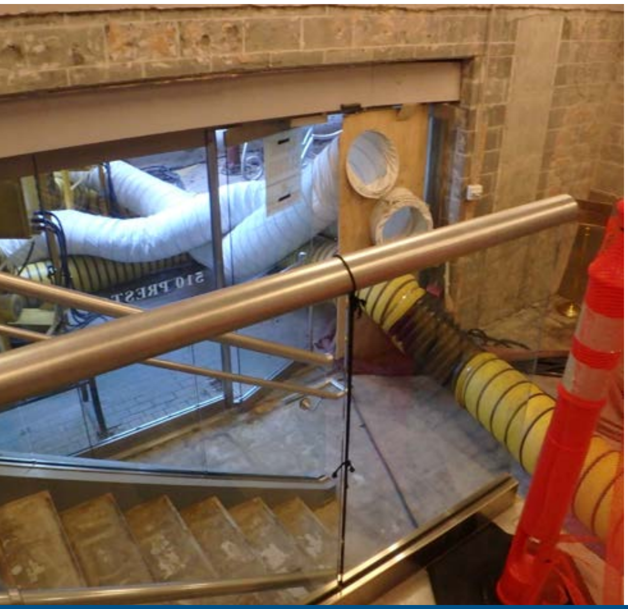

Mitigation Assessment Team Report

Hurricane Harvey in Texas

Building Performance Observations, Recommendations, and Technical Guidance

FEMA P-2022 / February 2019

U.S. Department of Homeland Security

FEMA

MITIGATION ASSESSMENT TEAM REPORT

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FEMA

Houston, TX
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All photographs and figures used in this report were taken by the MAT or developed for this report unless stated otherwise. Aerial imagery noted as “courtesy of the Texas Civil Air Patrol” was obtained by the Texas Civil Air Patrol as directed by FEMA.

All documents were prepared with accessibility and compliance with Section 508 of the Rehabilitation Act of 1973 in mind. For further information or clarification regarding items such as technical drawings or maps, please contact the FEMA Building Science Helpline at FEMA-BuildingScienceHelp@fema.dhs.gov or 866-927-2104.

Map imagery sources (unless otherwise noted in the report):

Aerial imagery: Google Earth Pro, https://www.google.com/earth/ (used with license, accessed September 2017 through December 2018).

FIRMs (Flood Insurance Rate Maps): FEMA Map Service Center, msc.fema.gov

Members of the Mitigation Assessment Team

Team Leader

Daniel Bass, RA, CFM
FEMA

Team Manager

Manuel Perotin, PE, CFM
CDM Smith

Report Manager

Samantha N. Krautwurst, PE
AECOM

Team Members

Gavin Allwright
CDM Smith

Jovannie Cartajena-Cabrera
FEMA

Edward Curtis, III, PE, CFM
FEMA

Kate De Gennaro
NOAA Texas Sea Grant

David Drnevich, PE
FM Global

Andrew Foote
FM Global

Jerry Frye
FEMA

Nathan Gould, PE, SE
ABS Consulting

Dennis Hwang
NOAA Hawaii Sea Grant

Javier Janer, RA
American Institute of Architects

Thomas Kane
FEMA

Dr. Thomas Kirsch, MD, MPH, FACEP
National Center for Disaster Medicine and Public Health

Phil Line, PE
American Wood Council

David Low, PE
DK Low & Associates

Joseph Main, PhD
National Institute of Standards and Technology

Robert Nystrom, PE
CDM Smith

Brian O'Connor, PE, CFM
CDM Smith

Walter Peacock
NOAA Texas Sea Grant

Michael Pfeiffer, PE
International Code Council

Rebecca Quinn, CFM
RCQuinn Consulting, Inc.

Paul Saphos, RA
FKP/Cannon Design

Kelsey Schill
CDM Smith

Pataya Scott, EIT
FEMA

Thomas Smith, AIA, RRC, F.SEI
TLSmith Consulting Inc.

Henry Snow
FEMA

James Snow, PE, SE
ABS Consulting

Eric Stafford, PE
AECOM

Larry Tanner, PE, RA
Tanner Consulting

Heather Wade
NOAA Texas Sea Grant

Donnie Walsh
FEMA

Gregory Wilson
FEMA

Internal Support

Drone Support:
Scott Aldridge, CDM Smith

GIS Specialist:
Caitlin Olson, CDM Smith

Graphic Artists:
Lee-Ann Lyons, AECOM
Billy Ruppert, AECOM

Technical Editors and Formatting:
Young Cho, AECOM
Susan Ide Patton, PG, AECOM
Ivy Porpotage, AECOM
Amy Siegel, AECOM

508 Compliance:
Carol Cook, AECOM

MITIGATION ASSESSMENT TEAM REPORT

HURRICANE
HARVEY
IN TEXAS

Executive Summary

Hurricane Harvey was the wettest rainfall event in U.S. history, dropping up to 70 inches of rain in portions of southeastern Texas.

Hurricane Harvey made landfall over San Jose Island, just north of Port Aransas, TX, on August 25, 2017, at 10 p.m. CDT. At landfall, Hurricane Harvey was a Category 4 hurricane with estimated sustained winds of 130 mph. It was the eighth named storm during the 2017 hurricane season and the first of the three major 2017 hurricanes to impact the U.S. mainland or territories.

NOTEWORTHY STORM METRICS

- First Category 4 hurricane to make landfall on the Continental United States since 2005 (NOAA NWS, 2017)
- Sustained winds of 130 mph winds (NHC, 2017)
- Dropped an estimated 70 inches of rainfall over parts of Texas during a 7-day period (NOAA NWS, 2017)
- One of the most destructive storms in U.S. history, with an estimated $125 billion (2017 dollars) in damages (NOAA NCEI, 2018), which is the second highest in U.S. history behind Hurricane Katrina

Mitigation Assessment Team Deployment and Observations

In response to a request for technical support from the Federal Emergency Management Agency's (FEMA's) Joint Field Office in Austin, TX, FEMA deployed a Mitigation Assessment Team (MAT) to Texas in November and December of 2017 to evaluate building performance during Hurricane Harvey. The MAT was deployed to Harris County to assess flood performance issues, and to Aransas, Nueces, Refugio, and San Patricio Counties to assess wind performance issues. MAT members evaluated building systems to determine the effectiveness of various design and construction practices and ascertain the effect of code adoption and enforcement on reducing flood and wind damage. To improve resiliency in future events, the lessons learned from MAT deployments and reports can either be incorporated into best practices for future retrofits or new hazard-resistant building design.

In Harris County, the MAT evaluated the relationship between residential building damage and the age of the building and assessed the performance of dry floodproofing measures in non-residential buildings. The MAT visited a mixture of new and old construction in the same general vicinity to help assess the performance of residential buildings constructed to both minimum floodplain management standards and higher standards under the same flood conditions. For non-residential buildings, the MAT visited dry floodproofed buildings that were mitigated with FEMA funding following Tropical Storm Allison (2001), as well as buildings that were dry floodproofed with private funding.

In Aransas, Nueces, Refugio, and San Patricio Counties, the MAT primarily examined the wind pressure performance of main wind force resisting systems (MWFRSs) and building envelopes, the effects of wind-borne debris on building envelopes, rain infiltration at building envelope breaches, and the performance of ground-mounted solar panel arrays. To assess building performance, the MAT reviewed the code requirements related to construction of buildings in high-wind areas. Although Texas has not adopted a building code at the State level, many communities visited by the MAT had adopted the 2009, 2012, or 2015 International Building Code® (IBC®) and International Residential Code® (IRC®). In addition, the Texas Department of Insurance (TDI), which is the administrator of coastal windstorm insurance, adopted the 2006 IRC in July 2007. To qualify for an insurance policy under the Texas Windstorm Insurance Association, buildings in all 14 coastal counties and parts of Harris County must meet the 2006 IRC with Texas Revisions, which references the 2005 edition of the American Society of Civil Engineers (ASCE) standard ASCE 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures.*

Hurricane Harvey's wind speeds produced pressures that approximated design pressures derived from various editions of ASCE 7, depending on a building's proximity to the track of the storm and building and site characteristics, which provided an opportunity for the MAT to evaluate building performance at near design conditions.

Summary of Damage Observed by the MAT

Hurricane Harvey caused widespread damage to buildings, power distribution systems, and water utility services in both the region impacted by its landfall and the area affected by the historic rainfall. Hurricane Harvey caused extensive sheet flow and riverine flooding in southeastern Texas; houses constructed before the communities had joined the National Flood Insurance Program (NFIP) and adopted floodplain management regulations and Flood Insurance Rate Maps (FIRMs) were hit the hardest. Although most of the damage from Hurricane Harvey was caused by flooding, at and near design-level wind pressures in accordance with ASCE 7-05, as referenced by the 2006 IBC and IRC, caused significant damage to older buildings in Aransas, Nueces, Refugio, and San Patricio Counties.

Flood. Flood damage from Hurricane Harvey was extensive and significant, impacting residential and non-residential buildings located in the 1.0-percent-annual-chance probability (100-year event) floodplain, 0.2-percent-annual-chance probability (500-year event) floodplain, and areas outside the 0.2-percent-annual-chance floodplain. In Harris County and municipalities in the county, including the City of Houston, 22 percent of buildings experienced flood damage. The majority of flood-damaged residential buildings were older, slab-on-grade buildings built before the communities joined the NFIP or were built outside the 0.2-percent-annual-chance probability floodplain. Houses built in the 1980s, to a lower base flood elevation than what is required by current FIRMs, also sustained inundation damage. Recently constructed NFIP-compliant houses suffered minor damage because of non-flood damage-resistant materials, mainly insulation and drywall, used below the elevation specified by regulation.

Figure ES-1 summarizes closed flood insurance claim data for a representative residential area in Texas. As shown in the figure, averaged claims were approximately $88,000 lower per building when local floodplain management regulations had been adopted before, rather than after, buildings were constructed.

Observed failures at dry floodproofed buildings resulted from overtopping of flood walls or barriers, structural failure of flood barriers, seepage through flood barriers, seepage through utility penetrations, and insufficient planning. As a result of these failures, critical building systems located in basements and first floors were damaged and rendered inoperable.

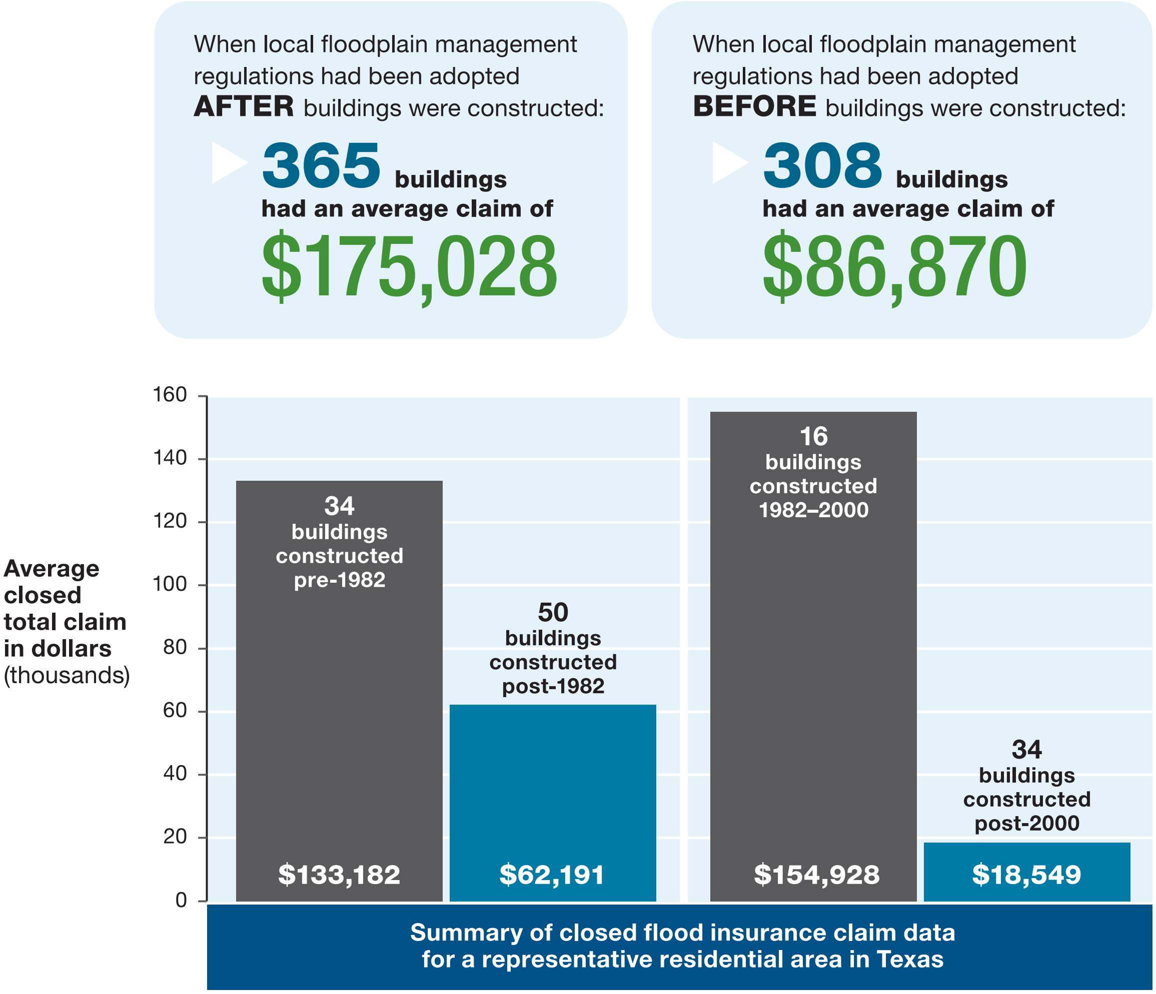

Figure ES-1: Effect of floodplain management on housing claims

Wind. Within the greater Rockport, TX, area, winds from Hurricane Harvey caused extensive damage to roof coverings and rooftop equipment, which resulted in rain damage of interior finishes, furnishings, and equipment. Wind-related building damage is primarily attributable to using improper materials in hurricane-prone regions; design deficiencies; poor installation or failure to follow installation guidelines for wall coverings, windows, and doors in high-wind zones; and inadequate attachment of roof coverings and roof-mounted equipment. MWFRS damage was observed mainly at older buildings; the observed building envelope damage for more recently constructed residential and non-residential buildings was less severe than that for older buildings.

MAT Recommendations

The recommendations developed by the MAT are based on its field observations. The recommendations are directed toward design professionals, contractors, building officials, floodplain administrators, and building owners along with some that are directed to FEMA. The higher priority recommendations for each general topic are summarized in the text that follows.

General recommendations. TDI should provide training to Windstorm Inspection Program inspectors and building code enforcement staff, placing emphasis on changes reflected in the latest adopted edition of the building code. The Texas Water Development Board and other stakeholders should develop/modify training on the flood provisions in model building codes and/or floodplain management ordinances. Facility and building owners should perform vulnerability assessment of their facility to help identify wind and flood hazards prior to a disaster.

Building codes and floodplain management ordinances. TDI should adopt the 2018 IBC and the IRC as the model codes for its Windstorm Inspection Program and consider developing a more stringent high-wind retrofit program. Communities should review and update portions of local floodplain management or flood damage prevention ordinances and guidance, particularly where they conflict with requirements in model ordnances and building codes.

Flood-related building performance. Communities and building owners should consider elevating new and Substantially Damaged/Substantially Improved buildings above the NFIP elevation requirements to protect them from flooding. Local floodplain administrators, design professionals, and building owners in Texas Recovery Advisory 1, *Dry Floodproofing: Planning and Design Considerations* (2018g) and *Florida Recovery Advisory 1, Dry Floodproofing: Operational Considerations* (2018f). Flood damage-resistant materials should be used below the design flood elevation inside dry floodproofed buildings when possible. Also, facility managers should develop an emergency operations plan for severe weather.

Wind-related building performance. Building owners and/or facility managers should ensure adequately roof-mounted equipment is adequately anchored and consider protecting the glazed openings on their existing buildings. Windstorm inspectors and local building officials should enforce the use of approved materials in high-wind regions and ensure they are installed in accordance with the manufacturers' requirements. Design professionals should specify, and contractors should use, face nails on fiber cement siding. Design professionals, contractors, and inspectors should place more emphasis on proper soffit installation in high-wind regions to limit wind-driven rain from entering building envelopes and damaging building interiors. FEMA should ensure that securing roof-mounted equipment is incorporated into eligible Public Assistance Hazard Mitigation Proposals.

FEMA technical publications and guidance. FEMA should complete *Guidelines for Wind Vulnerability Assessments for Critical Facilities*. FEMA should include lessons learned from the 2017 hurricane season in finishing this publication. FEMA should update the Risk Management Series guidance publications to include lessons learned from the 2017 hurricane season and to reflect updates to current building codes since the publications' release. FEMA should make the requirements for projects developed under the FEMA Public Assistance and the Hazard Mitigation Assistance programs consistent between the programs. Hazard Mitigation Proposals for dry floodproofing under the Public Assistance program should be required to reference ASCE 24, *Flood Resistant Design and Construction*. In addition, FEMA should update dry floodproofing guidance, in particular Technical Bulletin 3, *Non-Residential Floodproofing – Requirements and Certification* (1993). Furthermore, FEMA should evaluate existing dry floodproofing guidance and post-flood investigations to develop a recommendation for inclusion in ASCE 24. FEMA should update FEMA P-758, *Substantial Improvement/Substantial Damage Desk Reference* (2010) to incorporate new lessons learned and recommended guidance and clarifications since it was published in 2010; at the same time FEMA 213, *Answers to Questions about Substantially Damaged Buildings* (2018b), should be updated to be consistent with the updated FEMA P-758. Finally, FEMA should consider expanding existing training materials related to Substantial Improvement/Substantial Damage.

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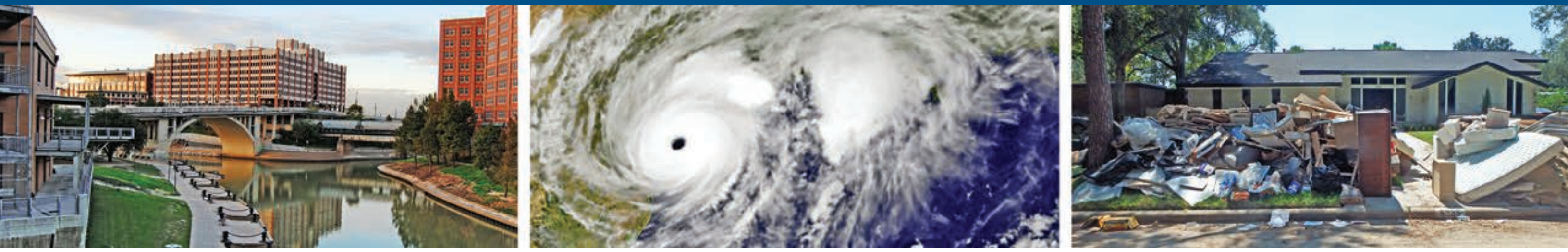
Acronyms and Abbreviations

AAMA	American Architectural Manufacturers Association
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASD	allowable stress design
BFE	base flood elevation
BIA	Brick Industry Association
BUR	built-up roofs
C&C	components and cladding
CDT	central daylight time
CFR	Code of Federal Regulations
CHI	Catholic Health Initiative
CMU	concrete masonry units
COM	College of Medicine (Baylor)
CRS	Community Rating System
DASMA	Door & Access Systems Manufacturers Association, International
DFE	design flood elevation
DoD	Department of Defense
EIFS	Exterior Insulation and Finish System
FEMA	Federal Emergency Management Agency
FIMA	Federal Insurance and Mitigation Administration
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
FM	FM Approvals
HCFCD	Harris County Flood Control District
HGSD	Harris-Galveston Subsidence District
HVAC	heating, ventilation, and air conditioning
HWM	high water mark
IBC	International Building Code
I-Codes	International Codes
IEBC	International Existing Building Code
IRC	International Residential Code
JFO	Joint Field Office

LiMWA	Limit of Moderate Wave Action
LPS	lightning protection systems
MAT	Mitigation Assessment Team
mb	millibars
MEP	mechanical, electrical, and plumbing
MH	manufactured housing
mph	miles per hour
MRI	mean recurrence interval
MWFRS	main wind force resisting system
NAMI	National Accreditation and Management Institute, Inc.
NAVD	North American Vertical Datum of 1988
NCEI	National Centers for Environmental Information
NFIP	National Flood Insurance Program
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PTAC	packaged terminal air conditioners
psf	pounds per square foot
PV	photovoltaic
SCADA	supervisory control and data acquisition
SFHA	Special Flood Hazard Area
SME	subject matter expert
SPRI	Single Ply Roofing Industry
TCH	Texas Children's Hospital
TCPIA	Texas Catastrophe Property Insurance Association
TDI	Texas Department of Insurance
TECO	Thermal Energy Corporation
TMC	Texas Medical Center
TWIA	Texas Windstorm Insurance Association
USACE	U.S. Army Corps of Engineers
USVI	U.S. Virgin Island
UT	University of Texas
U.S.C.	U.S. Code

MITIGATION ASSESSMENT TEAM REPORT



HURRICANE
HARVEY
IN TEXAS

1

Introduction

Hurricane Harvey made landfall in Texas on the night of August 25, 2017, as a Category 4 hurricane that dropped a historic amount of rainwater before it left the area 7 days later.

