case 1 and Case 4 at 130 mph, the probability of reaching 30% is 50%, and for Case 2 and Case 3 at 105 mph, neither of these two cases has damage greater than 30%, so the probability of reaching 30% damage state is 0.

As mentioned in literature part, the fragility function can be expressed using standard normal (Gaussian) cumulative distribution function (Porter, 2007), so according to the data obtained above, the fragility information for glass panels can be developed using Equations 5, 6, and 7. Certain assumptions are made to develop the fragility function. Although the wind speed at 50% of probability of failure is obvious, there is no way to define the wind speed at which the probability starts to reach 100% or 0. A better data point is preferred when the probability of failure falls between 0 to 1, but no such data can be obtained from the known case studies. To
better illustrate the methodology of developing fragility information, it will be assumed that (105, 0) and (130, 1) are two effective data points on the standard normal cumulative distribution function. The median value of the distribution $X_m$ and the logarithmic standard deviation $\beta$ can be calculated as shown in Table 6, and the fragility curves are illustrated in Figure 27.

Table 6. Fragility data for WBD

<table>
<thead>
<tr>
<th>Curve number</th>
<th>Predetermined damage degree</th>
<th>$X_m$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20%</td>
<td>90</td>
<td>0.0308</td>
</tr>
<tr>
<td>2</td>
<td>25%</td>
<td>105</td>
<td>0.0427</td>
</tr>
<tr>
<td>3</td>
<td>30%</td>
<td>130</td>
<td>0.0427</td>
</tr>
</tbody>
</table>

Figure 27. Fragility curves based on case study.
The fragility curves are plotted using Excel and reveals the probability of reaching 20%, 25% and 30% of total glass panels damage. Although limited data available to use restricts the accuracy of the fragility information, the approach, however, is straightforward. As more fragility information becomes available, more damage states (i.e., other than 20%, 25% and 30% shown in Figure 27) can be determined. These fragility information/curves can provide the damage condition at certain wind speed, which can be used to estimate the damage and conduct PBD.

6.4 Summary

In this chapter, the fragility information for glass panels under the impact of WBD was developed using actual hurricane cases. Kaskel (2017) proposed a method of generating data using hurricane reports. Hurricane damage reports from FEMA provide information for buildings that sustain building envelope damage during hurricanes. A useful data for fragility development can be obtained by combining the percentage of failure generated using AutoCAD and wind speed. Four actual cases generated from hurricane reports and two assumed cases based on actual cases are used in this study to generate fragility information. Cases 1, 2, 3 and 5 are actual cases in Hurricane Katrina, Hurricane Ike, and Hurricane Ivan, respectively. Cases 4 and 6 are two assumed cases based on other actual cases, and they are adopted to better address the issue of inefficiency of actual data and to illustrate the methodology in this study. Since only a methodology is developed in this study, certain assumptions had to be made.

In this study, three predetermined damage degrees are defined and used in developing fragility information. Three sets of data at three different wind speeds are used in this study to develop fragility information. The fragility information is developed using Method A (Porter et al. 2007) mentioned in Chapter 4, The fragility curves in Figure 27 show the probability of reaching
certain predetermined damage degree at each wind speed circumstance. To create fragility curves, an Excel workbook was utilized to plot the functions as mentioned in Chapter 5. This fragility information can be used towards performance-based design, and a case study using the fragility information developed in this chapter is presented in later chapters.
Chapter 7

Fragility information for WDR based on actual hurricane damage

7.1 Fragility information of WDR using hurricane report

According to Figure 15, a simplified method can be used for estimating wind-driven rain intrusion. As mentioned earlier, calculating WDR by modeling can be time-consuming, so it is appropriate to use Figure 15 summarized by Straube et al. (2000) to calculate. Although the approach does not provide high fidelity, the accuracy can be considered sufficient to develop the approach to derive WDR fragility.