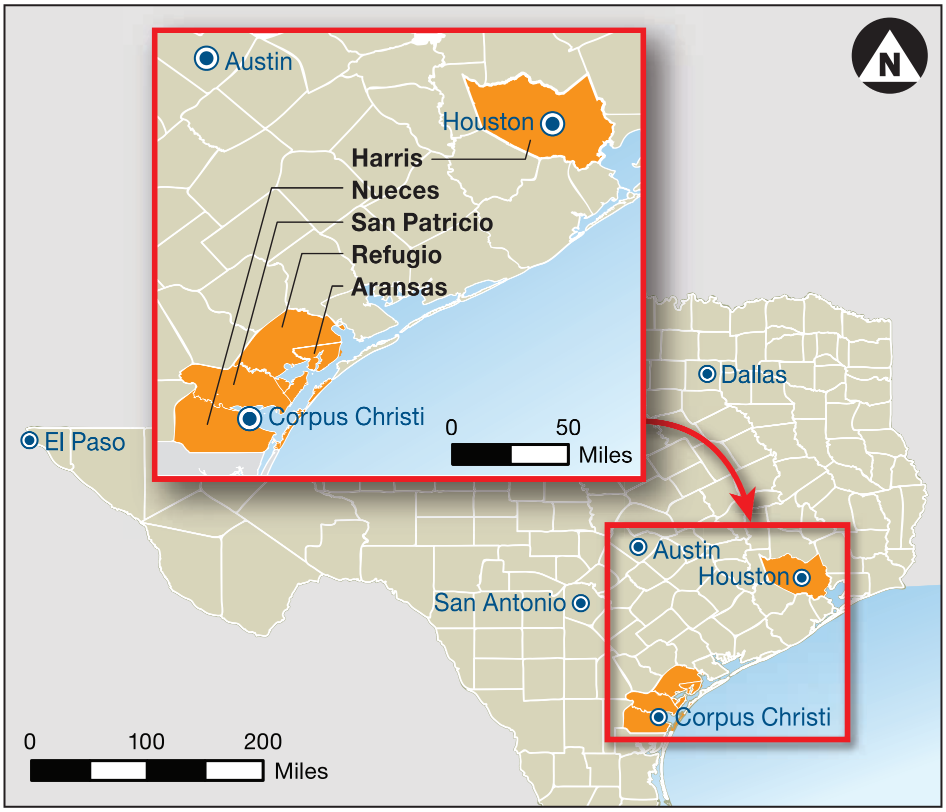
When Hurricane Harvey made landfall in Texas on the night of August 25, 2017, between Port Aransas and Port O'Connor, it was the first Category 4 hurricane to make landfall on the continental United States since Hurricane Charley in 2004 and the first Category 4 hurricane to make landfall in Texas since Hurricane Carla in 1961.

Hurricane Harvey struck the Texas coast with 130 miles per hour (mph) sustained winds and was the wettest rainfall event in the country's history, dropping an estimated 34 trillion gallons of rainwater, with local rainfall totals of 70 inches in some places over 7 days (NOAA NHC, 2018a). Hurricane Harvey was one of the most destructive storms in U.S. history. It caused extensive wind damage where it made landfalls and significant flood damage in the Houston metropolitan and Beaumont areas. The National Oceanic and Atmospheric Administration (NOAA) estimates damages at approximately $125 billion (NOAA NHC, 2018a).

As part of its response to the disaster, the Building Science Branch of the Federal Emergency Management Agency's (FEMA's) Federal Insurance and Mitigation Administration (FIMA) deployed a Mitigation Assessment Team (MAT). MATs are composed of national and regional experts in building science and other relevant disciplines who assess building performance to improve resilience by incorporating lessons learned into new construction and the retrofit of existing buildings. The MAT was deployed on November 7, 2017, and deployed again on December 12, 2017 to complete its field assessment work. The MAT focused on buildings located in the area of Hurricane Harvey's landfall in Aransas, Nueces, Refugio, and San Patricio Counties and the flooded areas of Harris County and the City of Houston (see Figure 1-1).

This report describes the MAT's observations during its field assessments and the conclusions and recommendations developed based on those observations. The purpose of this MAT report is to evaluate the key causes of building failures and successes, describe lessons learned to help property owners and stakeholders mitigate damage from future natural hazard events, and provide recommendations to improve the resilience of buildings and communities. The report provides information that will help communities, businesses, design professionals, contractors, residential and non-residential building owners and operators, code officials, various planners, individuals, and other stakeholders to recover more quickly. The information can also be used to design and construct more robust buildings so that loss of life, injuries, and property damage resulting from future natural hazard events are minimized.

Figure 1-1:
MAT area of focus



Flood-related topics investigated by the MAT include floodplain management regulations and codes, the performance of residential buildings damaged in locations mapped on FEMA's Flood Insurance Rate Maps (FIRMs), the performance of dry floodproofing systems in Harris County, the performance of FEMA-funded dry floodproofing mitigation projects, and the role and effectiveness of select emergency management and planning efforts.

Wind-related topics studied by the MAT include building code design requirements, the wind pressure performance of main wind force resisting systems (MWFRSs) and building envelopes (including rooftop equipment and solar panels), the effects of wind-borne debris on building envelopes, rain infiltration at building envelope breaches, and the performance of ground-mounted solar panel arrays on residences and commercial and critical facilities.

MAIN WIND FORCE RESISTING SYSTEM (MWFRS)

An assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface.

BUILDING ENVELOPE / COMPONENTS AND CLADDING (C&C)

Elements of the building envelope that do not qualify as a part of the MWFRS are identified as C&C in American Society of Civil Engineers (ASCE) standards.

SOURCE: ASCE, 2010

1.1 Organization of Report

This MAT report is divided into five chapters and three appendices.

- This chapter describes Hurricane Harvey, historic hurricanes in Texas, and the MAT background and process.
- Chapter 2 discusses building codes, standards, and regulations as they relate to wind design and floodplain management and their effect on design and construction in Texas.
- Chapter 3 describes MAT observations related to the performance of residential and non-residential buildings under flood conditions and provides emergency management and planning considerations for non-residential buildings and critical facilities.
- Chapter 4 describes MAT observations related to the performance of buildings exposed to high winds and evaluates the effect building codes have had on wind performance.
- Chapter 5 presents the MAT's conclusions and recommendations and is intended to help guide recovery efforts for communities prone to hurricanes and floods and to provide strategic recommendations to help improve codes and standards, design and construction guidance, code enforcement, and planning on a regional and national scale.

In addition, the following appendices are included:

- Appendix A: Acknowledgments
- Appendix B: References
- Appendix C: Recovery Advisories
    - Texas Recovery Advisory 1, *Dry Floodproofing: Planning and Design Considerations*
    - Texas Recovery Advisory 2, *Asphalt Shingle Roofing for High-Wind Regions*

1.2 Hurricane Harvey: The Event

Hurricane Harvey was the first major[1] hurricane to make landfall on the United States since Hurricane Wilma in 2005. Hurricane Harvey formed from a tropical wave off the west coast of Africa on August 12, 2017 (NOAA NHC, 2018a). On August 17, Harvey developed into a tropical storm that impacted the Lesser Antilles, later degenerating back into a tropical wave as it moved west across the Caribbean Sea. It rapidly strengthened in the Bay of Campeche on August 23, 2017, reforming into a tropical storm and becoming a Hurricane on August 24, 2017. Hurricane Harvey made its first landfall in the United States over San Jose Island, just north of Port Aransas, TX, on August 25, 2017, at 10 p.m. as a Category 4 hurricane with estimated sustained winds of 130 mph and a minimum pressure of 937 millibars (mb). Hurricane Harvey's second landfall occurred 3 hours later on the Texas mainland southeast of Refugio with estimated sustained winds of 121 mph and a minimum pressure of 948 mb. Hurricane categories are rated on the Saffir-Simpson Hurricane Wind Scale (Table 1-1).

HARVEY'S TRACK

Hurricane Harvey was unique in its formation but not its track. Hurricane Harvey rapidly developed from a tropical depression to a Category 4 hurricane in 56 hours.

Although the magnitude of the event was unprecedented, the stalling of Hurricane Harvey over southeastern Texas was not; other tropical cyclone flood events, most notably Tropical Storm Allison in 2001, have followed similar tracks.

Table 1-1: Saffir-Simpson Hurricane Wind Scale Wind Speeds and Barometric Pressures

Strength	Sustained Wind Speed (mph)	Gust Wind Speed (mph)	Pressure (mb)
Category 1	74–95	89–116	>980
Category 2	96–110	117–134	965–979
Category 3	111–129	135–158	945–964
Category 4	130–156	159–190	920–944
Category 5	157 or higher	>190	<920

Sustained Wind Speed = 1-minute sustained over open water
Gust Wind Speed = 3-second gust over open water
mb = millibars
SOURCE: NOAA NHC, 2018B

After Hurricane Harvey made landfall, it continued northwest until the center of the storm stopped northwest of Victoria, TX. For the next 24 hours, the center of the storm remained almost stationary, making a slow loop that caused bands of heavy rain to continually fall over the Houston metropolitan area and southeastern Texas. On August 27, 2017, now downgraded to Tropical Storm Harvey, the storm proceeded in an easterly direction, re-entering the Gulf of Mexico on August 28 and slightly strengthening. Tropical Storm Harvey made its third and final landfall on August 30 near Cameron, LA, with sustained winds of 45 mph. Figure 1-2 shows Hurricane Harvey's track from August 17, 2017 through September 1, 2017.

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[1] A major hurricane is a Category 3, 4, or 5 storm on the Saffir-Simpson Hurricane Wind Scale.

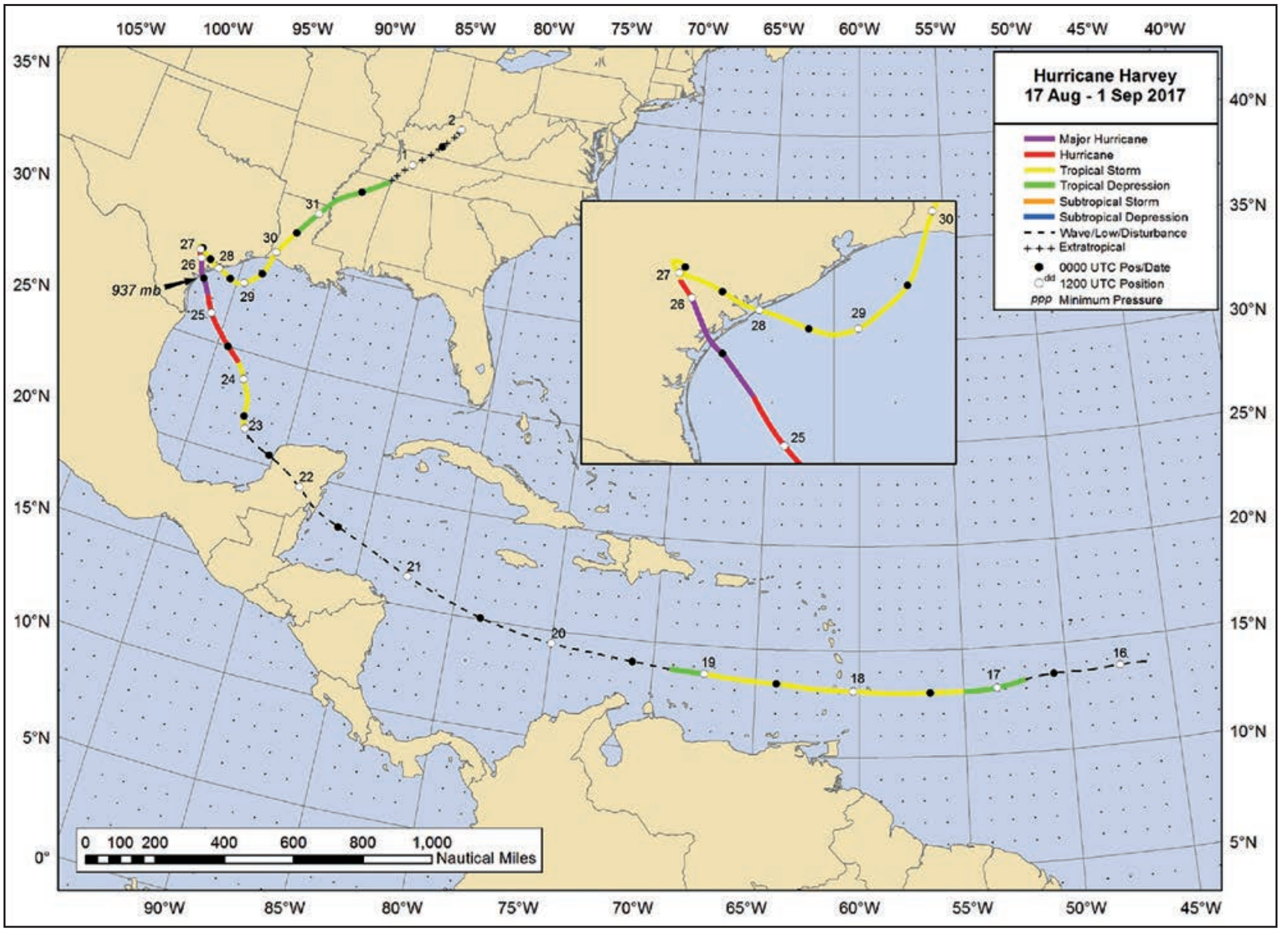

Figure 1-2: Hurricane Harvey storm track

SOURCE: NOAA NHC, 2018a

THE SIGNIFICANCE OF HURRICANE HARVEY

- Hurricane Harvey was the highest categorized hurricane to strike the U.S. coastline since Hurricane Charley hit Florida in 2004.
- At landfall, Hurricane Harvey was approximately 250 miles in diameter, with a wind speed of 74 mph (sustained) across a width of 80 miles.
- Harvey made landfall in the U.S. three times: twice in Texas and once in Louisiana as a tropical storm, causing widespread damage in Texas and southwestern Louisiana.
- Local rainfall totals in southeast Texas ranged from 20 inches to 70 inches over 7 days, making it the wettest hurricane in U.S. history; rainfall totals exceeded the 0.1-percent-annual-chance probability (1,000-year) event in some areas.
- Within Harris County, 300,000 vehicles were flooded.
- Advance warning 2 days before the hurricane's landfall resulted in mandatory evacuations of multiple counties; an estimated 560,000 people evacuated in advance of the hurricane.

1.3 Hurricane Harvey: The Impact

The path of Hurricane Harvey, with two landfalls on the Texas Gulf Coast and a third landfall in Louisiana, resulted in a widespread storm impact, with coastal storm surge in the areas around its three U.S. landfalls and historic inland flooding caused by 7 days of rain throughout southeastern Texas. Additionally, the greater Rockport, TX, area incurred significant wind damage during Hurricane Harvey's first two U.S. landfalls.

1.3.1 Flood

Flooding impacts from Hurricane Harvey were caused by the storm surge and historic rainfall, which resulted in significant inland flooding; the history of subsidence in Harris County also contributed to the damage observed. Aerial imagery revealed that approximately one-third of Harris County was under water at one point, and approximately half of the inundated area was outside of the FEMA-mapped 500-year floodplain. Within Harris County, 204,267 buildings flooded. Among the flooded buildings were 154,170 houses. Of the houses that were flooded, 48,850 were located in the Special Flood Hazard Area (SFHA)/1-percent-annual-chance probability (100-year event) floodplain, 34,970 were located inside the 0.2-percent-annual-chance probability (500-year event) floodplain, and 70,370 were located outside the 1-percent- and 0.2-percent-annual-chance probability floodplain.

1.3.1.1 Storm Surge

Although most of the damage in the area where the storm made landfall was a result of high winds, the coastal counties of Aransas, Nueces, Refugio, and San Patricio were inundated with storm surge that damaged at-grade buildings, enclosed areas below elevated residences, docks, and piers. The combined effects of surge and tide produced maximum inundation levels of 6 to 10 feet above ground level. This occurred to the north and east of Hurricane Harvey's center at Texas landfall areas in the back bays between Port Aransas and Matagorda, including Copano Bay, Aransas Bay, San Antonio Bay, and Matagorda Bay. Higher inundation levels were recorded near the Aransas National Wildlife Refuge, where high water marks (HWMs) suggested water levels up to 12 feet. However, these water levels likely include the effects of wave runup. The tide gages in the Houston area recorded readings of 7.27 feet and 10.35 feet. These water levels were mostly caused by excessive rainfall runoff and not storm surge. Figure 1-3 shows high storm surge readings (in feet above ground level) measured during Hurricane Harvey.

1.3.1.2 Rainfall

Hurricane Harvey was the largest rainfall event in U.S. recorded history. The rainfall totals for Hurricane Harvey exceeded the 0.1-percent-annual-chance probability (1,000-year event) for many areas in southeast Texas, causing record flood levels for many creeks, rivers, and bayous. Figure 1-4 shows the annual exceedance probabilities for the most severe 4-day rainfall totals that occurred during the 7-day rainfall event; NOAA records rainfall rates and determines corresponding recurrence intervals for 1-hour, 2-hour, 3-hour, 6-hour, 12-hour, 24-hour, 2-day, and 4-day rainfall events. Within Harris County, Hurricane Harvey established rainfall event records for 1-hour, 2-hour, 3-hour, 2-day, and 4-day rainfall events. See Table 1-2.

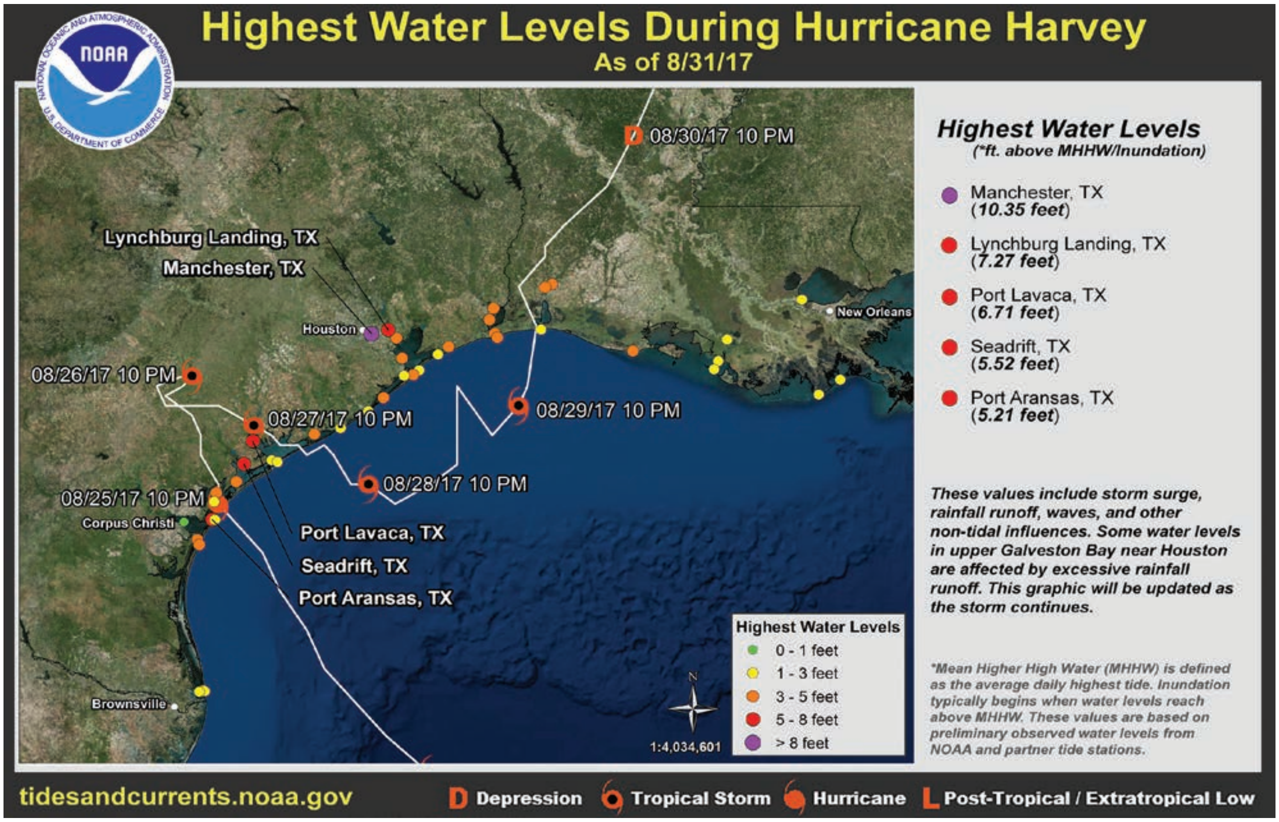

Figure 1-3: Hurricane Harvey storm surge levels recorded by NOAA

SOURCE: NOAA NHC, 2018a

Table 1-2: Harvey Rainfall Rate Compared to Other Major Flood Events

Duration (cumulative)	Hurricane Harvey (August 2017)	Tropical Storm Allison (June 2001)	Tax Day Flood (April 2016)
	(inches)		
1 hour	6.8(a)	5.7	4.7
2 hours	11.9(a)	9.9	7.3
3 hours	14.8(a)	13.5	8.3
6 hours	18.9	21.2(a)	13.9
12 hours	20.9	28.3(a)	16.7
24 hours	25.6	28.4(a)	17.4
2 days	35.2(a)	28.5	17.5
4 days	47.7(a)	38.5	NA

NA = Not Applicable

(a) Indicates a record level of rainfall

SOURCE: HCFCD, 2018a

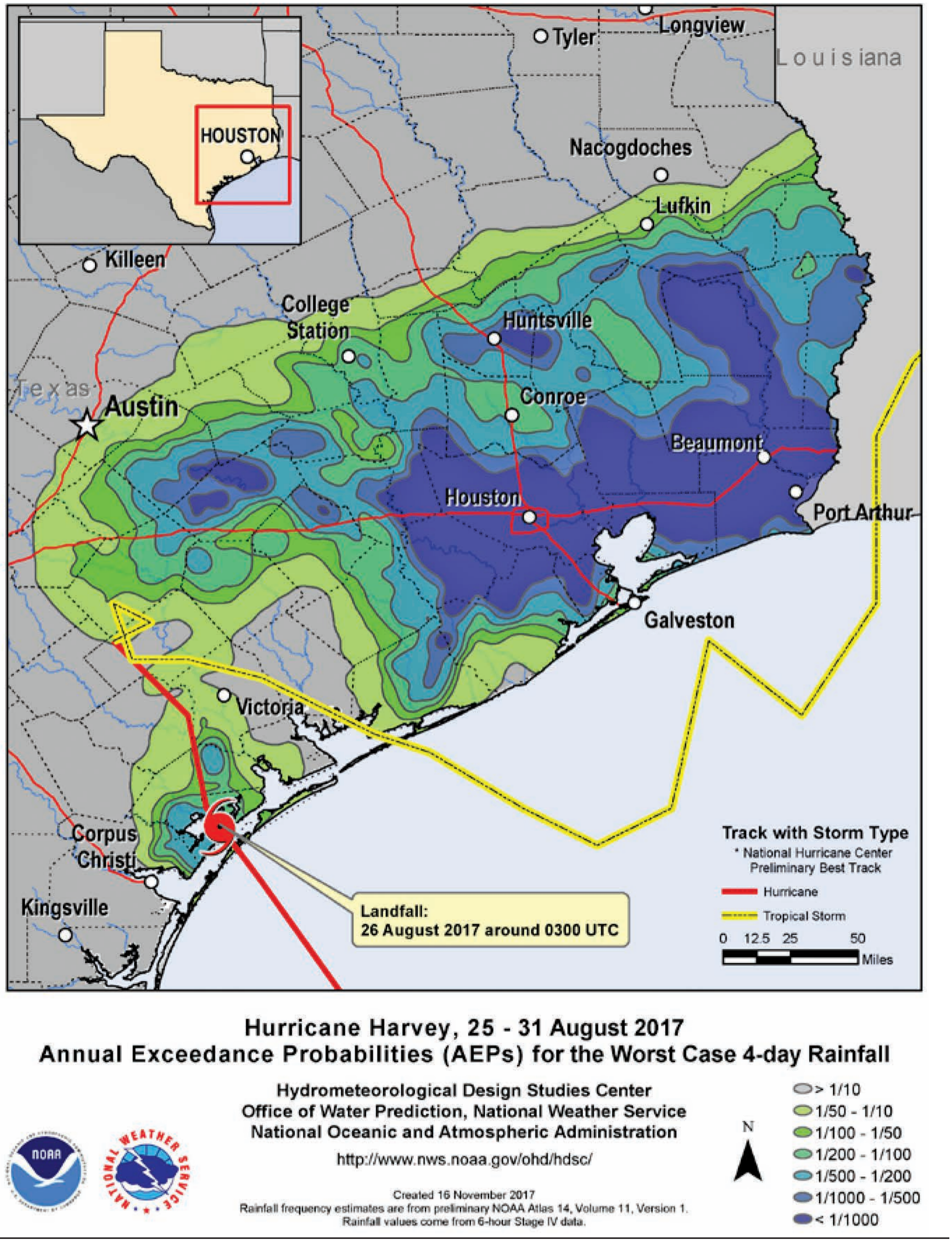

Figure 1-4: Hurricane Harvey annual exceedance probabilities for the worst-case, 4-day rainfall according to NOAA

SOURCE: NOAA NHC, 2018a

The rainfall totals resulted from Hurricane Harvey remaining nearly stationary northwest of Victoria, TX, which allowed inflow bands originating over the warm waters of the Gulf of Mexico to continually pass over the same regions. The heavy bands of rain, some exceeding 6 inches of rainfall per hour, were concentrated in the northern regions of the storm. The heavy bands entered the Houston area on August 25, with the heaviest rainfall on August 27. The rain did not stop falling in Houston until August 30, when Hurricane Harvey moved toward Louisiana.

The highest total rainfall for the storm was recorded at a gage in Nederland, TX, with a reading of 60.58 inches. Weather radar indicates that rainfall totals in southeastern Texas were as high as 65 to 70 inches. The majority of Harris County received a minimum of 25 inches of rainfall, with a maximum rainfall reading of 54 inches recorded in the southwestern corner of the county. One trillion gallons of rainwater fell in Harris County over a 4-day period. Figure 1-5 shows rainfall totals for southeastern Texas and the Houston metropolitan area.

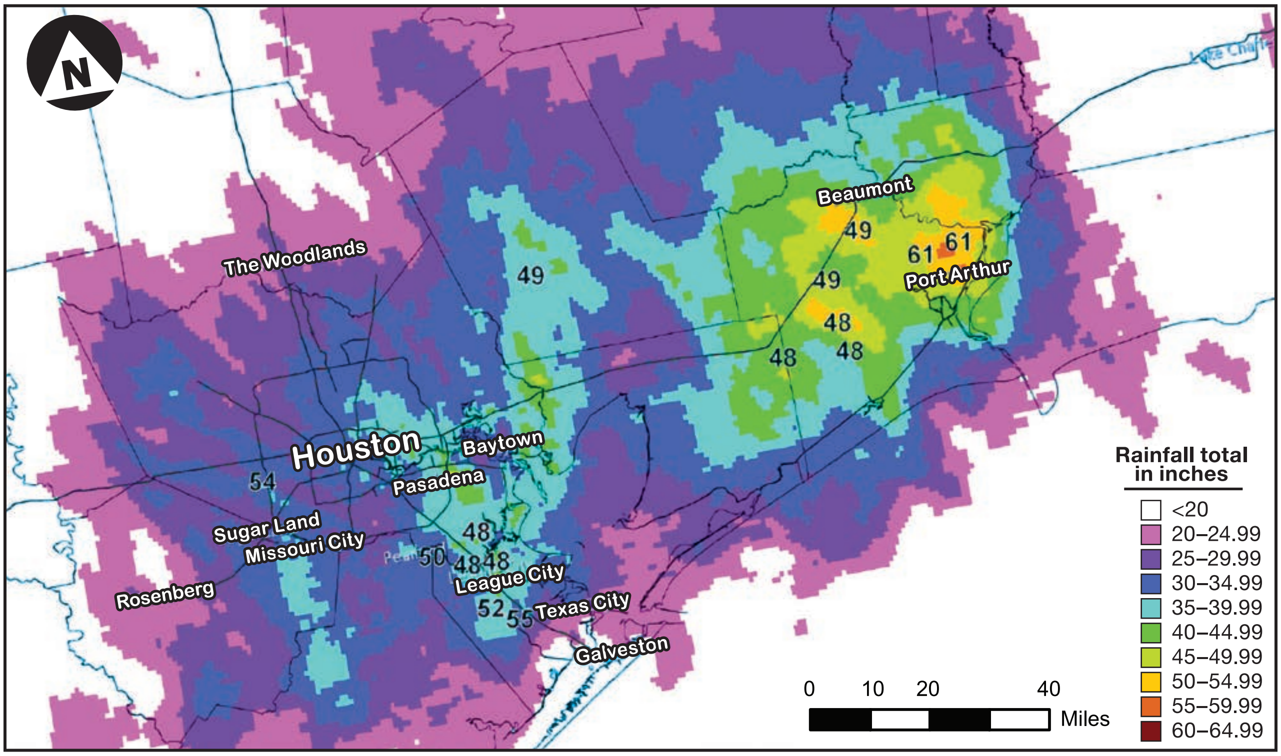

Figure 1-5: Rainfall totals of southeastern Texas and the Houston metropolitan area

SOURCE: MODIFIED FROM NOAA NHC, 2018a

Prior to Hurricane Harvey, Tropical Storm Allison in 2001 was considered the benchmark rainfall and flooding event for Houston. Dry floodproofing systems installed in Houston were designed to protect against an event similar to Tropical Storm Allison. During Hurricane Harvey, all of Harris County experienced more than 25 inches of rain, with large areas exceeding 36 inches of rain and a maximum recorded rainfall of 54 inches. Tropical Storm Allison, by comparison, had isolated areas where rainfall exceeded 36 inches, with a maximum of 40 inches in Harris County. Figure 1-6 compares total rainfall between Tropical Storm Allison and Hurricane Harvey.

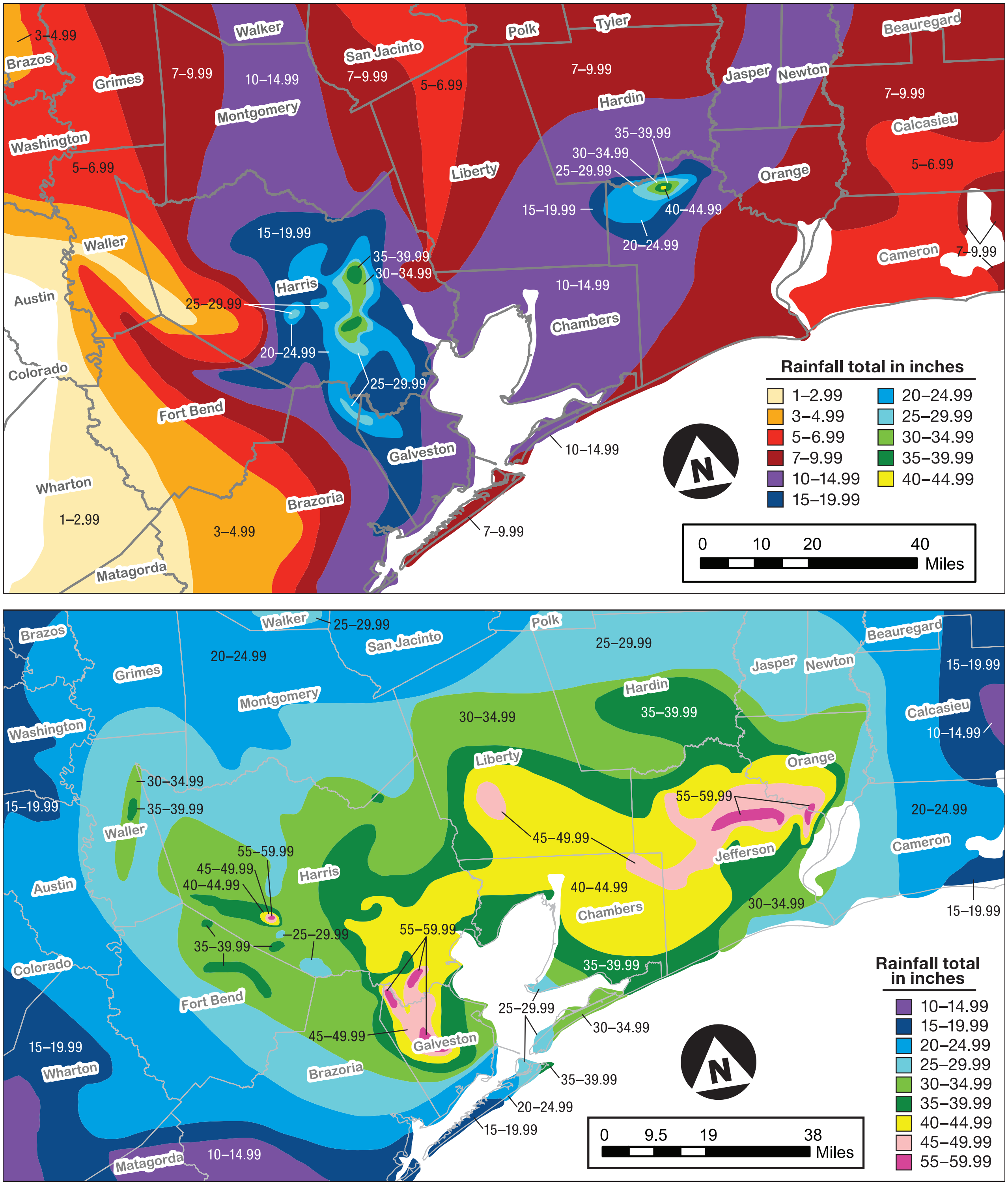

Figure 1-6: Tropical Storm Allison (2001) rainfall totals (top) versus Hurricane Harvey rainfall totals (bottom). Rainfall totals scale uses the same color coding for both maps.

SOURCE: MODIFIED FROM NOAA NHC, 2018a

1.3.1.3 Inland Flooding

The historic rainfall amounts produced by Hurricane Harvey resulted in extensive riverine flooding in southeastern Texas. This rainfall caused all of the major creeks, rivers, and bayous to exceed flood stage (Figure 1-7).

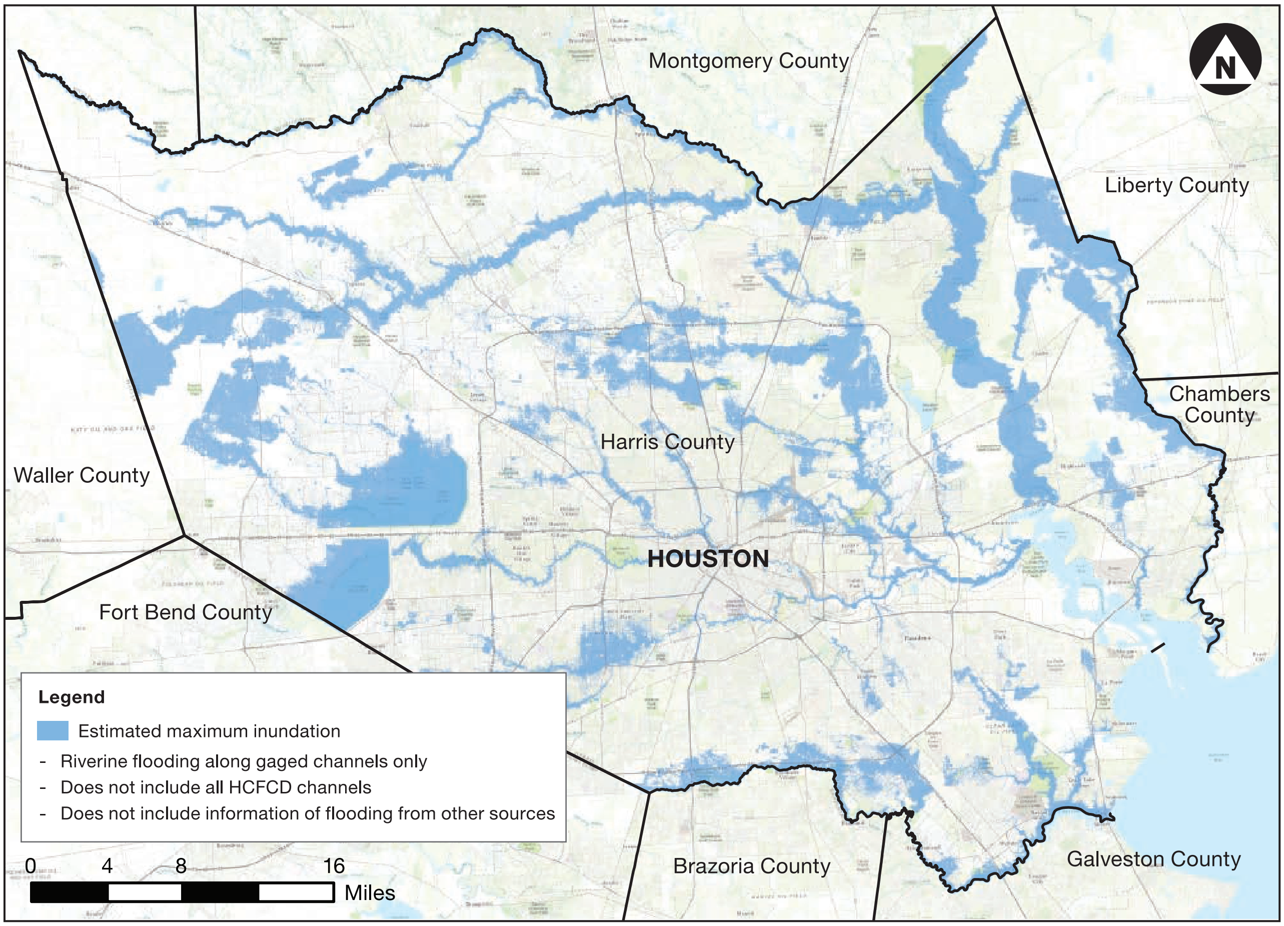

Figure 1-7: Overview of riverine flooding in Harris County (map does not show sheet flow flooding effects in the county)

SOURCE: MODIFIED FROM HCFCD, 2017

In addition to the flooding from riverine sources, sheet flow flooding damaged thousands of buildings located outside of both the 1-percent- and 0.2-percent-annual-chance probability floodplain. The historic rainfall overwhelmed stormwater drainage networks, causing sheet flow flooding, which resulted in backups. These backups caused rainwater to flow across the ground to the nearest natural drainage, flooding buildings in its path (Figure 1-8).