In order to better develop WDR fragility functions, the following assumptions and estimations are made:

1. RAF (rain admittance factor) of the tall building (Figure 15) is used to define the RAF of a certain area of the building. In this study, the upper part (0.9 – 1.0+) uses 0.9 as RAF value, while the middle and lower parts use 0.7 and 0.5, respectively. Since this study mainly focuses on the approach for the development of fragility due to WDR, the proper extent of estimation on the value of RAF in the same part is reasonable.

2. In this study, the assumption is made that all building envelope systems discussed in this study are well-sealed, so the predetermined rate of water intrusion (limit state) is zero.

3. The amount of WDR is the summation of direct intrusion from opening and the surface runoff rainwater. In this study, the surface runoff water is omitted so the total amount of water intrusion is equal to the amount of water from the opening.
Case 1

Figure 28 is generated based on Section 6.2 Case 1 (Figure 21) and RAF of the tall building (Figure 15). From this figure, the probability of failure in each part can be calculated. 23 out of 100 glass panels in upper part were broken, 21 out of 104 glass panels in middle part were broken, and 70 out of 192 glass panels in lower part were broken. Therefore, the probability of failure for upper, middle and lower part at a wind speed of 130 mph is 23.0%, 20.2%, and 36.5%, respectively.

![Image](image)

Figure 28. Damage to different parts of Case 1.

Case 2

Figure 29 shows the damages in three parts of the building mentioned in Section 6.2 Case 2 (Figure 22). The probability of failure can be determined for each part. There are 63 out of 270 glass panels broken in the upper area, 87 out of 238 glass panels broken in the middle area, and
158 out of 612 glass panels broken in the lower area. Therefore, the probability of failure for this building at a wind speed of 105 mph is 23.3%, 36.6%, and 24.8%, respectively.

Figure 29. Damage to different parts of Case 2.

Case 3

Figure 30 shows damages in different parts of the building discussed in Section 6.2 Case 3 (Figure 24). By counting for the damaged window panels, the probability of failure for each part of the building can be obtained. For the upper, middle, and lower parts, the broken windows are 18 out of 88, 19 out of 122, and 51 out of 180, respectively. This gives us a probability of failure at a wind speed of 105 mph equal to 20.5%, 15.6%, and 28.3%, respectively.
Case 5

Figure 31 shows damages in different parts of the building discussed in Section 6.2 Case 5 (Figure 26). By counting for the damaged window panels, the probability of failure for each part of the building can be obtained. For the upper, middle, and lower parts, the broken windows are 6 out of 53, 10 out of 83, and 34 out of 134, respectively. This gives us a probability of failure at a wind speed of 90 mph equal to 11.3%, 12.0%, and 25.4%, respectively.
Results based on hurricane reports

In this study, fragility information is developed based on the data obtained from the actual hurricane reports. Since the limited source of damaged commercial building information is available in open literature, collecting a considerable amount of data becomes a highly challenging task. As mentioned in Chapter 3.5, an assumed case based on three actual cases is added to help illustrate the methodology. Similarly, based on the failure information of Case 2 and Case 3 at 105 mph wind speed, a set of data related to the probability of failure at a wind speed of 130 mph is assumed as shown in Table 7 Case 4.
Table 7. Probability of failure for different parts of building facade

<table>
<thead>
<tr>
<th>Case</th>
<th>Wind speed (mph)</th>
<th>Probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Upper</td>
</tr>
<tr>
<td>1</td>
<td>130</td>
<td>23.0%</td>
</tr>
<tr>
<td>2</td>
<td>105</td>
<td>23.3%</td>
</tr>
<tr>
<td>3</td>
<td>105</td>
<td>20.5%</td>
</tr>
<tr>
<td>4*</td>
<td>130</td>
<td>25.8%</td>
</tr>
<tr>
<td>5</td>
<td>90</td>
<td>11.3%</td>
</tr>
<tr>
<td>6*</td>
<td>90</td>
<td>14.1%</td>
</tr>
</tbody>
</table>

* Case 4 and Case 6 are assumed cases

7.2 Fragility development of WDR using hurricane report

Since in hurricane events, water intrusion always comes along with building façade damage (glass panel breakage) and causes significant damage (FEMA 549, FEMA 757), it’s necessary to determine the amount of WDR when considering PBD under hurricane conditions. As mentioned in the literature review part, different sections of the building façade sustain different levels of water intrusion damage, so it is important to calculate the WDR separately, section by section. The amount of WDR is assumed to be equal to the amount of water intrusion from the broken glass panels, and as discussed in Section 3.7, a relationship needs to be developed between wind speed and damage in different parts of the building façade.