Analysis of aerial imagery revealed that approximately one-third of Harris County, which contains the City of Houston, was under water from riverine and/or sheet flow floodwater. Approximately half of the inundated area was outside of the mapped 0.2-percent-annual-chance probability (500-year event) floodplain.

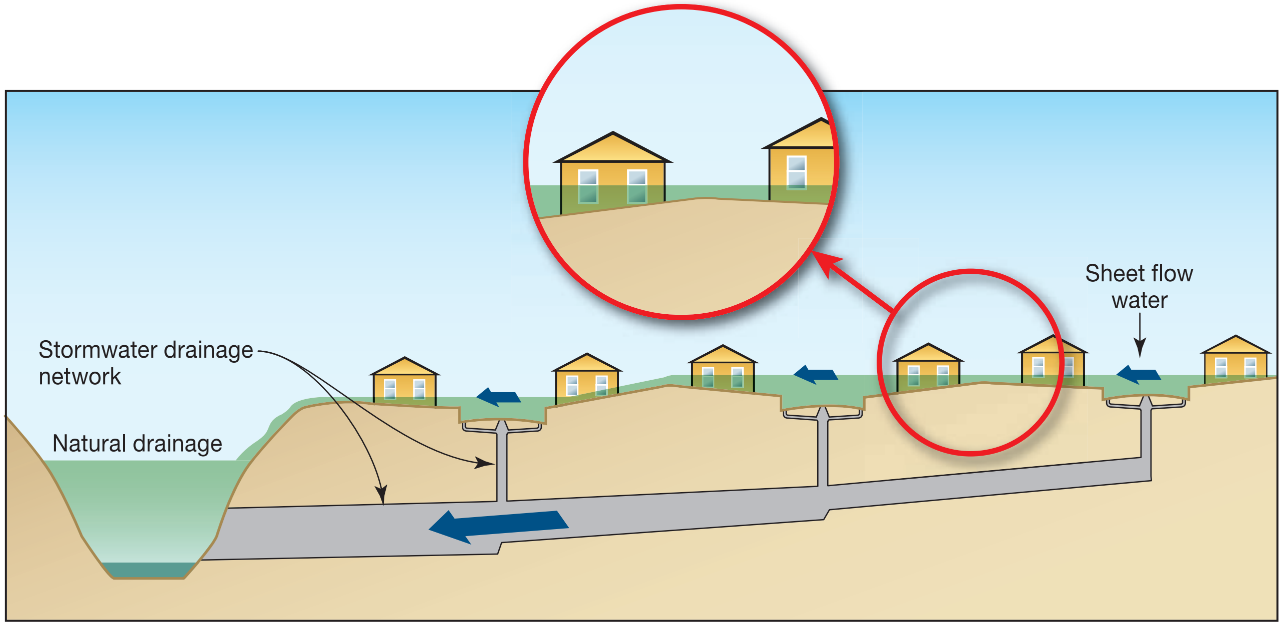

Figure 1-8: Example of rainwater flowing across the ground, flooding buildings in its path when stormwater drainage networks are overwhelmed

During Hurricane Harvey, 14 of the 22 watersheds in Harris County experienced flood depths at or exceeding the 0.2-percent-annual-chance probability level; whether any of the watersheds experienced flood depths at or exceeding the 0.1-percent-annual-chance probability (1,000-year event) level is unknown. An additional seven watersheds experienced flood depths at or above the 1.0-percent-annual-chance probability (100-year event) level (Figure 1-9).

The severity and extent of the flooding varied significantly between and among the watersheds within the Harris County Flood Control District (HCFCD), as did the width of the flooded areas between waterways. In some watersheds, flood-damaged buildings were located close to the primary channel, whereas in other watersheds, damaged buildings were miles from a channel. The width of the mapped 1.0-percent-annual-chance probability (100-year) floodplain for Brays Bayou in Meyerland and Bellaire exceeds 3 miles in some places, whereas the 1.0-percent-annual-chance probability floodplains for the White Oak and Buffalo Bayous are typically less than a half mile wide, excluding portions of the shipping channel, as they flow through Downtown Houston. Figure 1-10 shows a comparison of these floodplain widths.

Within individual waterways, record-setting water surface elevations were recorded (some exceeded the 0.2-percent-annual-chance water surface elevations); while farther downstream, the water surface elevations were below the 1-percent-annual-chance water surface elevations. The lower water surface elevations in the downstream sections were the result of the channel naturally having a wider cross section at its entrance into Galveston Bay. Additionally, HCFCD has implemented numerous stormwater projects that have increased the depth or width of many channels. Most of these projects start at the entrance to Galveston Bay or at a confluence with a larger river or bayou and continue upstream.

For example, during Hurricane Harvey, an HCFCD gage at the Dairy Ashford Road bridge crossing Buffalo Bayou recorded a peak water surface elevation of 76.90 feet, exceeding the 0.2-percent-annual-chance probability flood elevation of 74.70 feet. However, at the HCFCD gage located at Turning Basin, approximately 20 miles downstream where Buffalo Bayou enters the shipping channel, a flood elevation of 12.10 feet was recorded, which is slightly below the 1.0-percent-annual-chance probability elevation of 12.20 feet, and did not exceed the record HWM elevation of 15.00 feet that occurred during Hurricane Ike in 2008.

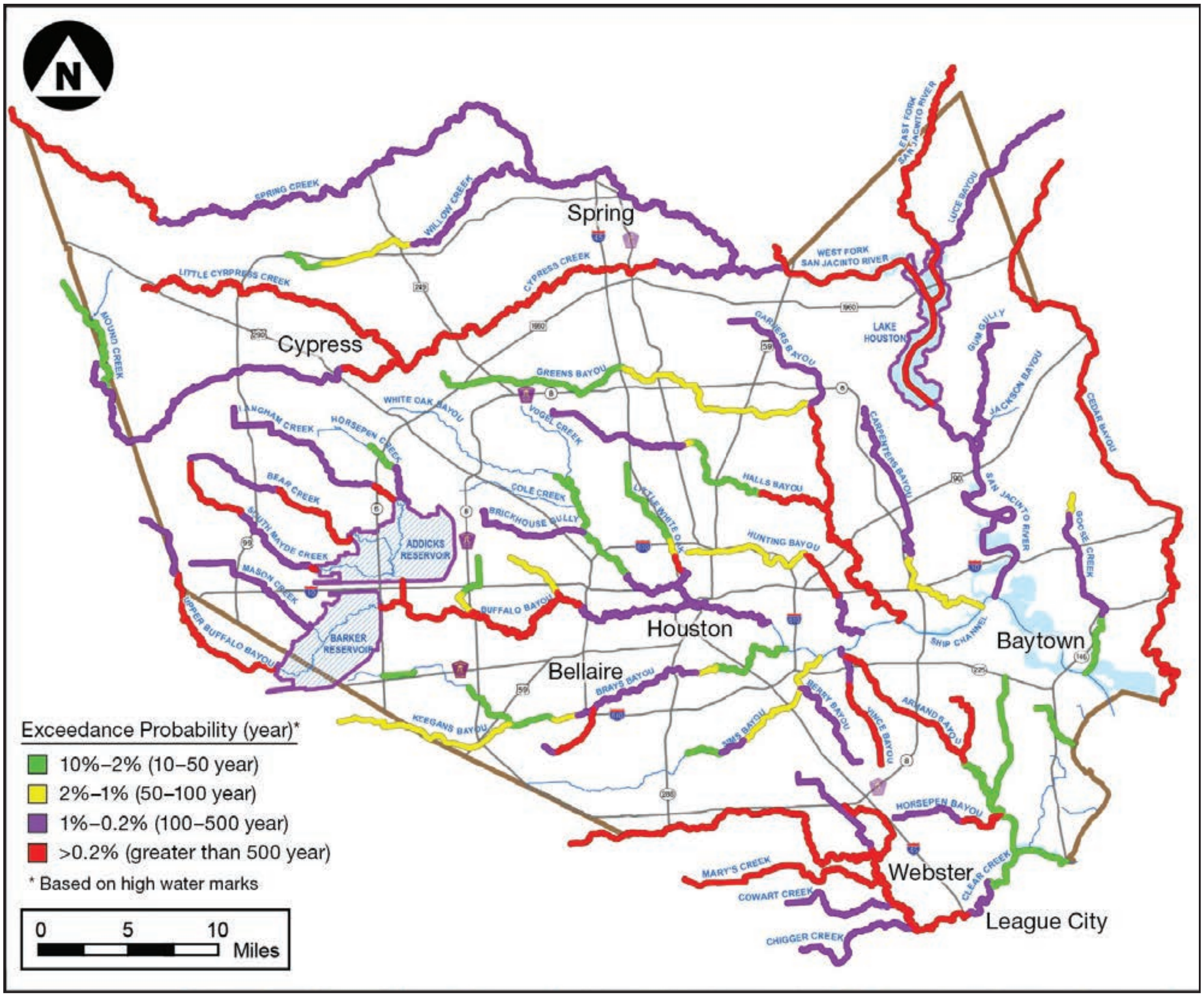

Figure 1-9: Map showing exceedance probabilities, based on HWM, for Harris County watersheds

SOURCE: MODIFIED FROM HCFCD, 2018a

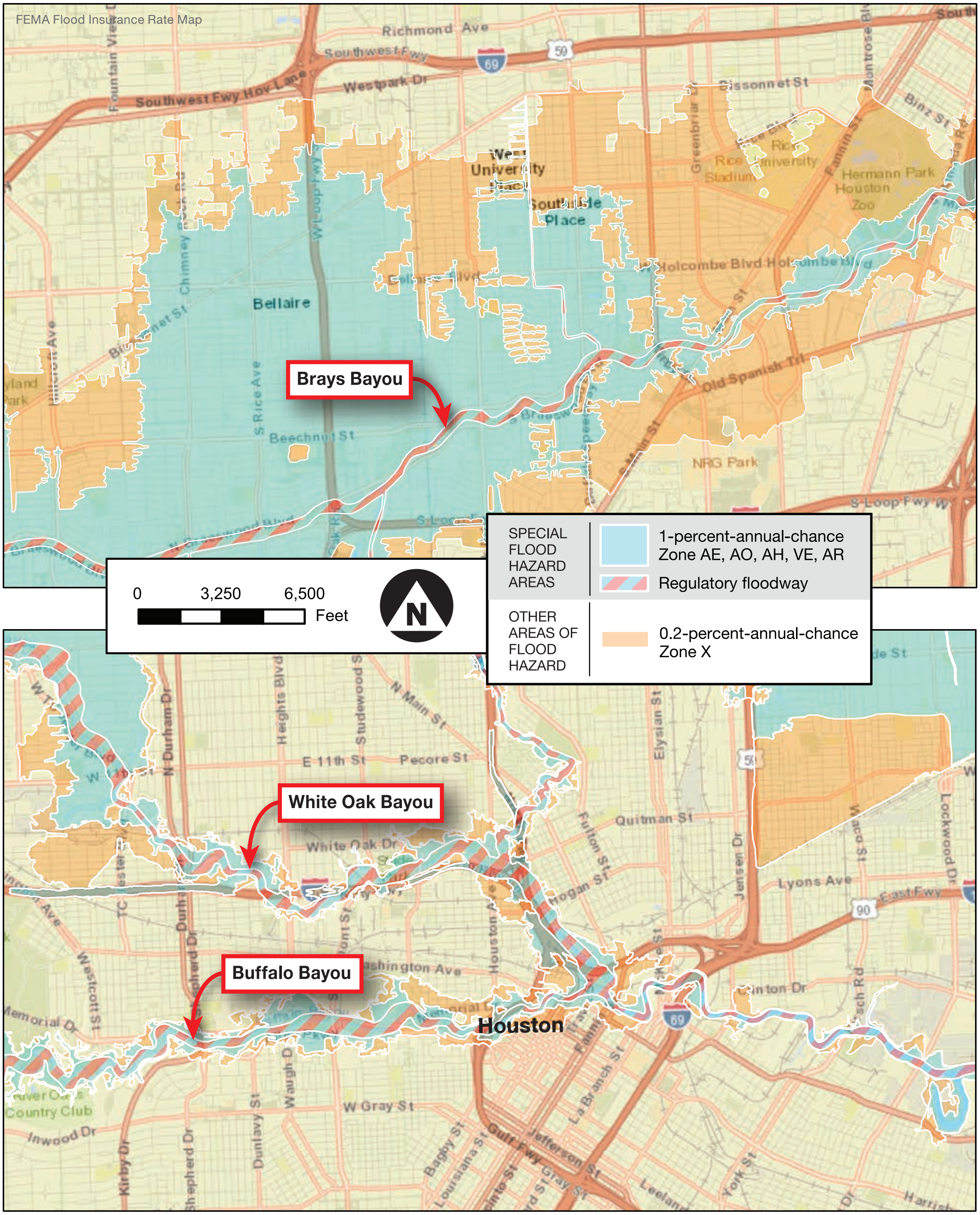

Figure 1-10: Comparison of 1-percent-annual-chance flood hazard width for Brays Bayou in the southwest portion of Houston (top image), which has a very broad SFHA, and the SFHAs for White Oak Bayou and Buffalo Bayou near Downtown Houston (bottom image), which are much narrower

1.3.1.4 Subsidence

One factor that increases the vulnerability of flooding in southeastern Texas is land subsidence, the lowering of the ground surface with respect to a fixed elevation. Subsidence can lead to increased inland flooding along streams and waterways due to changes in stream gradient and due to ponding caused by localized subsidence in the vicinity of major groundwater extraction areas used for industrial and drinking water treatment. Subsidence in southeastern Texas is primarily caused by the withdrawal of groundwater (HGSD, 2014). Subsidence has been measured in the area since 1906; from 1906 to 2000, areas of Harris County have experienced subsidence of up to 10 feet (see Figure 1-11).

In response to the subsidence that has occurred in the region, the Harris-Galveston Subsidence District (HGSD) was formed in 1976. The HGSD implemented restrictions on groundwater pumping with the goal of reducing 2003 groundwater usage rates by 80 percent by 2030. Since its formation, subsidence rates across the district have decreased. Current subsidence rates range from 0.3 foot/decade to no measurable change across the 90 extensometers (subsidence measuring stations) located in the district.

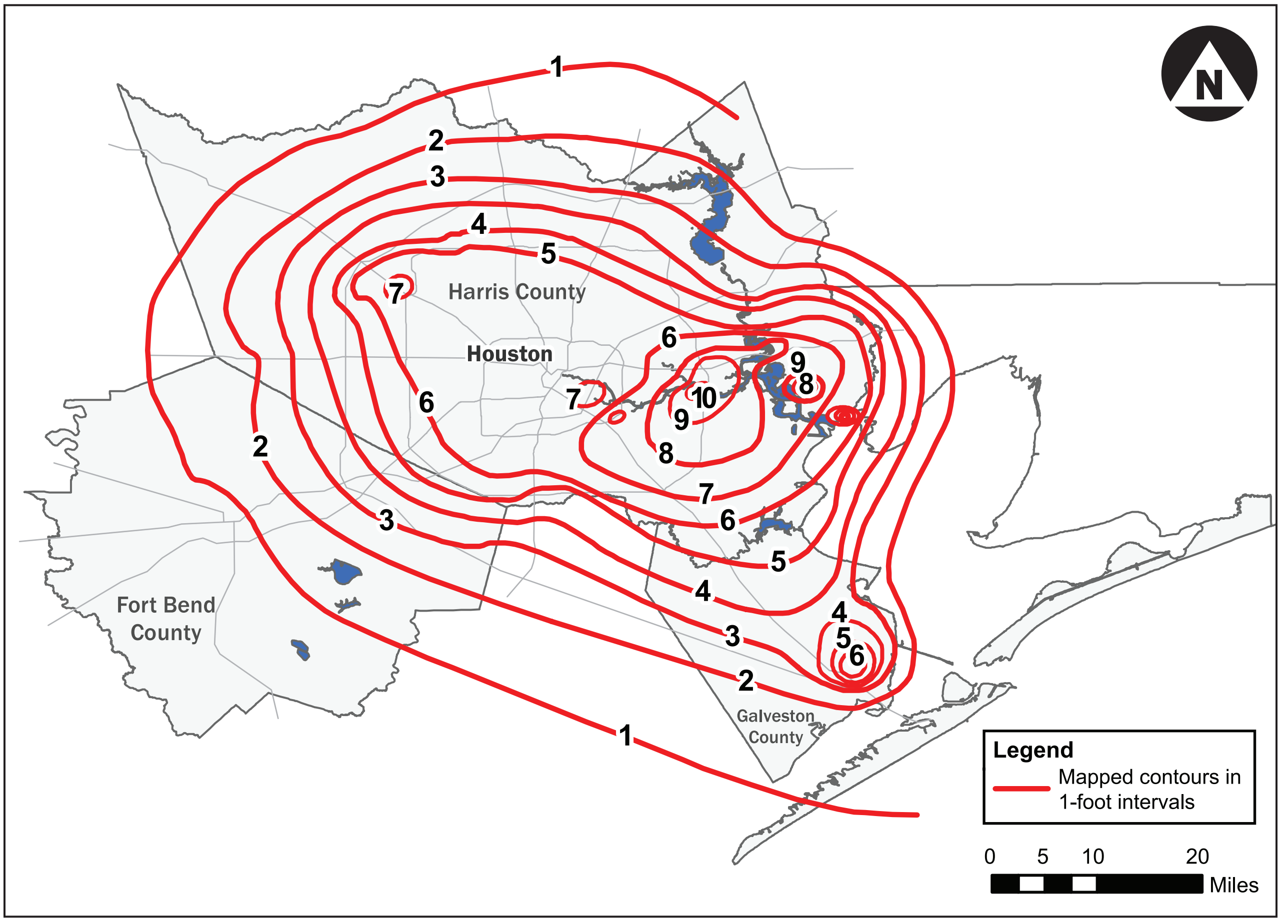

Figure 1-11: Land subsidence in the Houston-Galveston Subsidence District, 1906-2000, retrieved May 2018

SOURCE: MODIFIED FROM HGSD, 2013

In the past, the presence of subsidence in this region complicated flood hazard mapping and rendered some flood hazard maps obsolete before they would otherwise need to be updated. As a result, some older construction may have been built to an elevation that subsequently subsided, causing the building to be susceptible to flooding. However, all FIRMs within the HGSD have been updated, with the oldest effective maps dated June 18, 2007; the current maps include the high levels of subsidence that occurred in the past so the impact of subsidence-influenced flooding can be accounted for in new construction.

1.3.2 Wind

Hurricane Harvey was a Category 4 hurricane with estimated sustained winds of 130 mph. At landfall, Hurricane Harvey was approximately 250 miles in diameter, with an eye that was approximately 20 miles in diameter. Its hurricane force winds extended 45 miles from the right side of the track and 35 miles from the left side of the track.