Development of breakage information

From previous case studies, damage percentages for upper, middle and lower parts are expected to be different under different wind speed conditions. As part of the building envelope system, the fragility information for different parts of the building façade follows the fragility methodology developed for the whole building envelope system.
Using standard normal cumulative distribution function, the fragility information for each part of the building façade at different speed can be developed. The mathematical basis for fragility development is the same as that discussed in Section 4.2. The median value of the distribution \( X_m \) and the logarithmic standard deviation \( \beta \) can be calculated as shown in Table 8. A plot based on the functions for upper, middle and lower area can be generated using Excel as shown in Figure 32.

Table 8. Fragility data for WDR

<table>
<thead>
<tr>
<th>Curve number</th>
<th>Part of the building</th>
<th>( X_m )</th>
<th>( \beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Upper</td>
<td>143.145</td>
<td>0.3950</td>
</tr>
<tr>
<td>2</td>
<td>Middle</td>
<td>291.987</td>
<td>1.5832</td>
</tr>
<tr>
<td>3</td>
<td>Lower</td>
<td>191.718</td>
<td>0.9965</td>
</tr>
</tbody>
</table>

![Figure 32. Percentage of different parts of building envelope system.](image-url)
In Figure 32, the three curves show the relationship between the wind speed and the percentage of glass breakage for each part of the building. The percentage of damage for upper, middle and lower parts of the building increase as the wind speed increase. For different parts of the building, the slopes of fragility curves vary as the wind speed changes. For the upper part of the building, the percentage of damage is relatively low at a lower speed (e.g., 70 mph), and it increases sharply as the wind speed increases. For the middle and lower part of the building, at a lower wind speed, the percentages of damage are larger compared with the upper part, but the increasing rates are smaller than the upper part, which leads to a relatively small percentage of damage compared with the upper part when the building sustains a high wind speed hurricane. The exact percentage of the damage can be obtained if the wind speed is provided so these curves as the fragility information of the building façade provide a good reference to the damage status of the building façade, which then can be converted to the water intrusion distribution according to the Straube’s approach (Straube et al., 2000).

**Development of water intrusion information**

In order to study the loss due to the rain penetration, it’s necessary to determine the amount of water that goes through the breakage of the building façade and accumulates in the building. Based on previous study (Lacy, 1965), an equation can be derived from Equation (9) and Equation (10) to describe the relationship between rate of WDR deposition on the vertical face of building envelope and a given hurricane (wind speed, wind direction, and rainfall intensity) as shown below:

\[ r_{by} = RAF \cdot DRF \cdot \cos(\theta) \cdot V \cdot r_h \quad (15). \]
In this equation, RAF denotes the rain admittance factor, DRF denotes the driven rain factor, $\theta$ is the angles between the wall and the wind direction, $V$ is the wind speed and $r_h$ is the rainfall intensity.

Since the building envelope can be divided into upper, middle and lower parts according to the different values of RAF, the total amount of water penetration is the summation of each of these three parts. The rate of each part of the building can be calculated using the following relation:

$$ r_{\text{total}} = \sum r_{hv} \cdot Area_n $$  \hspace{1cm} (16)

where $Area$ denotes the total breakage area of the certain part of the building façade.