The wind damage caused by Hurricane Harvey was concentrated in the area where the first two landfalls occurred; Harris County did not experience high winds. In the greater Rockport area (i.e., the area shown in the bottom image in Figure 1-12), Hurricane Harvey's wind speeds produced pressures that approximated design pressures derived from various editions of American Society of Civil Engineers (ASCE) publication ASCE 7,[2] depending on a building's proximity to the track of the storm and building and site characteristics. In Aransas, Nueces, Refugio, and San Patricio Counties, wind forces damaged 40,929 buildings, resulting in $4.58 billion in damage (NOAA NWS Corpus Christi, 2018).

Figure 1-12 compares Hurricane Harvey's estimated 3-second gust wind speeds to the basic (design) speed from ASCE 7-10 for Risk Category II buildings.

The MAT observed MWFRS damage at older residential and non-residential buildings. However, the most common wind damage observed was to roof coverings and rooftop equipment. Blown-off, low-slope roof membranes were observed on older and newer buildings. However, newer roof membranes were observed that did not experience wind uplift problems. Many older and newer roof membranes were punctured or torn by wind-borne debris. Rooftop equipment was often displaced due to lack of anchoring or insufficient anchoring. Wind-borne equipment often punctured roof membranes. Roof covering and rooftop equipment breaches resulted in rain infiltration and subsequent interior water damage. Residences also sustained fiber cement siding damage and broken glazing.

Building siding and veneers were another common source of failure and water infiltration. The MAT observed significant brick veneer failures due to missing ties, improper spacing of ties, or corroded ties. MATs have previously identified brick tie spacing, missing ties, and tie corrosion as reasons for brick veneer failure.

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[2] The 1998, 2005, and 2010 versions of ASCE 7 are all titled *Minimum Design Loads for Buildings and Other Structures*. For the 2016 version, the title was revised to *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*.

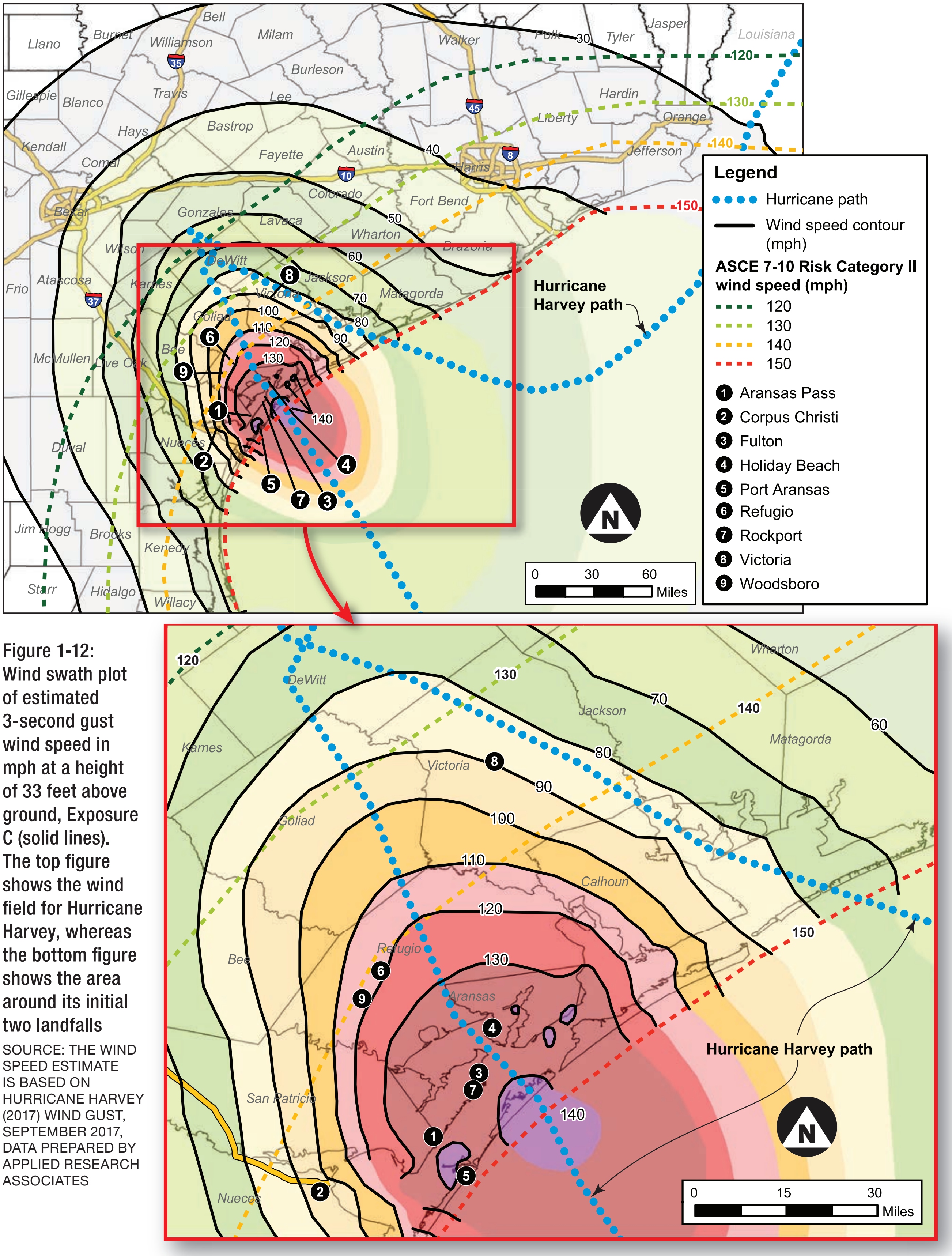


Figure 1-12: Wind swath plot of estimated 3-second gust wind speed in mph at a height of 33 feet above ground, Exposure C (solid lines). The top figure shows the wind field for Hurricane Harvey, whereas the bottom figure shows the area around its initial two landfalls

SOURCE: THE WIND SPEED ESTIMATE IS BASED ON HURRICANE HARVEY (2017) WIND GUST, SEPTEMBER 2017, DATA PREPARED BY APPLIED RESEARCH ASSOCIATES

1.4 Historic Storm Events in Texas

The State of Texas has suffered numerous hurricane, tropical storm, and severe inland flooding events in recent history, causing tremendous damage across the Texas coastal region. The Texas coast averages a hurricane every 3 years and has experienced 63 hurricanes since 1851; 22 of those hurricanes can be classified as major hurricanes. Before Hurricane Harvey, the Houston area alone experienced four significant flooding events within a 16-year timeframe (Tropical Storm Tax Day 2016, Tropical Storm Memorial Day 2015, Hurricane Ike 2008, and Tropical Storm Allison 2001). The frequency of significant natural disasters should shape how local governments, communities, businesses, and critical facilities prepare for them; it is not a question of if, but when the next natural hazard event will occur.

GALVESTON HURRICANE OF 1900

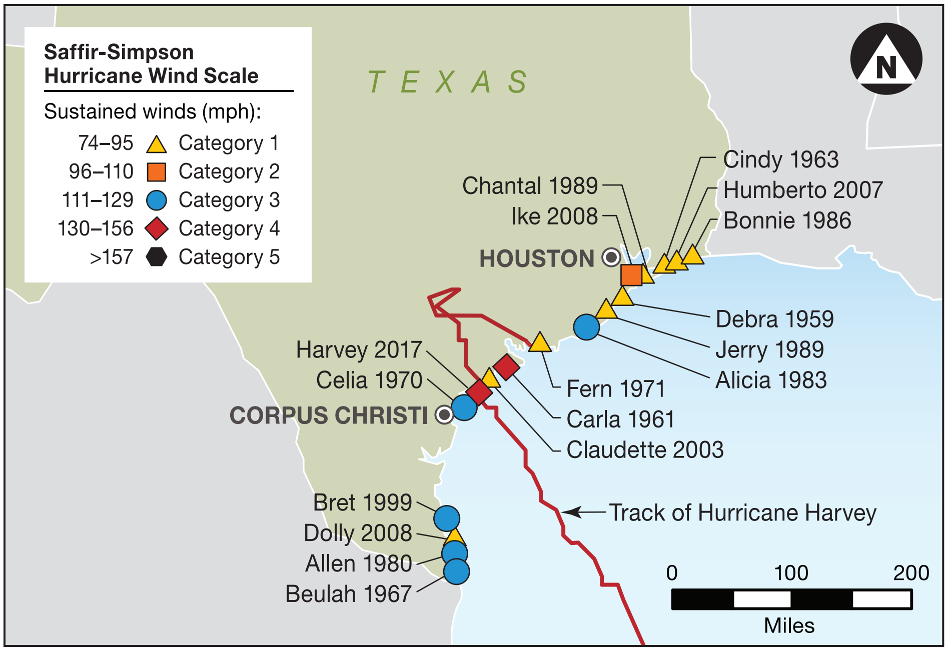
The deadliest hurricane in U.S. history was the Great Galveston Hurricane that occurred on September 7 to 8, 1900. This hurricane claimed approximately 8,000 lives. The population of Galveston in 1900 was approximately 37,000. This hurricane traveled the Caribbean as a tropical storm before making landfall across the southern United States where it hit Florida, Mississippi, Louisiana, and Texas. The storm then traveled through the central United States and up through the Great Lakes, making its way through Canada. The Great Galveston Hurricane was classified as Category 4 at landfall, with sustained winds of 100 mph and gusts over 125 mph (NOAA NHC, n.d.). The minimum central pressure was 931 mb or 27.49 inches of mercury.

The storm surge and high water level from the Great Galveston Hurricane washed out the four bridges linking Galveston to the mainland and downed telephone lines, cutting off the island from the mainland. The highest land elevation on Galveston Island in 1900 was 8 feet; the storm surge reached 15 feet. Over 3,600 properties were destroyed, resulting in an estimated $30 million in property damage at the time of the event (NOAA NOS, 2017). The horrific devastation of the hurricane motivated the people of Galveston to find a way to protect themselves against another disaster of this magnitude. Construction of a 17-foot-high seawall began in 1902 to protect 3 miles of oceanfront. Sand was dredged from Galveston Bay to elevate the city portion of the island by 8 feet.

This section describes some of the historical hurricane, tropical storm, and flooding events that severely impacted the Texas coastline. The timeline in Figure 1-13 highlights significant hurricanes that have impacted the Texas coast. In addition to hurricanes, Tropical Storm Allison caused significant damage to the Texas coast, as did significant flood events known as the Memorial Day Flood (2015) and the Tax Day Flood (2016).

The data for the total estimated damages for each storm event discussed were obtained from the NOAA National Centers for Environmental Information (NCEI) (2018). Information about each storm event comes from data provided by the HCFCD (HCFCD, 2016) and various National Hurricane Center reports on tropical systems (NOAA NHC, 2014; NOAA NHC, 2001; and NOAA NHC, 1998) unless noted otherwise.

Figure 1-13: Track of Hurricane Harvey (red line) relative to landfall locations of significant historic hurricanes in Texas between 1950 and 2017



Tax Day Flood, 2016

On April 17 and 18, 2016, storms congregated over Harris County, producing severe rainfall and catastrophic flooding. Harris County received 8 inches of rain, with isolated pockets of up to 17 inches, within a 24-hour timeframe. This event claimed the lives of seven people, and over 1,800 people were rescued from the high waters. The storms resulted in an estimated $2.8 billion in property damage.

Memorial Day Flood, 2015

From May 23 to 26, 2015, severe storms developed in Texas and Oklahoma, producing heavy rainfall and flooding. Harris County received up to 11 inches of rain within a 10-hour timeframe, and downtown Houston received up to 6 inches of rainfall during the storm. The short timeframe of the storm resulted in hundreds of rescues within Houston alone. Thirty-one people lost their lives during this event. The storm produced an estimated $2.7 billion in property damage, $1.1 billion of which was in Texas.

Spring Flood, 2009

Beginning on April 17, 2009, a 12-day storm event caused extensive flooding throughout Harris County. More than 2,300 structures were flooded and five people lost their lives as a direct result of this storm.

Hurricane Ike, 2008

Hurricane Ike, which became a Category 4 hurricane before weakening prior to landfall, transformed from a tropical storm into a hurricane over the tropical Atlantic Ocean. Ike migrated west-northwestward, directly impacting Turks and Caicos, the southeastern Bahamas, and Cuba. The hurricane was downgraded to a Category 2 event prior to landfall on the northern side of Galveston Island on September 13, 2008. Ike traveled northward across eastern Texas with 3-second gust wind speeds of 109 mph. Southeastern Texas and southwestern Louisiana received 3 inches or more of rainfall, while just north of Houston received 18.90 inches of rainfall during this event. Heavy rainfall led to severe flooding in Missouri, Illinois, and Indiana. Hurricane Ike directly claimed the lives of 112 people, and the estimated U.S. property damage was nearly $35.4 billion.

Summer Flood, 2006

On June 19, 2006, a storm event produced 8 to 10 inches of rainfall within a 3-hour time period. Over 4,000 structures were flooded in Harris County (HCFCD, 2016).

Tropical Storm Allison, 2001

On June 5, 2001, a tropical wave in the Gulf of Mexico developed into Tropical Storm Allison due south of Galveston, TX. Tropical Storm Allison formed rapidly and traveled inland toward the upper Texas coastline, where it stalled and looped around southeastern Texas, causing severe rainfall and flooding throughout the Houston area. The storm drifted back into the Gulf of Mexico, changed direction, and migrated toward Louisiana for a second landfall. Tropical Storm Allison continued northeastward across the entire east coast of the United States, causing heavy rainfall and flooding for 13 days.

Houston received approximately 38 inches of rain over a 6-day period. Most of the city's bayous overran their banks, flooding 73,000 homes and leaving many residents without power for days (NOAA NHC, 2001). The storm directly claimed the lives of 43 people, 22 of whom were in the Houston area. Tropical Storm Allison caused an estimated $12.1 billion in property damage, with approximately 20 percent of the Houston property damage incurred by the TMC.

Tropical Storm Frances, 1998

On September 8, 1998, Tropical Storm Frances developed in the Gulf of Mexico and traveled northward toward the coastline of central Texas. Frances produced three tornadoes with wind gusts up to 66 mph across Texas. Severe flooding was recorded across Harris County, with 21 inches of rain reported in the Houston metropolitan area (NOAA NHC, 1998). This event claimed the lives of two people. The storm resulted in the flooding of an estimated 1,400 structures and caused $1.1 billion in property damage.

Texas Flooding, Severe Storm (FEMA DR-937), 1994

Beginning on October 15, 1994, a 5-day storm event in southeast Texas caused extensive flooding in 29 counties. The event resulted in the flooding of an estimated 26,000 structures and caused an estimated $1.7 billion in property damages. This storm event claimed the lives of 19 people.

Hurricane Alicia, 1983

Hurricane Alicia, a Category 3 hurricane, struck southwest Galveston Island on August 17, 1983. Alicia had maximum sustained winds of over 96 mph, with 3-second gusts of up to 125 mph along the coast. William P. Hobby Airport in Houston reported sustained winds of 94 mph, with 3-second gusts of 107 mph (NOAA NHC, n.d.). Hurricane Alicia was notable because it resulted in extensive glazing damage in high-rise buildings in downtown Houston. Storm surges of 12 feet were recorded at Morgan Point along Galveston Bay (FEMA, 2009a). It was reported that 21 people lost their lives in this storm and estimated property damage was $7.7 billion.

Hurricane Allen, 1980

Hurricane Allen was one of the top five most intense storms in history. The storm transformed into a hurricane on August 3, 1980, about 120 miles east of Barbados as it traveled westward across the Atlantic Ocean. On August 7, 1980, the storm became the strongest hurricane recorded at that time, with sustained winds of 185 mph (NOAA NWS, 2010) and a central pressure of 899 mb (26.55 inches of mercury). Hurricane Allen made landfall as a Category 3 hurricane near Port Mansfield, TX, on August 10. The highest wind gust reported was from Port Mansfield, registering at 138 mph (NOAA NWS, 1983). Storm surges reached 12 feet at Port Mansfield (NOAA NCEI, 2018). Twelve tornadoes from this hurricane touched down across south Texas (NOAA, 1983).[3] About 300,000 people were evacuated (FEMA, 2009a). This event directly claimed the lives of 13 people, and the estimated damages in Texas and Louisiana were $1.9 billion.

Hurricane Celia, 1970

On August 3, 1970, Hurricane Celia made landfall in Texas midway between Corpus Christi and Aransas Pass. Hurricane Celia had strong wind gusts estimated as high as 180 mph that far exceeded the reported hurricane sustained winds of 130 mph. However, the hurricane did not produce torrential rains and massive flooding over a large area as storms of this magnitude typically do. The heaviest rainfall was in Robstown, a suburb of Corpus Christi, where 7.26 inches fell. Rains of 3 to 4 inches or less accompanied the hurricane along its path across south Texas. The major cause of damage from this storm was the extreme winds. The estimated damage was approximately $2.97 billion. Fifteen deaths and 466 injuries were a direct result of the storm. Information on Hurricane Celia is summarized from the National Weather Service (NWS) website (NOAA NWS, n.d.).

1.5 The FEMA Mitigation Assessment Team

FEMA conducts building performance studies after unique or nationally significant disasters to better understand how natural and manmade events affect the built environment. A MAT is generally deployed when FEMA believes the findings and recommendations derived from field observations will result in design and construction guidance that will help improve the disaster resistance of the built environment in the affected State or Region and will be of national significance to other disaster-prone regions. FEMA bases its decision to deploy a MAT on information such as:

- Magnitude of hazard
- Potential type and severity of damage in the affected areas
- Pre-storm site conditions, such as the presence of older housing stock and aging infrastructure
- Potential value of study results to the recovery effort
- Strategic lessons that can be learned and applied, potentially on a national level, related to improving building codes, standards, and industry guidance

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[3] The reported number of tornadoes produced varies across information sources. The Ike MAT (FEMA, 2009a) reports 34 tornadoes, but the NOAA Technical Report NWS 35 (1983) reports 12.

- Possibility that the field assessment would reveal pertinent information regarding the effectiveness of certain FEMA grants and key engineering principles and practices that FEMA promotes in published guidance and best practice documents
- Gaps in knowledge or information for improving performance of buildings or their utility systems to help in planning, design, construction, code enforcement, strengthening community resilience, enhancing capabilities or training for various skillsets or organizations, providing or developing guidance, advancing building codes and standards, or documenting research needs

The MAT studies the adequacy of current building codes and floodplain management regulations, local construction requirements, building practices, and building materials in light of the building performance observed after a disaster. Lessons learned from the MAT's observations are communicated through recovery advisories, fact sheets, and a comprehensive MAT report, all of which are made available to communities and the public at large to aid recovery efforts and enhance disaster resilience of buildings and utility systems, whether for existing buildings or new construction. Conclusions and recommendations from MAT reports are often the basis for FEMA's building code proposals at code hearings to help improve design and construction standards and mitigate damage.

1.5.1 Team Composition

The Harvey MAT was composed of 27 subject matter experts (SMEs), split into four units. MAT members included:

- FEMA Headquarters and Regional Office architects, engineers, and specialists
- Staff from other Federal agencies, including:
    - Department of Defense (DoD)
    - National Institute of Standards and Technology (NIST)
    - NOAA Sea Grant
- Construction and building code industry specialists
- Design professionals
- Insurance company hazard mitigation specialists

MAT members included architects; structural, civil, coastal, and electrical engineers; experts in floodplain management, building codes, construction materials, critical facilities, urban floodproofing, and housing; mechanical, electrical, and plumbing (MEP) specialists; and healthcare specialists. The members of the MAT are listed in the front of this report.