The area of the upper, middle and lower part of a building can be determined by studying at the percentage of each part of the total building façade. According to the simplified RAF calculation method (Straube et al., 2000), the percentage of each part of the building is shown in Table 9. Therefore, the total breakage area of certain part of the building façade can be calculated using the following relation:

$$ Area = PBF \cdot Area_{\text{TOTAL}} \cdot Percentage $$  \hspace{1cm} (17)

where $PBF$ denotes the probability of failure of that part of the building and can be obtained using Figure 32 at a given wind speed, $Area_{\text{TOTAL}}$ denotes the total area of the building façade, and the $Percentage$ for each part can be obtained using Table 9.

Table 9. Percentage of each part of the building
### 7.3 Summary

WDR information based on actual hurricane damage was developed this chapter. In the WDR study, six cases, as used in Chapter 6, including four actual cases generated from hurricane reports and two assumed cases were used to develop fragility. The actual hurricane damage cases were generated using the simplified method proposed by Straube et al (2000). The damage percentage in upper, middle, and lower part of the building envelope was calculated separately. Since in this study, only a methodology of WDR development is discussed, certain assumptions were made to simplify the approach. Fragility information on damage information for different parts of the building is shown in Figure 32, and it helps to determine the damage status for different parts of the building envelope at a certain speed, which can help in the calculation of the amount of water penetration into the building. Research by Lacy (1965) provides a relationship between WDR and rain intensity and wind speed. In this study, by combining the fragility information of the building envelope damage and the previous study (Equation 15, the amount of WDR at a given hurricane can be obtained using Equation (16). This information can be used to performance-based design, and a case study is presented in the next chapter.
Chapter 8

Repair Cost

The objective of this study was to develop the fragility information of glazing systems by gathering real hurricane damage information. Based on the percentage damage to each building envelope system, the ratio of total repair cost to the initial (or replacement) cost of the system is approximated as a damage ratio for a building (Leicester et al., 1979).

8.1 Repair cost of the exterior of the building

Given the building damage, the cost of rebuilding a structure is computed using a combination of explicit and implicit loss methods (Vickery et al., 2006). The explicit cost functions are used to estimate the replacement and repair cost of the components of the exterior of the building (glass panels in this study) that are damaged and can be determined directly.

To estimate repair costs for different types of building components, information on replacement thresholds (e.g., the minimum amount of damaged roof cover required for a total roof cover replacement to be performed) should be obtained. Such information for residential, commercial, and industrial buildings are typically obtained through the examination of insurance company claim files and then converted into analysis models in software such as HAZUS (Vickery et al., 2006). In this study, the damage information is presented as the damage percentage of the total glass panels, which leads to a clear way to estimate the amount of glass panels that need replacement. Therefore, the total amount of repair cost is the cost of the labor cost and the cost of the material.

Based on the percentage damage to the building component, the damage ratio of a building is approximated (Leicester et al., 1979). In this study, after obtaining the damage ratio
using method discussed in Chapters 6 and 7, the initial cost of the building was obtained from construction cost databases such as R.S. Means Commercial Renovation Cost Data.

In this study, a method of determining the repair cost of the material is discussed, so certain assumptions were made to better illustrate the problem. Different materials are given in R.S. Means Commercial Renovation Cost Data, and 1/8” thick window glass is used in this study as an example. Table 10 shows the repair cost breakdown for the window glass.

Table 10. Repair cost breakdown for the window glass

<table>
<thead>
<tr>
<th>Sheet glass (S.F.)</th>
<th>Material ($)</th>
<th>Labor ($)</th>
<th>Total ($)</th>
<th>Total Incl. O&amp;P ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8” thick, clear float</td>
<td>3.60</td>
<td>1.47</td>
<td>5.07</td>
<td>6.35</td>
</tr>
<tr>
<td>Replace broken window lite, 1/8” glass</td>
<td>5.15</td>
<td>7.35</td>
<td>12.50</td>
<td>17.55</td>
</tr>
<tr>
<td>Minimum labor/equipment charge</td>
<td>/</td>
<td>141</td>
<td>141</td>
<td>141</td>
</tr>
</tbody>
</table>