1.5.1.1 Involvement of State and Local Agencies

FEMA encouraged the participation of county and local government officials and locally based specialists in the assessment process. FEMA's involvement was critical and helped improve the MAT's understanding of local construction practices; facilitated communications among Federal, State, and local governments and the private sector; and improved the State and local understanding of the MAT's observations, conclusions, and recommendations, enabling them to bring about changes in their communities.

The MAT met with local emergency management and government officials in many of the areas visited during the field assessment. These officials gave an overview of the damage in their area and helped identify key sites where the MAT should deploy. The MAT also coordinated with the FEMA Joint Field Office (JFO) that had been established shortly after Hurricane Harvey made landfall. Individuals who assisted the MAT with its field operations and report development are listed in the front of this report.

1.5.1.2 Pre-MAT Deployment and Site Selection

To be able to develop the focus areas for the MAT, FEMA deployed three pre-MAT units to the regions impacted by Hurricane Harvey on September 8 through September 12, 2017. The pre-MAT units were each composed of three people, consisting of FEMA Headquarters personnel and SMEs with a range of expertise. Prior to deploying the pre-MAT, FEMA and pre-MAT members relied on a desktop analysis, news reports of storm damage, social media, NOAA and Civil Air Patrol photos, and locations of FEMA-funded mitigation projects to identify regions and specific locations for the three pre-MATs to visit.

The pre-MATs visited Harris and Galveston Counties to observe flood damage and Aransas, Calhoun, Nueces, Refugio, and San Patricio Counties to observe storm surge and wind damage. The pre-MAT observations on types and magnitude of damage were used to identify unique conditions and areas to guide the MAT's focus. The conclusion was that the MAT should focus on the following locations and topic areas for flood- and wind-related damage:

- Flood-related: Dry floodproofing mitigation in Harris County
- Flood-related: Residential flooding in Aransas, Harris, and Nueces Counties
- Flood-related: Texas Medical Center (TMC) in Harris County
- Wind-related: Residential and non-residential wind damage in Aransas, Nueces, Refugio, and San Patricio Counties

1.5.2 Hurricane Harvey MAT

Using the information collected by the pre-MAT, the MAT was divided into four specialty units, two for flood-related damage and two for wind-related damage. Each unit was deployed to several locations to assess the performance of specific building and facility types. The Harvey MAT was initially deployed November 7 to 15, 2017, and redeployed December 12 to 15, 2017, to complete field assessment work. The mission of the MAT was to assess the performance of residential and non-residential buildings affected by Hurricane Harvey in Texas.

MITIGATION

Any action taken to reduce or eliminate vulnerabilities to life and property from a hazard event.

To assess the effectiveness of flood and wind mitigation efforts previously undertaken, the MAT evaluated select buildings of interest that had previously undergone mitigation to improve their resilience to hurricane conditions (either flood or wind), as well as residential and non-residential buildings that had not been mitigated. The MAT focused on buildings located in the area of Hurricane Harvey's landfall in Aransas, Nueces, Refugio, and San Patricio Counties and the flooded areas of Aransas, Harris, and Nueces Counties.

Field Deployment of MAT Units

Four MAT units were deployed, each with a distinct focus area (see Table 1-3). Figure 1-14 through Figure 1-16 depict the approximate locations where the MAT units assessed building performance.

Table 1-3: Details of MAT Units Deployed for Hurricane Harvey

MAT Units	Deployment Date	Focus Area
Flood Unit	November 9, 2017 – November 15, 2017	*Dry Floodproofing Subunit* Assessed the performance of dry floodproofing at commercial facilities, underground parking and tunnel complexes, government facilities, courthouses, prisons, and residential high-rise facilities in Harris County. *Residential Flooding Subunit* Identified neighborhoods with a mixture of new and old construction along Brays, Buffalo, and White Oak Bayous for use in a desktop analysis. The desktop analysis assessed the effect of floodplain regulations on flood insurance claims in those neighborhoods.
Texas Medical Center (TMC) Flood Unit	December 12, 2017 – December 15, 2017	Assessed performance of dry floodproofing mitigation measures and reviewed emergency operations planning and dry floodproofing implementation plans at the TMC in Harris County.
Residential Wind Unit [(a)]	November 7, 2017 – November 10, 2017	Assessed performance of coastal single-family residential buildings in Aransas, Nueces, Refugio, and San Patricio Counties that were exposed to high wind pressures.
Non-Residential Wind Unit		Assessed performance of non-residential buildings, such as schools, hospitals, and hotels, in Aransas, Nueces, Refugio, and San Patricio Counties that were exposed to high wind pressures.

(a) Members of the Residential Wind Unit took note of the performance of residential buildings that were exposed to storm surge.

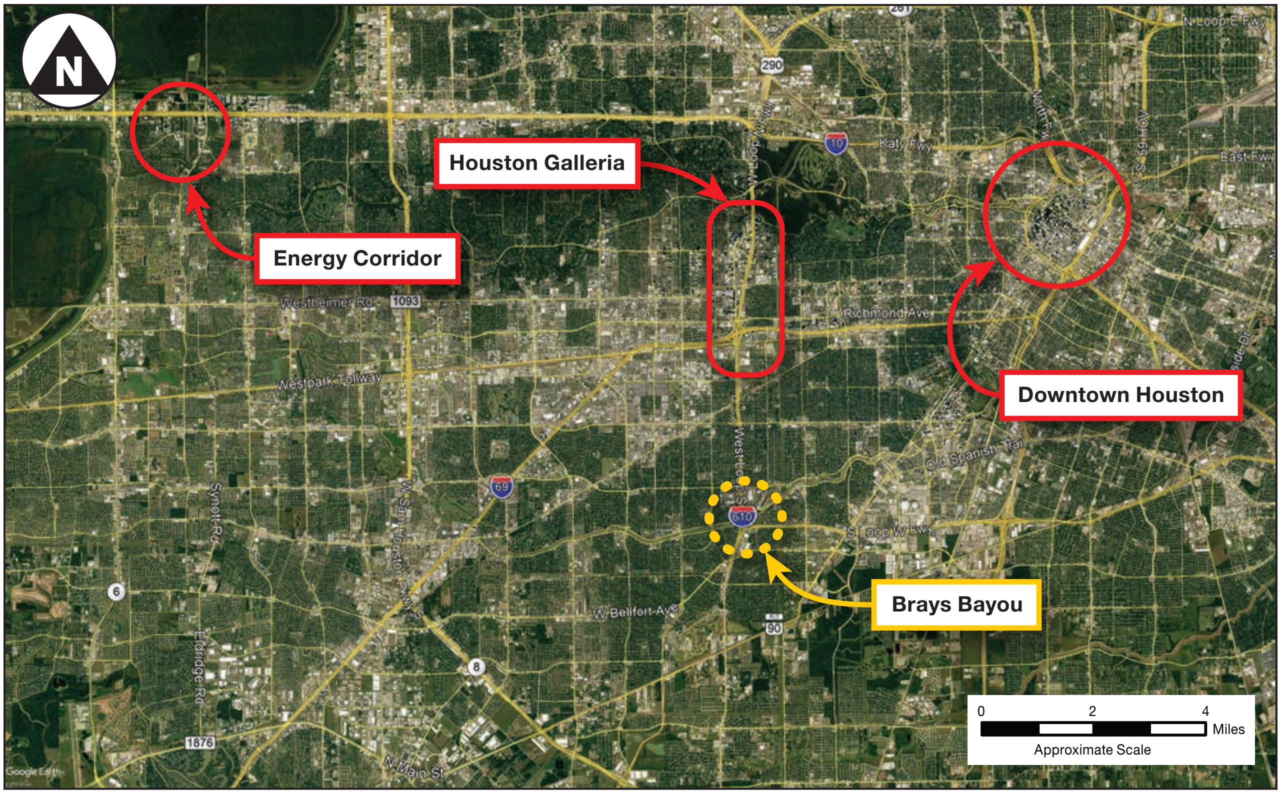


Figure 1-14: Areas of operations for the MAT Flood, Dry Floodproofing subunit in Harris County

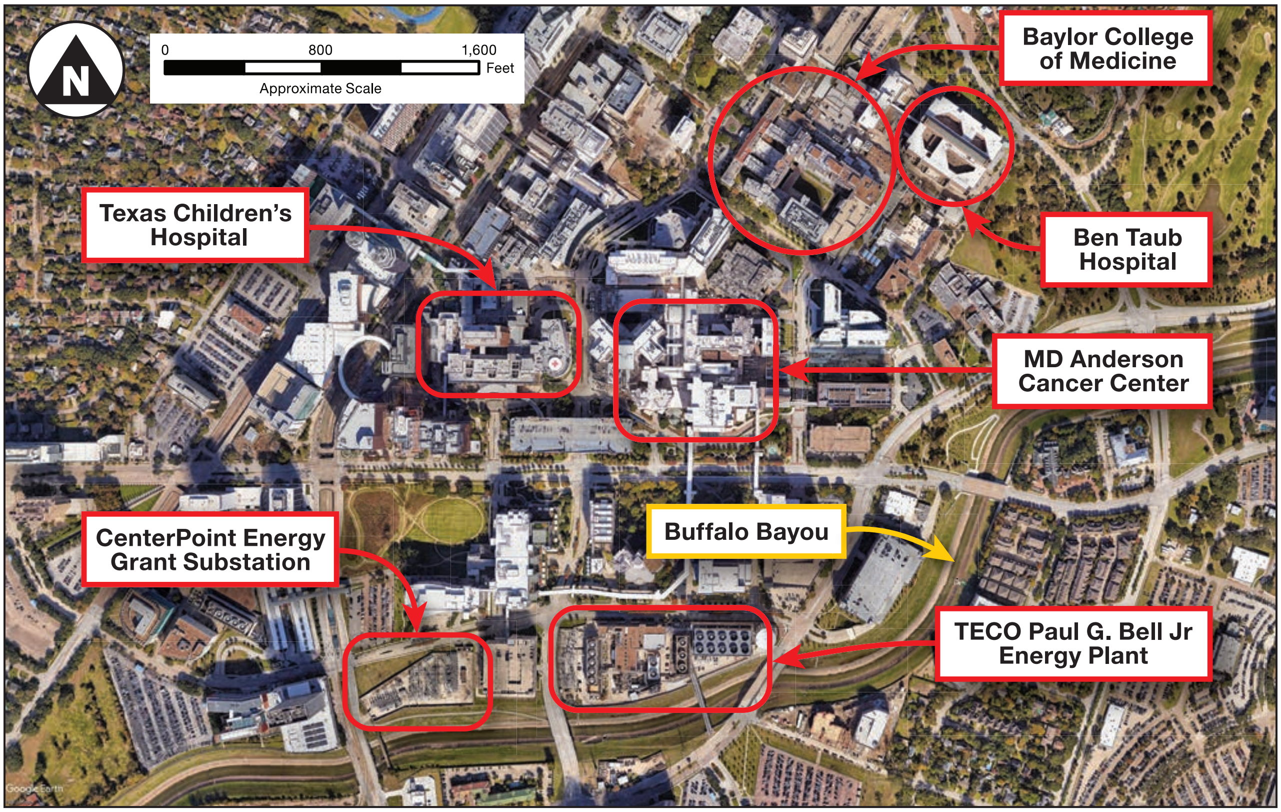


Figure 1-15: Locations of facilities observed by the MAT TMC Flood Unit

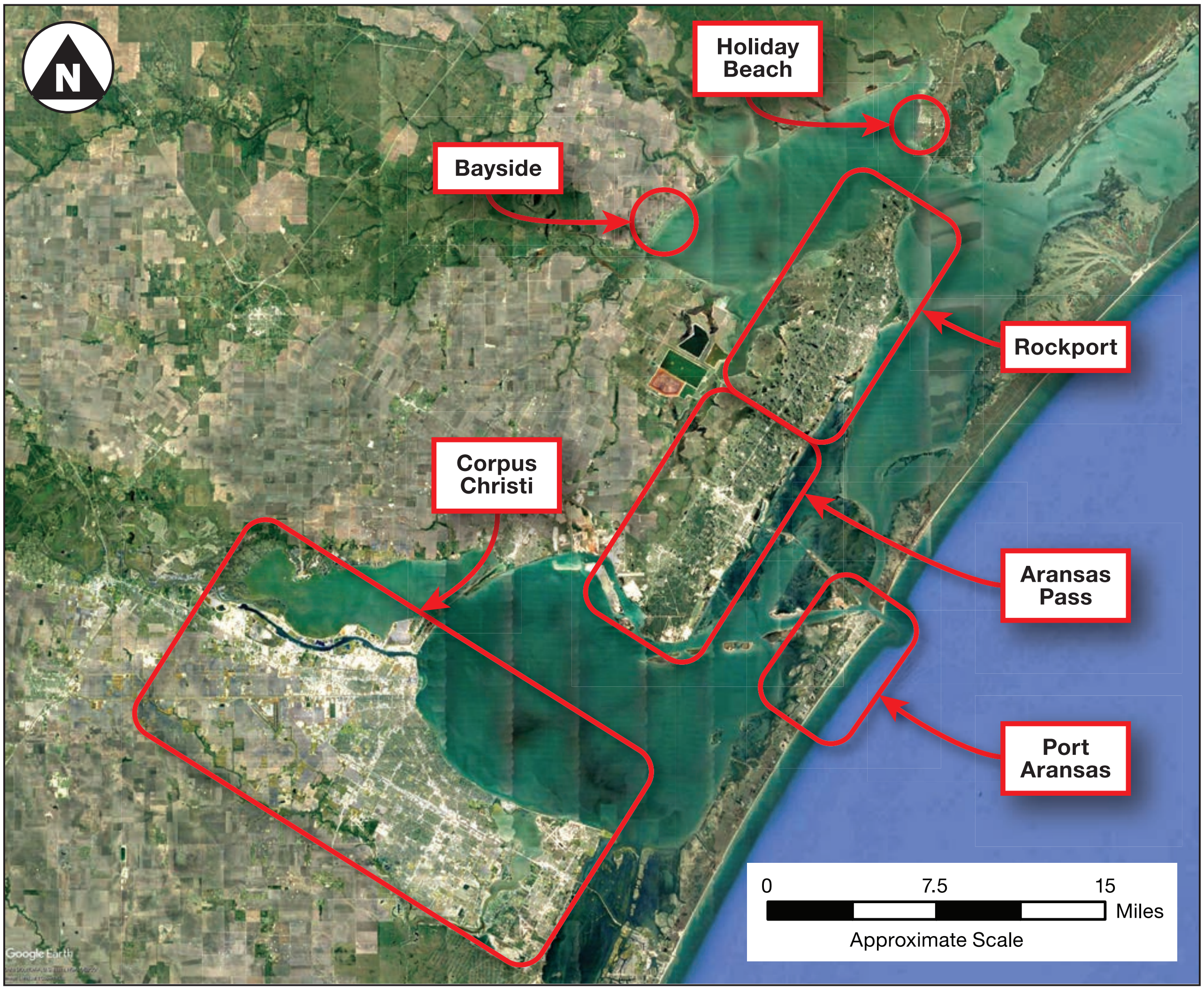


Figure 1-16: Primary areas of operations for the MAT Residential and Non-Residential Wind units were Aransas Pass, Bayside, Corpus Christi, Holiday Beach, Port Aransas, and Rockport (including Estes and Fulton)

When possible, the MAT interviewed building and facility owners to gain insight into how their buildings and facilities performed during Hurricane Harvey. The interviews focused on how buildings and facilities performed during other recent events and how recovery efforts were progressing. In addition, the MAT used an aerial drone for part of the deployment to supplement observations of wind damage (refer to the text box titled “Aerial Drone” for details). Each MAT unit took considerable time assessing successes and failures for its focus area to determine why certain buildings performed better than others and what lessons could be learned from the event. To help ensure that consistent information was obtained from each site and keep track of which buildings were visited, the MAT used a cloud-based data collection application (refer to text box titled “MAT Data Sharing” for more information).

AERIAL DRONE

A drone and drone pilot accompanied a portion of the MAT's deployment. This was the first time that a MAT used a drone. The drone provided high-resolution photos to augment the MAT's observations of wind damage. Using a drone allowed large areas to be surveyed, identifying locations for more detailed evaluation, and provided access to inaccessible areas to study wind damage. The drone took photos of the surrounding area, which helped the MAT analyze the site exposure (including the influence of "open patches" [as defined in ASCE 7]). The MAT used the photos of the surrounding area for qualitative comparison of the performance of other buildings in the vicinity. In instances where the MAT could not access a roof, the drone photo was used to determine the presence of damage to the roof system or rooftop equipment (Photo 1). Drone photos were also used to analyze wall covering damage at upper levels of mid-rise buildings (Photo 2).

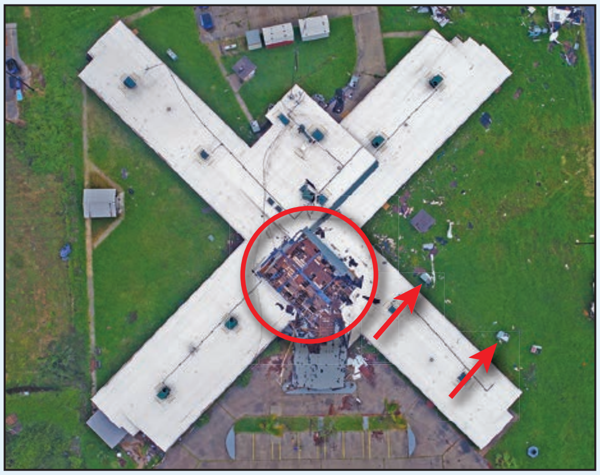


Photo 1: Drone image of a nursing home. The red arrows indicate rooftop heating, ventilation, and air conditioning (HVAC) units that blew off the roof. The roof deck blew off the area within the red circle. See Section 4.2 for further discussion of this facility.

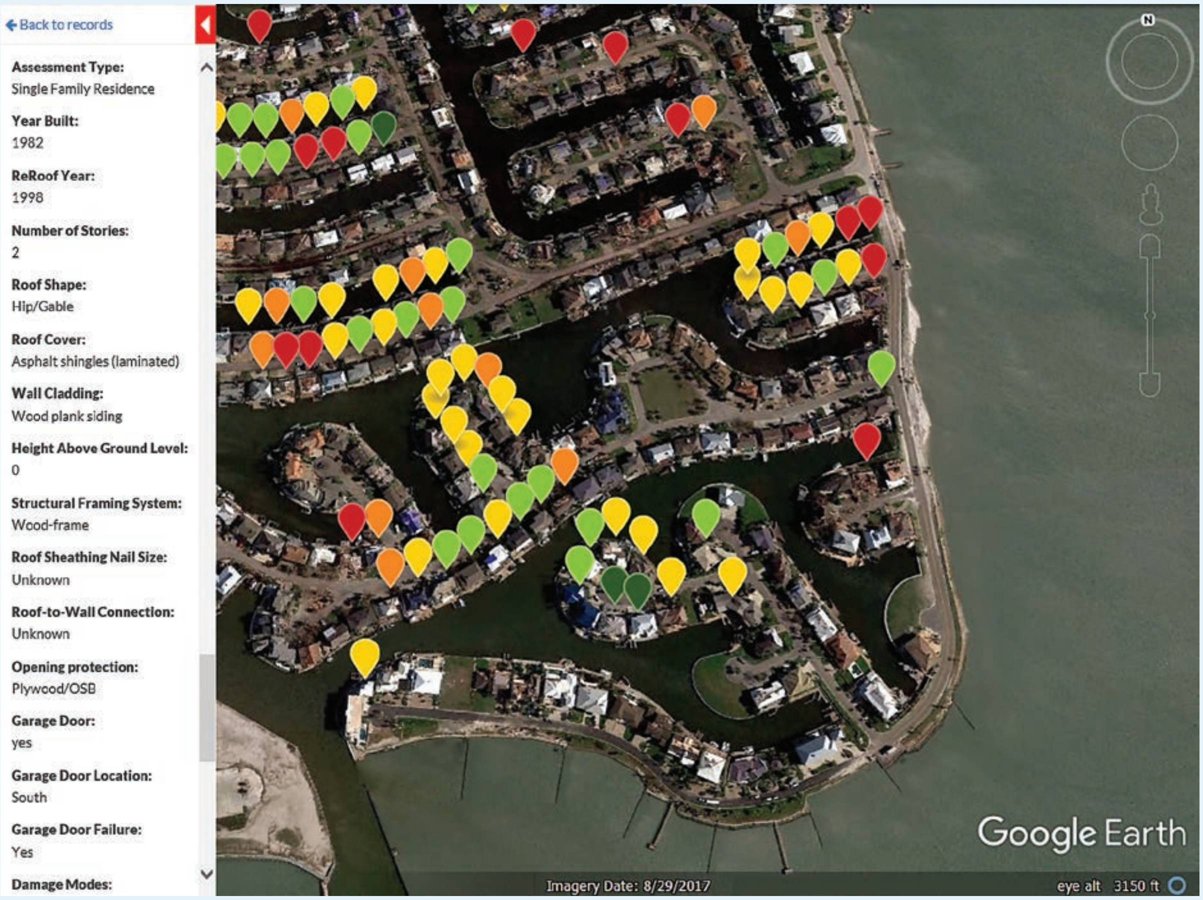
Photo 2: Drone image of brick veneer failure at a mid-rise building.

MAT DATA SHARING

The MAT Wind Units used a cloud-based data collection application to collect and store residential and non-residential wind damage assessments in the field. The cloud-based data collection application facilitated rapid post-disaster research reconnaissance to document perishable data that could be used by members of academia and design professionals to understand the effects the natural hazard had on the built environment.

The mobile application contains mapping capabilities, data collection functions, field report generation capability, and secure import and export options. Standardized inspection forms were provided on the platform to ensure consistent information was collected at each location by the various members performing wind damage assessments.

The data collected by the Wind Units were uploaded to a database that contained wind damage assessments collected from the other members of the MAT. The image below is an example of the cloud-based data collection application data and interface. Inspected buildings are shown on a map and identified by a color-coded pin, where the color indicates the severity of damage based upon the inspection. Inspection photos and information are stored for each building inspected.



Assessment Type:
Single Family Residence

Year Built:
1982

ReRoof Year:
1998

Number of Stories:
2

Roof Shape:
Hip/Gable

Roof Cover:
Asphalt shingles (laminated)

Wall Cladding:
Wood plank siding

Height Above Ground Level:
0

Structural Framing System:
Wood-frame

Roof Sheathing Nail Size:
Unknown

Roof-to-Wall Connection:
Unknown

Opening protection:
Plywood/OSB

Garage Door:
yes

Garage Door Location:
South

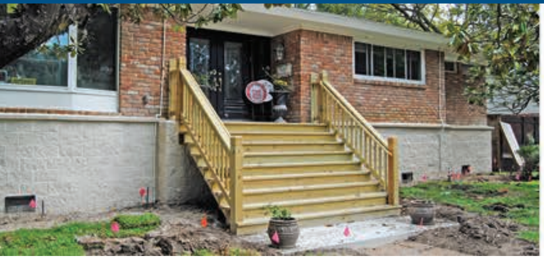
Garage Door Failure:
Yes

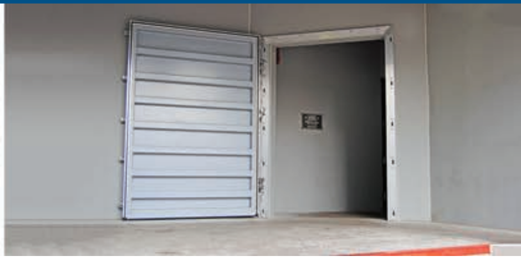
Damage Modes:

Example of cloud-based data collection application interface

SOURCE: FULCRUM COMMUNITY, 2018

MITIGATION ASSESSMENT TEAM REPORT





HURRICANE
HARVEY
IN TEXAS

2

Building Codes, Standards, and Regulations

Texas cities and counties look to the Texas constitution and statutes to determine what they may or may not do. In Texas, regulatory authority is generally determined through home rule law.

Texas has a long history of home rule whereby cities with a population of 5,000 or more may elect a home rule charter. Home rule cities have the authority to enforce building codes and other regulations that affect hazard mitigation. Small cities (those with populations of less than 5,000) that do not adopt a home rule charter are limited as general law municipalities. Counties and small cities are restricted to doing only what the State directs or permits them to do.

State statute explicitly authorizes counties to regulate housing and other structures and allows counties to adopt resolutions or orders requiring permits. Texas counties and municipalities generally have the authority to adopt a building code, but those that elect to adopt codes must, at a minimum, adopt certain editions of the International Building Code® (IBC®)/International Residential Code® (IRC®). Texas Statutes Chapters 214 and 233 apply to the adoption of the minimum building codes in municipalities and counties, respectively. For municipalities, Section

214.212 specifies the 2000 IRC and Section 214.216 specifies the 2003 IBC. Municipalities may adopt more recent editions of these codes.

Section 233.153 specifies the 2006 IRC as the minimum residential code for unincorporated areas of a county. Counties may elect to adopt the version of the IRC that is applicable in the county seat. However, Section 233.154 places the burden of inspection of new single-family dwellings on builders. Section 233.155, modified in 2017, authorizes counties to take action when notices provided by builders do not indicate compliance with the applicable building code.

State statute gives the governing bodies of each city and county the authority to adopt ordinances or orders and "to take all necessary and reasonable actions that are not less stringent than the requirements and criteria" of the National Flood Insurance Program (NFIP).

Incorporated cities in Texas have limited authority for various purposes in areas beyond their city limits. Extraterritorial jurisdiction extends for different distances depending on the number of inhabitants in a city. An extraterritorial jurisdiction area enables a city to extend regulations related to certain aspects of development to outside its city limits.

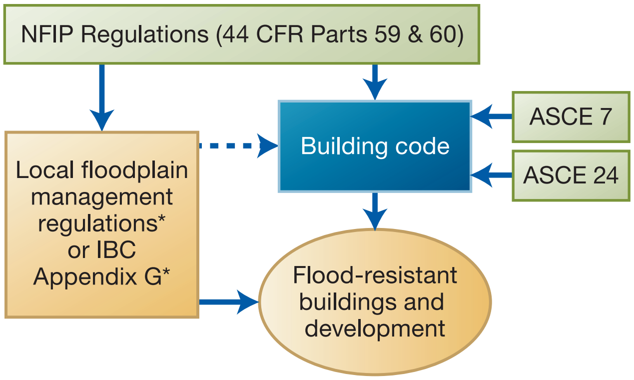
The remainder of this chapter presents requirements related to floodplain management and construction of buildings in high-wind areas. Section 2.1 includes a summary of the NFIP and the minimum requirements for buildings that communities must adopt and enforce to participate in the NFIP. The MAT reviewed the floodplain management regulations and building codes of selected cities impacted by Hurricane Harvey flooding; observations based on that review are included.

Section 2.2 summarizes the wind requirements in the International Codes® (I-Codes®) and the referenced standard that specifies wind loads for the design of buildings and structures. The section also briefly describes the Texas Windstorm Program administered by the Texas Department of Insurance (TDI) because the program has significant influence on construction and building codes in the coastal communities.

2.1 Floodplain Management Requirements

NFIP regulations, described in Section 2.1.1, form the basis of local government programs to guide and regulate development in flood hazard areas. The NFIP requirements for buildings have been integrated into national consensus standards (ASCE 7 and ASCE 24, *Flood Resistant Design and Construction)* and model building codes. FEMA deems the flood provisions in the 2009 and later editions of the I-Codes to meet or exceed the minimum requirements of the NFIP for buildings and structures. When IBC Appendix G, Flood-Resistant Construction, is also adopted, the minimum requirements for non-building development are satisfied. Figure 2-1 illustrates how floodplain management regulations and building codes can be coordinated to fulfill the requirements for participation in the NFIP.

As previously discussed, Texas communities are authorized to adopt and enforce building codes. The I-Codes include provisions for buildings and structures in SFHAs. To address the coordination issues between locally adopted floodplain management regulations and the building codes and referenced standards, communities may wish to refer to *Reducing Flood Losses Through the International Codes: Coordinating Building Codes and Floodplain Management Regulations,* 4th Edition (ICC/ FEMA, 2014). This publication, written by the International Code Council in cooperation with FEMA, also describes differences between the flood provisions in the I-Codes and the NFIP minimum requirements.



* NFIP-consistent administrative provisions, community-specific adoption of Flood Insurance Study (FIS) and maps, and technical requirements for development outside the scope of the building code (and higher standards, in some communities).

ASCE = American Society of Civil Engineers

Figure 2-1: Floodplain management regulations and building design in communities with adopted building codes

BUILDING CODES AND LOCAL FLOODPLAIN REGULATIONS

Communities that enforce locally adopted floodplain management regulations and also enforce building codes with flood provisions should examine the differences and determine in advance how best to resolve those differences. Resolving them on a case-by-case basis may result in varying interpretations or failure to enforce the more restrictive of the requirements.

2.1.1 National Flood Insurance Program

The authorizing legislation for the NFIP is the National Flood Insurance Act of 1968, as amended (Title 42 of the U.S. Code [U.S.C.] §§ 4001 et seq.). In the act, the U.S. Congress found that "a program of flood insurance can promote the public interest by encouraging sound land use by minimizing exposure of property to flood losses." Since 1968, the act has been modified several times.

The NFIP is based on the premise that the Federal Government will make flood insurance available to communities that adopt and enforce floodplain management requirements that meet or exceed the minimum NFIP requirements.

The regulations of the NFIP are the basis for local floodplain management ordinances adopted to satisfy the requirements for participation in the NFIP. In addition, the NFIP minimum requirements are the basis for the flood-resistant design and construction requirements in model building codes and standards. When decisions result in development in SFHAs, application of NFIP criteria is intended to minimize exposure to floods and flood-related damage.

MORE PROTECTIVE STANDARDS FOR FLOODPLAIN MANAGEMENT

FEMA encourages States and communities to adopt standards that are more protective than the NFIP minimum requirements. The most common higher standard that affects buildings is "freeboard," a requirement to elevate buildings above the base flood elevation (BFE). Table 2-2 (Section 2.1.3) shows requirements for selected communities impacted by Hurricane Harvey.

The most convincing evidence of the effectiveness of the NFIP minimum requirements is found in flood insurance claim payment statistics. Buildings that pre-date the NFIP requirements were generally not constructed to resist flood damage, while buildings that post-date the NFIP are designed to resist flood damage. The NFIP aggregate loss data show that buildings that meet the minimum requirements experience 80 percent less flood damage than buildings that pre-date the NFIP. Additionally, ample evidence suggests that buildings designed to standards that exceed the minimum requirements are even less likely to sustain damage.

At the Federal level, the NFIP is managed by FEMA and has three main elements:

- Hazard identification and mapping, in which engineering studies are conducted and flood maps and studies are prepared to delineate areas expected to be subject to flooding under certain conditions
- Floodplain management criteria, which establish the minimum requirements for communities to adopt and apply to development in mapped flood hazard areas; the expectation is that communities will recognize hazards throughout their entire land development process
- Flood insurance, which provides some financial protection for property owners to cover flood-related damage to buildings and contents

At the State level, each Governor or State legislature designates an agency or office to function as the NFIP State Coordinating Agency. The duties and responsibilities of these agencies, typically called the “NFIP State Coordinator,” are found in Title 44 of the Code of Federal Regulations (CFR) § 60.25. Common functions performed by NFIP State Coordinators include:

- Enact, whenever necessary, legislation to enable communities to regulate development in flood hazard areas
- Establish minimum State standards consistent with NFIP requirements
- Ensure coordination with other State, area-wide, and local agencies
- Encourage and assist communities in qualifying for participation in the NFIP
- Guide communities and help develop, implement, and maintain floodplain management regulations
- Provide technical assistance to communities and the general public
- Assist with disseminating information on flood hazards and regulatory requirements
- Participate in training opportunities
- Assist in delineating floodprone areas
- Notify FEMA of problems with community programs if such problems cannot be resolved through technical assistance

DEVELOPMENT

Any manmade change to improved or unimproved real estate, including, but not limited to, buildings or other structures, mining, dredging, grading, paving, excavation or drilling operations, or storage of equipment or materials (44 CFR § 59.1).

2.1.1.1 General Performance Requirements for Buildings

NFIP performance requirements for development in SFHAs are set forth in Federal regulations at 44 CFR Parts 59 and 60. The requirements apply to all types of development proposed in

SFHAs. The NFIP broadly defines the term "development," and the requirements apply to new development, new buildings and structures, Substantial Improvement of existing buildings and structures, and repair of existing buildings and structures that sustain Substantial Damage (refer to the text boxes on "Development" and "Substantial Damage / Substantial Improvement").

The NFIP provisions guide development to lower-risk areas by requiring compliance with performance measures to minimize exposure of new buildings and buildings that undergo major renovation or expansion (called "Substantial Improvement" or "repair of Substantial Damage"). Taken together, administration of NFIP-consistent requirements helps achieve the long-term objective of building flood-resistant communities.

SUBSTANTIAL DAMAGE

Damage of any origin for which the cost to restore a damaged building to its pre-damage condition equals or exceeds 50 percent of the building's market value before the damage occurred.

SUBSTANTIAL IMPROVEMENT

Any reconstruction, rehabilitation, addition, or other improvement of a building, the cost of which equals or exceeds 50 percent of the building's pre-improvement market value. When repairs and improvements are made simultaneously, all costs are totaled and used in the determination.

The NFIP's broad performance requirements for new buildings and the Substantial Improvement or repair of Substantial Damage of existing buildings in SFHAs specify that:

- Buildings must be designed and adequately anchored to prevent flotation, collapse, or lateral movement resulting from hydrodynamic and hydrostatic loads, including the effects of buoyancy.
- Building materials must be resistant to flood damage.
- Buildings must be constructed by methods and practices that minimize flood damage.
- Buildings must be constructed with electrical, heating, ventilation, plumbing, and air-conditioning equipment, and other service facilities that are designed and/or located to prevent water from entering or accumulating within the components.

Beyond the general requirements, specific NFIP requirements for buildings are functions of the flood zone and flood characteristics that affect specific locations. Requirements for SFHAs that are designated Zone A (including AE, A, A1–30, AO, and AH) are summarized in Section 2.1.1.2, and requirements for Coastal High Hazard Areas that are designated Zone V (including VE and V1–30) are summarized in Section 2.1.1.3.

2.1.1.2 Minimum Requirements for Buildings in Zone A

In addition to the general requirements summarized in Section 2.1.1.1, the NFIP minimum requirements for buildings and structures located in Zone A specify the level of protection (elevation) and limitations on enclosures below elevated buildings, including crawlspace foundations.

Building Elevation and Foundations (Zone A)

In Zone A, where FEMA designates base flood elevations (BFEs), the NFIP requirements specify that the lowest floors, including basements, of new buildings and Substantially Improved buildings, must be elevated to or above the BFE. There are no limitations on the type of foundation used to elevate buildings. Buildings may be elevated on perimeter walls (crawlspace), filled stem walls, columns, piers, pilings, or slabs on earthen fill (for NFIP insurance purposes, wood-framed walls are not recognized as foundation walls). Non-residential buildings may be elevated or protected by dry floodproofing that protects to or above the BFE.

LOWEST FLOOR

The lowest floor of the lowest enclosed area (including basement). An unfinished or flood-resistant enclosure, usable solely for parking of vehicles, building access, or storage in an area other than a basement area is not considered a building's lowest floor, provided that such enclosure is not built so as to render the structure in violation of the applicable non-elevation design requirements of Section 60.3 (44 CFR § 59.1).

Some SFHAs, referred to as "unnumbered A zones," are shown without BFEs. In these areas, BFE data from other sources must be used if available. If data are not available, the BFE may be estimated using established methods, and communities are required to ensure that buildings are constructed using methods and practices that minimize flood damage. Once the elevation or height of the lowest floor above grade is established, the remaining requirements for Zone A apply.

The Zone AO designation is used where flooding is characterized by shallow depths (averaging 1 to 3 feet) and/or unpredictable flow paths. In these areas, lowest floors, including basements, are required to be at or above the highest grade adjacent to the building plus the depth number (in feet) shown on the FIRM. For example, if the depth number is 3 feet, the top of the lowest floor must be at least 3 feet above the highest grade adjacent to the building. If no depth is shown, the minimum required height above the highest adjacent grade is 2 feet. Once the elevation or height of the lowest floor above grade is established, the remaining requirements for Zone A apply.

Enclosures Below Elevated Buildings (Zone A)

The NFIP requirements specify that areas below the lowest floors may be enclosed; however, the use of enclosures is restricted to parking of vehicles, building access, and storage.

The walls of enclosures below elevated buildings are required to have flood openings designed to allow the automatic entry and exit of floodwater so that interior and exterior hydrostatic pressures can equalize during flooding. Designs for openings must either meet a prescriptive requirement (1 square inch of net open area for every square foot of enclosed area) or be "engineered openings" that are certified by a registered design professional as meeting a specific performance expectation. The following installation specifications apply to all flood openings: (1) there must be a minimum of two openings for each enclosure, (2) the bottom of openings must be no higher than 1 foot above grade (exterior grade or interior floor/grade), and (3) screens, louvers, valves, or other coverings or devices, if any, must permit the automatic entry and exit of floodwater. Refer to NFIP Technical Bulletin 1, *Openings in Foundation Walls and Walls of Enclosures* (2008d).

FEMA NFIP TECHNICAL BULLETINS

FEMA publishes a series of technical bulletins that provide specific guidance for complying with the minimum requirements of NFIP regulations. The technical bulletins and information on updates are provided at www.fema.gov/nfip-technical-bulletins.The following NFIP technical bulletins are cited in this MAT report:

- Technical Bulletin 1, *Openings in Foundation Walls and Walls of Enclosures* (2008d)
- Technical Bulletin 2, *Flood Damage-Resistant Materials Requirements* (2008b)
- Technical Bulletin 3, *Non-Residential Floodproofing—Requirements and Certification* (1993)
- Technical Bulletin 5, *Free-of-Obstruction Requirements* (2008c)
- Technical Bulletin 9, *Design and Construction Guidance for Breakaway Walls Below Elevated Coastal Buildings* (2008a)

Dry Floodproofing Non-Residential Buildings (Zone A)

The NFIP requirements establish performance expectations for dry floodproofing non-residential buildings as an alternative to elevation. Non-residential buildings may be designed so that below the BFE the buildings are "watertight with walls substantially impermeable to the passage of water and with structural components having the capability of resisting hydrostatic and hydrodynamic loads and effects of buoyancy." Designs must be certified by a registered professional engineer or architect, stating the "methods of construction are in accordance with accepted standards of practice." The dry floodproofing provisions of ASCE 24 are accepted standards of practice. The current edition of FEMA Form 086-0-34, *Floodproofing Certificate for Non-Residential Structures* (2015), may be used to certify designs.

Before a dry floodproofed building is designed, numerous planning considerations should be addressed to determine that dry floodproofing is a viable option. Property owners and design professionals should examine uses of the building, mode of entry and exit and the site in general, floodwater velocities, flood depths, debris impact potential, and flood frequency. A critical consideration is whether locations where dry floodproofing may be specified have sufficient flood warning, which has significant bearing on whether designs that rely on human intervention are viable. For guidance on design and planning, refer to FEMA P-936, *Floodproofing Non-Residential Buildings* (2013) and NFIP Technical Bulletin 3, *Non-Residential Floodproofing—Requirements and Certification* (1993).