In Table 10, the cost for 1/8” thick clear float glass is shown in terms of material cost and labor cost. The Total Incl. O&P column is the total cost, including overhead and profit, which the installing contractor will charge the customer. This represents the cost of material plus 10% profit, the cost of labor plus labor burden and 10% profit, and the cost of equipment plus 10% profit (R.S. Means, 2014) According to the fragility information developed in Section 6.3, at a given wind speed of the hurricane, the probability of different damage state can be obtained. Therefore, the repair cost can be written as follows:

\[ RC = Area \cdot Percentage \cdot R_{C_0} \]  \hspace{1cm} (18)

where \( RC \) denotes the repair cost of the damage to exterior of the building (building envelope damage), \( Area \) denotes the total area of building envelope the building has, \( Percentage \) is the damage state that is predefined in Section 6.3 for the fragility information, and \( R_{C_0} \) denotes the
unit cost of repair. In this study, the unit cost is 17.55 as the work after the hurricane damage is to replace the damaged glass panels.

8.2 Repair cost of the interior of the building

The implicit cost methods are used to estimate the cost of repairing the interior of the building. Since the damage information for the building envelope system only provides estimates of damage to the exterior of the building, the method that is usually used now involves a combination of engineering judgment and insurance company loss data.

The damage ratio of the structural system is the weighted-average of the damage percentages of all structural components considered in the integrated vulnerability model (roof cover, roof-sheathing panels, and others), with the weights proportional to the repair cost of the corresponding component. Similarly, damage ratios may be defined for the interior system and the utility system, which, when combined with the structural system, would constitute an entire building structure. However, unlike that of the structural system, the damage on the interior system and utility system are not readily analyzable using (structural) engineering models. The total damage ratio of a building, which is a measure of insurance loss, is the weighted-average of the damage ratios of each subassembly, with the weights proportional to the respective repair costs. Content loss, additional living expenses, and business interruption are usually also counted in economic loss estimation in the insurance industry (Yau et al., 2011).

According to HAZUS implicit functions study, the cost of repair interior damage during the hurricane damage is related to the physical damage to the exterior of the building, coupled with estimates of the amount of water that has entered the building following envelope breaches associated with failures of the windows (Vickery et al., 2006). Therefore, the repair cost of the
interior of the building can be related to the wind speed through the fragility information
developed in Section 7.2.

8.3 Case study using fragility information

In this section, an assumed case study is presented to illustrate the application of fragility
information developed in Chapter 6 and Chapter 7.

Assume the building is located in the coastal area and may sustain hurricane damage. The
area of the glass panels building envelope system is $A$ ft$^2$, and the impacting hurricane discussed
in this case has a wind speed of 100 mph and rainfall intensity is $B$ in/ft$^2$/h, and the average
rainfall degree is 45°.

The fragility information of impact by WBD can be obtained using fragility curve in
Figure 27. Since the average wind speed of the hurricane is 100 mph, the probability of reaching
each predetermined damage degree can be obtained shown in Table 11.

<table>
<thead>
<tr>
<th>Predetermined damage degree</th>
<th>Probability of failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>0.999688</td>
</tr>
<tr>
<td>25%</td>
<td>0.126596</td>
</tr>
<tr>
<td>30%</td>
<td>4.01427E-10</td>
</tr>
</tbody>
</table>

Since the cost of replacement for the glass panels is discussed in this chapter and
presented in Table 12, the repair cost for glass panels for each predetermined damage state can be
calculated by the definition of repair costs (R.S. Means, 2014).
Table 12. Repair cost for each predetermined damage degree

<table>
<thead>
<tr>
<th>Predetermined damage degree</th>
<th>Repair cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>3.51*A</td>
</tr>
<tr>
<td>25%</td>
<td>4.39*A</td>
</tr>
<tr>
<td>30%</td>
<td>5.27*A</td>
</tr>
</tbody>
</table>

*The rounding of the costs should follow R.S. Means 2014

For the WDR calculation, the percentage of different parts of building envelope system should be determined using fragility information developed for WDR in Figure 32, and the area for each part can also be calculated using Table 13.

Table 13. Damage area for each part of the building envelope

<table>
<thead>
<tr>
<th>Part</th>
<th>Damage percentage</th>
<th>Total area</th>
<th>Area of damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>18.19%</td>
<td>0.2447*A</td>
<td>0.0445*A</td>
</tr>
<tr>
<td>Middle</td>
<td>24.93%</td>
<td>0.2871*A</td>
<td>0.0715*A</td>
</tr>
<tr>
<td>Lower</td>
<td>25.03%</td>
<td>0.4682*A</td>
<td>0.1172*A</td>
</tr>
</tbody>
</table>

The amount of WDR intrusion can be calculated using Equation (16), and the results for different parts of water intrusion are shown in Table 14.

Table 14. Water intrusion in each part of the building envelope

<table>
<thead>
<tr>
<th>Part</th>
<th>Rate of WDR deposition</th>
<th>Rate of WDR deposition in each part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>12.726*B</td>
<td>0.0566<em>A</em>B</td>
</tr>
<tr>
<td>Middle</td>
<td>9.898*B</td>
<td>0.0708<em>A</em>B</td>
</tr>
<tr>
<td>Lower</td>
<td>7.070*B</td>
<td>0.8286<em>A</em>B</td>
</tr>
</tbody>
</table>
Chapter 9

Summary and Conclusions

This study has focused on the development of fragility information for glass panels as building envelope system under hurricane condition. Reviews of past hurricane damage reports (FEMA 549, FEMA 75) were conducted, and two kinds of damage, i.e., WBD and WDR, were determined to be the primary damage types for commercial buildings during hurricane conditions. Fragility information for WBD was developed based on both lab tests data and actual hurricane data, and fragility information for WDR was developed based on lab tests data.

For WBD, lab tests have been conducted on missile impact on glass panels (Shah, 2009), and the fragility information based on previous lab test results were developed in this study. Three groups of specimens with different sizes and thicknesses were tested with the same impacting speeds and the same impacting missiles. The fragility curves show that compared with 1/8” thick glass panels, 3/16” thick glass panels have a better performance at an impacting speed of 8 m/s to 21 m/s. At an impacting speed of 18 m/s, 3/16” thick glass panels have 32.86% less probability of failure compared with 1/8” thick glass panels. For the 1/8” thick specimens, 2x2 glass panels and 2x4 glass panels have similar performance. The impacting speed for breakage for the 1/8” panels is about 7 m/s and the impacting speed for 100% breakage is 19 m/s. The median breakage speeds for 1/8” 2x2 glass panels, 1/8” 2x4 glass panels and 3/16” 2x2 glass panels are 11.57 m/s, 12.06 m/s, and 17.28 m/s, respectively, which indicates the thicker glass panels have a better performance with a higher breakage speed.

Some key findings for the fragility information based on lab test data:

- Medians of the impacting speed to break the glass panels are 11.57 m/s for 1/8” 2x2 glass panels, 12.06 m/s for 1/8” 2x4 glass panels, and 17.28 m/s for 3/16” 2x2 glass panels.
• All three types of glass panels will fail when impacting speed is greater than 21.5 m/s.

• The thicker glass panels perform better with a higher impacting speed to start breakage (13.4 m/s).

• Compared with thickness, the size of the glass panels has a less contribution to the performance, with less than 5% of difference for the median impacting speed to fail.

However, limitations of the lab experiments do not allow direct use of the test results into the analysis of actual hurricane case and design. Since in the lab tests, all impacting missiles hit the glass panels, while in the actual case, not all glass panels are hit by the WBD. The alternative way of obtaining valid data for building envelope under real hurricane condition analysis.

For the WBD study based on actual hurricane damage data, three predetermined damage degrees (20%, 25%, and 30%) were used in developing fragility information. The WBD damage curves show the damage conditions start to reach 20%, 25%, and 30% at 85 mph, 97 mph, and 117 mph, respectively. At a wind speed of 117 mph, the damage of the building envelope is sure to sustain at least 20% of damage and has a probability of 99.4% of reaching predetermined damage degree 25% and 0.7% probability to reach 30% damage degree.

For WDR fragility information, the WDR curves show the damage percentage of different parts of the building envelope system. At a relatively low wind speed condition (<80 mph), the damage for each part of the building envelope is less than 20%, and the upper part of the building sustains a less damage percentage. However, at a relatively high wind speed condition, the upper part of the building envelope sustains a higher percentage of damage, compared with middle and lower part of the building envelope.
Some key findings for the fragility information based on actual hurricane damage data are as follows:

- For WBD, the glass panel starts to sustain a 20% damage at a wind speed of 85 mph, a 25% damage at a wind speed of 97 mph, and a 30% damage at a wind speed of 117 mph.

- The fragility curves show that at a wind speed of 145 mph, the glass panel building envelope has 99.5% possibility to sustain more than 30% damage, while at a wind speed of 85 mph, the building envelope has 3% of possibility of 20% damage.

- For WDR fragility curves, compared with middle and lower part, the upper part sustains less damage at a low wind speed (7% damage at 80 mph), but sustain greater damage at a high wind speed (60% damage at 160 mph).

- The middle and lower part of the building envelope have similar performance at a relatively low wind speed, with only 5% of difference at 90 mph.

- The upper part of the building is more vulnerable to the high-speed wind and the damage percentage increase quickly as wind speed increase.

With this developed fragility information, the performance of a building with glass panels building envelope under hurricane condition can be evaluated. The cost of repair can then be analyzed using R.S. Means information based on the developed fragility information.

Some key findings for the case study based on fragility information for WBD and WDR:

- The cost of replacing the broken glass panels is 99.97% probability over 3.51*A, 12.65% probability over 4.39*A, and not likely more than 5.27*A.

- The lower part has the most amount of water intrusion (0.0708*A*B), which leads to
most interior damage of the building.

- The case study shows the repair cost of lower part of the building is greater for exterior and interior of the building at a wind speed of 100 mph compared to the upper and middle part of the building.

There are still many limitations for this study. Studies on fragility information can benefit from using lab tests data, but in this study, data from actual cases obtained from hurricane reports were used for the analysis. Due to the lack of past studies and shortage of available actual damage cases, limited data were used in developing fragility information of the glass panels. Therefore, certain assumptions were made to simplify the problem, as development of the methodology was of greater interest in this study. Due to the limitation of the amount of the data available, the fragility curves of the glass panels under WBD and the fragility information for WDR developed should be considered at best as preliminary and draft, and are not for practical use. The accuracy for the fragility information can be expected to improve as more data become available in the future.

In addition, the analysis of repair cost of the interior of the building also relies on the types of the building interior furniture and the business types of the building, which was not considered in this study, rather, only the direct loss due to the WDR was discussed.

Based on limitation of available data identified in this study, the following recommendations are made for follow-up studies:

- Need more real hurricane damage data, including wind speeds and glass damage on many more buildings to increase the accuracy of fragility information. Inspection of damaged buildings after hurricane impact should preferably not be limited in taking photos. The wind speeds at locations of buildings damaged and glass types are also key factors to determine during hurricane damage.
reconnaissance efforts, which will provide very useful information for more accurate fragility development. It is expected that more data will become available as more detailed reconnaissance reports are prepared following future damaging hurricanes.

- New laboratory experiments to help understand the probability of missile impact on the nearby buildings will be of great value. For example, wind tunnel tests can be conducted to determine the probability and conditions that shingles or other types of WBD from a shorter model building may strike glass panels on taller model buildings. In this way, the lab test data can be used for more realistic hurricane damage analysis.

- Further lab tests on the relationship between wind speed and WBD impact speed will help refine the fragility information. There can be a significant difference between the impact speed and the wind speed leading to breakage of glass panels. Appropriate tests should be designed to determine the relationship between WBD impact speed and the hurricane wind speed so that the result of lab tests for WBD can be used in analysis of real hurricane damage.
References