For floodplain management purposes, the NFIP requirements specify that non-residential buildings must be dry floodproofed or elevated to or above the BFE. However, for NFIP flood insurance rating purposes, non-residential buildings must be dry floodproofed to at least 1 foot above the BFE to be rated as dry floodproofed. If dry floodproofing measures do not extend to the BFE plus 1 foot, the floor of the building is the lowest floor for rating purposes, and will result in higher premiums. The FEMA *Floodproofing Certificate for Non-Residential Structures* must be submitted with applications for NFIP flood insurance coverage.

2.1.1.3 Minimum Requirements for Buildings in Zone V

In addition to the general requirements summarized in Section 2.1.1.1, the NFIP minimum requirements for buildings and structures in Zone V specify the level of protection (elevation), type of foundation, and limitations on obstructions and enclosures below elevated buildings. Because of the greater hazard posed by breaking waves, structural designs and methods of construction are required to be developed, reviewed, and certified by a registered design professional as capable of resisting the effects of wind and flood loads acting simultaneously.

Building Elevation and Foundations (Zone V)

In Zone V, the NFIP requirements specify that the bottom of the lowest horizontal structural member (excluding vertical foundation members) of the lowest floor of new buildings and Substantially Improved buildings (including buildings that have sustained Substantial Damage) are required to be at or above the BFE. Open foundations such as pilings and columns are required. The use of fill for structural support is not permitted. Concrete slabs, including patios, walkways, pool decks, and slabs used as the floor of enclosures, are required to be structurally independent or, if attached, building foundations are required to be designed to account for the added loads and effects of wave action. If structurally attached to a foundation, the presence of a concrete slab may be considered the building's lowest floor for flood insurance rating purposes.

Obstructions and Enclosures Below Elevated Buildings (Zone V)

The NFIP requirements specify that the space below the lowest floor of elevated buildings must be free of obstructions. The intent is to minimize obstructions that could interfere with the free passage of floodwater and debris underneath the buildings. Areas below lowest floors may be enclosed; however, the use of enclosures is restricted to vehicle parking, building access, and storage.

Obstructions to be avoided—or minimized and constructed to meet the performance requirement—include stairs and ramps, decks and patios, equipment attached to foundation elements, foundation bracing, grade beams, shear walls, and slabs. Other site development that may create obstructions includes accessory structures, erosion control structures, fences and privacy walls, fill used for landscaping, septic systems, and swimming pools and spas. Refer to NFIP Technical Bulletin 5, *Free-of-Obstruction Requirements* (2008c).

Walls of enclosures, if any, are required to be non-supporting breakaway walls, open wood lattice-work, or insect screening intended to collapse under wind and base flood or lesser conditions without causing structural collapse, displacement, or damage to the elevated building or supporting foundation. When walls collapse under specific lateral loads, floodwater can flow through column or pile foundations without obstruction. Refer to NFIP Technical Bulletin 9, *Design and Construction Guidance for Breakaway Walls Below Elevated Coastal Buildings* (2008a).

The NFIP regulations specify a prescriptive design approach for breakaway walls having a safe loading resistance of not less than 10 pounds per square foot and not more than 20 pounds per square foot (in almost all cases, water loads will significantly exceed the upper limit, as will most wind loads and seismic loads). Breakaway walls that do not meet those loading requirements may be used if a registered professional engineer or architect certifies that the walls will collapse under a water load less than that which would occur during the base flood and that the elevated portion of the building and supporting foundation system will not be subject to collapse, displacement, or other structural damage due to the effects of wind and water loads acting simultaneously on all building components.

2.1.1.4 NFIP Community Rating System

The NFIP Community Rating System (CRS) is a voluntary incentive program that recognizes community floodplain management activities that exceed NFIP requirements. The CRS gives discounts on flood insurance premiums in communities that elect to undertake activities that support three goals: reduce flood damage to insurable property, strengthen and support the insurance aspects of the NFIP, and encourage a comprehensive approach to floodplain management.

Communities apply to the CRS and are assigned a class based on the activities they undertake. Classes range from 1 to 10, with 1 representing the most active communities with the most flood hazard-resistant practices. NFIP flood insurance premium rates are discounted in increments of 5 percent. For example, a Class 1 community receives a 45 percent premium discount, a Class 9 community receives a 5 percent discount, and a Class 10 community receives no discount. The CRS classes are based on 18 creditable activities organized under four categories: (1) public information, (2) mapping and regulations, (3) flood damage reduction, and (4) flood preparedness.

COMMUNITY RATING SYSTEM

For more information on the CRS, visit: www.fema.gov/national-flood-insurance-program-community-rating-system.

2.1.2 Floodplain Management in the State of Texas

In 2007, the Texas Water Development Board was designated as the NFIP State Coordinating Agency by the State Legislature (Section 16.316, Water Code). The NFIP State Coordinator is the liaison between the Federal component of the program and the communities, with the primary duty to provide assistance, guidance, and education for community officials. The State Coordinator also supports communities in the CRS.

Sections 16.3145 and 16.315 of the Texas Water Code give the governing bodies of each city and county the authority to adopt ordinances or orders and "to take all necessary and reasonable actions that are not less stringent than the requirements and criteria" of the NFIP. The State of Texas has no floodplain management requirements established at the State level.

FLOODPLAIN MANAGEMENT IN TEXAS

As of July 2018, 1,251 Texas communities participate in the NFIP, and 141 Texas communities are identified as floodprone by FEMA, but have elected not to participate.

As of April 2018, 64 Texas communities were in the CRS. The highest class achieved in Texas, by four communities, is Class 5, providing NFIP policyholders in the SFHA discounts of 25 percent and those outside of the SFHA discounts of 10 percent.

2.1.3 Floodplain Management in Selected Communities Impacted by Hurricane Harvey

The MAT reviewed the floodplain management regulations and building codes adopted by Harris County and the Cities of Houston, Bellaire, and Port Aransas. Each community adopts and enforces floodplain management regulations that contain provisions required for participation in the NFIP. Table 2-1 summarizes NFIP and CRS data for those communities, and Table 2-2 summarizes elevation requirements for buildings in SFHAs in effect before September 2017. Table 2-2 also identifies the building codes in effect before September 2017. The following sections summarize the MAT observations on local regulations for each community.

Table 2-1: NFIP and CRS Data for Selected Communities

Community	NFIP Entry Date	Current Effective FIS/FIRM	CRS Entry Date	Effective Date of Current CRS Class	Current CRS Class
Harris County	5/26/1970	1/6/2017	5/1/2004	10/1/2014	7
City of Houston	12/11/1979	1/6/2017	5/1/2002	10/1/2009	5
City of Bellaire (Harris County)	9/30/1981	6/18/2007	10/1/1993	5/1/2014	7
City of Port Aransas (Aransas/Nueces Counties)	6/25/1971	2/17/2016	Not in CRS	Not in CRS	Not in CRS

CRS = Community Rating System; FIRM = Flood Insurance Rate Map; FIS = Flood Insurance Study; NFIP = National Flood Insurance Program

SOURCE: FEMA, 2018n AND FEMA, 2018h

Table 2-2: Building Elevation Requirements in Effect Prior to Hurricane Harvey

Community	Building Elevation Requirements (Before Harvey)				Building Code(a)
	Residential	Non-residential	Manufactured Housing	Critical Facility	
Harris County (defines "habitable floor" rather than "lowest floor")	Zone A: Floor 18 inches above BFE (or depth number in Zone AO) or to the level of crown of nearest public street, whichever is higher	All Zone A: • Elevated: same as residential • Dry Floodproofed: BFE (implied only with basement)	All Zone A: 18 inches above BFE	All Zones: 3 feet above BFE	2012 IBC and "IRC … as adopted by state law," with amendments.
	Zone A, floodway: bottom of lowest supporting member 18 inches above BFE				
	Unnumbered A zone and Zone AO without depth number: 3 feet above highest adjacent grade				
	Zone V: 18 inches above BFE	Zone V: 18 inches above BFE	Zone V: 18 inches above BFE		
Houston, City	BFE + 12 inches	BFE + 12 inches	BFE + 12 inches	12 inches above 500-year	2012 IBC and IRC. Amended to remove flood provisions and refer to floodplain management regulations.
Bellaire (Harris County)	BFE + 1 foot	• Elevated: BFE + 1 foot • Dry Floodproofed: BFE	BFE + 1 foot	N/A	"Current edition" of IBC, IRC, and "all appendices."
Port Aransas (Aransas/ Nueces Counties)	BFE	BFE	BFE	N/A	2003 IBC and IRC, and 1997 "Standard Existing Building Code," "together with all future revisions."

(a) Building, Residential, and Existing Building only

(b) Where full elevation required (i.e., not in pre-FIRM MH park/subdivision and not if Substantially Damaged by flood)

BFE = base flood elevation; IBC = International Building Code; IRC = International Residential Code

2.1.3.1 Harris County

The *Regulations of Harris County, Texas for Flood Plain Management* (adopted November 2011) were in effect prior to Hurricane Harvey. The regulations apply to all unincorporated areas (not restricted to the SFHA), and thus also serve as the basis for enforcement of the residential building code. The regulations were amended on December 5, 2017 and effective January 1, 2018. The MAT made the following observations regarding the pre-Harvey regulations:

- Creates Class "I" and Class "II" permits (refer to text box).
- Adopts a requirement for buildings to be elevated higher than the BFE (see Table 2-2), while permitting non-residential buildings to be dry floodproofed to the BFE. (The MAT did not determine the effective date of the freeboard requirements listed in Table 2-2.)
- Adopts the "Flood Insurance Study (FIS) and Flood Insurance Rate Map (FIRM) adopted on June 18, 2017" and subsequent amendments and revisions and "adopts as its regulatory floodways the floodways shown on the said FIRM."

HARRIS COUNTY CLASS "I" AND CLASS "II" PERMITS

Class "I" permits are issued for properties with ground elevations above the BFE (not in the SFHA).

Class "II" permits are issued for properties with ground elevations below the BFE "or subject to flooding as determined by these Regulations" (in the SFHA).

- Requires "Certificates of Non-Compliance" to be issued by the County Engineer to advise owners when sites are not in compliance with the regulations of the County; advises that legal action may be taken and a request for denial of flood insurance may be processed with FEMA. Certificates may be filed in the real property records.
- Defines "habitable floor" (includes bathrooms, utility rooms, and storage areas greater than 150 square feet), and uses it instead of "lowest floor." The implication is that only storage areas less than 150 square feet are permitted below the required elevation.
- Does not define "lowest floor"; this term is used for recreational buildings, critical facilities, and manufactured housing.
- Embeds the definition of "substantial damage" in the definition for "substantial improvement." Among triggers for substantial damage is "[i]n cases where the structure is covered by insurance and the insured losses for damage to the structure (excluding contents) amount to over 95 percent of the value of the structure, the structure shall be deemed substantially damaged regardless of any other data submitted."
- Specifies in Section 3.02 that if land is lower than the BFE, the ground elevation serves as the basis for regulation even if the FIRM shows otherwise.
- Cites FEMA Bulletins 1-93, 2-93, and 3-93 in Sections 4.05(b)(3), 4.05(b)(4), and 4.05(j) and states that these editions "or subsequent revisions will serve as guidance" for methods and practices that minimize flood damage and for materials.
- Places limits on fill in Section 4.05(b)(9), which must be the minimum necessary to achieve the intended purpose, with "any excess fill material… properly mitigated on a one-for-one

basis and shall not interfere with existing drainage patterns." A maximum of 3 feet of fill is permitted for residential structures in subdivisions developed prior to September 16, 1976.

- Requires in Section 4.05(e) the "reduction in floodplain storage or conveyance capacity" to be offset with "hydraulically equivalent (one-to-one) volume of mitigation," with a "fully hydrological and hydraulic analysis" required if mitigation is requested outside the boundaries of the property being developed.
- Specifies in Section 4.05(g) that new manufactured housing parks/subdivisions are not permitted in floodways or Zone V.
- Specifies in Section 4.05(m) additional requirements for floodways, including elevation using posts or pilings (fill not permitted). In the San Jacinto River Floodway, foundation designs must account for scour and requirements are detailed. This section also specifies that the area below the BFE shall not be enclosed, although it permits storage areas less than 150 square feet, provided "the walls perpendicular to flow are constructed of materials allowing the free flow of water and that these walls are no greater than 12 feet wide."
- States in Section 4.05(o) that structures in Zone V must be "on posts or pilings" and specify piling depth. This section also requires "the bottom of the lowest horizontal structural member of the structure" to be elevated (rather than the lowest horizontal structural member "of the lowest floor," as specified in the NFIP regulations). It does not use the defined term "habitable floor" and does not limit the size of enclosures. It requires development (not just new construction) to be landward of the reach of mean high tide and does not permit alteration of sand dunes and mangrove stands.

2.1.3.2 City of Houston

The *Code of Ordinances for the City of Houston, Texas,* including Chapter 1, General Provisions, and Chapter 19, Floodplain, were in effect prior to Hurricane Harvey. Chapter 19 was amended by Ordinance No. 2018-258 on April 4, 2018. The MAT made the following observations regarding the pre-Harvey regulations:

Chapter 1, General Provisions:

- Defines "Construction Code" to mean "the Building Code, the Plumbing Code, the Electrical Code, or the Mechanical Code." Further, "[a]lthough they do not constitute part of the Construction Code for other purposes, the International Residential Code and the International Energy Conservation Code, both as adopted by state law and amended by the city, shall be considered to be included within the term 'Construction Code.'"
- Amends the 2012 IBC and IRC to delete the flood provisions and instead, refer to Chapter 19 (floodplain regulations).

HOUSTON FLOODPLAIN "GUIDELINES"

The City produces a "Guidelines" version of Chapter 19 containing text in gray boxes intended to "establish an operational and procedural framework for administration." The guidelines refer to the 1993 editions of FEMA NFIP Technical Bulletins 1, 2, and 3. Despite the City's intent that the guidelines provide guidance, the City enforces compliance with the out-of-date technical bulletins.

The "Guidelines" are available at edocs.publicworks.houstontx.gov/engineering-and-construction/flood-plain-guidelines.html.

Chapter 19, Floodplain:

- Adopts requirement for buildings to be elevated higher than the BFE (see Table 2-2), while permitting non-residential buildings to be dry floodproofed to the BFE. (The MAT did not determine the effective date of date the freeboard requirement listed in Table 2-2.)
- Defines “repetitive loss” and includes it in the definition of “substantial improvement.”
- Requires operators of manufactured housing parks and subdivisions to file evacuation plans indicating alternate vehicle access and escape routes prior to obtaining permits.

2.1.3.3 City of Bellaire

The *Code of Ordinances for the City of Bellaire, Texas,* Chapter 9, Buildings, includes Article II, Building Codes, and Article II-A, Flood Damage Prevention. The regulations were in effect prior to Hurricane Harvey. The MAT made the following observations regarding the pre-Harvey regulations:

Chapter 9, Buildings, Article II, Building Codes:

- Section 9-18, “Drainage requirements for residential construction,” specifies “fill credit,” a form of limiting fill.
  - Outlines requirements for structures in the SFHA that are elevated with and without fill with respect to how the fill credit is applied.
  - Outside the SFHA, limits fill to that necessary to achieve adequate drainage.
  - For all residential projects, requires an “as-built” elevation survey and an engineer’s statement of conformance with site and drainage plans prior to issuance of certificates of occupancy.

Chapter 9, Article II-A, Flood Damage Prevention (adopted October 6, 2014):

- Does not explicitly reference the adopted building codes, which have flood provisions.
- Adopts requirement for buildings to be elevated higher than the BFE (see Table 2-2), while permitting non-residential buildings to be dry floodproofed to the BFE. (The effective date of the freeboard requirements noted in Table 2-2 has not been verified.)
- “Lowest Floor” definition refers to the “nonelevation design requirement of section 60.3” rather than the City’s regulations. Adds the following non-standard and partially incorrect description of how lowest floor elevations are “measured” for residential structures: (a) concrete slab (lowest point on the exterior perimeter of the slab, excluding ledges for facades); (b) crawl space (top of the wood sub-flooring); (c) with basement (top surface of the basement floor; wine cellars and elevator pits are basements). The MAT notes FEMA has not granted the City of Bellaire a “basement exception” to allow residential basements in SFHAs.

BELLAIRE: COSTS OF REPAIRS

A 2017 document published on the *City of Bellaire, Texas Official Nextdoor Page,* “How Does the City Apply the ‘50%’ Rule?” (referring to the Substantial Improvement and Substantial Damage requirements), states “non-flood-related renovation or remodeling costs will no longer be counted toward the ‘50% rule.’ Only previous flood-related repair costs, plus Harvey-related repair costs, will be included.”

- Adopts the "Flood Insurance Study (FIS) for the City of Bellaire, Texas," dated June 28, 2007, "and any revisions thereto." (The NFIP Community Status Book identifies the FIS date of June 18, 2007 and the Map Service Center shows the City of Bellaire is included in the January 6, 2017 FIS. The City's only FIRM is dated June 18, 2007; thus, the date in the regulations appears to be in error.)
- States that residential and non-residential construction "shall have lowest floors elevated as a minimum, to one foot above the highest of the base flood elevation shown on the effective FIRM and the flood hazard recovery data map."
- Non-residential construction, if not elevated, must "be designed so that below the base flood level the structure is watertight with walls substantially impermeable ….", thus not requiring freeboard for dry floodproofed structures.

2.1.3.4 City of Port Aransas

The *City Code of Port Aransas, Texas,* including Chapter 5, Buildings and Building Regulations, and Chapter 8, Flood Damage Prevention, were in effect prior to Hurricane Harvey. The MAT made the following observations regarding the pre-Harvey regulations:

Chapter 5, Buildings and Building Regulation:

- Section 5-2, requires that "[a]ny work or repair costing more than a total set by resolution by the city council shall be required to have a permit."
- Section 5-52, states that, in the event of "hurricane disaster," the Building Official is required to "waive building codes for a period of up to one (1) year in order to allow lots to be cleaned and temporary housing to be placed on site during the rebuilding process" (emphasis added).
- Section 5-83, states that "any person wishing to make minor repairs or remodeling must make application for a permit," except if the total cost is less than $1,500; there is no major structural change in size, shape, or location of the building; and the person doing the work "complies with this chapter as a homeowner."

Chapter 8, Flood Damage Prevention (amended January 15, 2015):

- Does not explicitly reference the adopted building codes, which have flood provisions.
- "Lowest Floor" definition refers to the "nonelevation design requirement of section 60.3" rather than comparable provisions in the City's regulations.
- Adopts the FIS for Aransas County (May 4, 1992) and Nueces County (May 4, 1992) "and any revisions thereto." (Current effective date for Aransas County is February 17, 2016.)

2.2 Building Code Wind Requirements

Model building codes provide criteria for designers on the minimum loads buildings and other structures must be designed to withstand, including minimum elevation requirements for buildings located in flood hazard areas. The most widely adopted building codes in the United States are the IBC and the IRC, which are updated every 3 years, with the 2018 being the most recent edition.

The State of Texas does not mandate the adoption and enforcement of building codes throughout the State; therefore, municipalities can choose to adopt and enforce any or none of the model building code editions (refer to the beginning of this chapter for more information on statutory requirements for building code adoption in Texas). Because of this, the jurisdictions impacted by Hurricane Harvey had adopted different editions of the IBC and IRC, ranging from the 2009 editions to the 2015 editions (see Table 2-3). However, the Texas Windstorm Inspection Program, through the TDI, wields a significant influence on construction and building codes in the coastal counties. TDI refers to these counties as "Designated Catastrophe Areas" or "First Tier Counties." TDI requires compliance with the 2006 IBC and IRC with Texas Revisions, which are based on and reference ASCE 7-05 for wind loads. As discussed in Sections 2.2.1 and 2.2.2, wind loads are generally higher in ASCE 7-05 than ASCE 7-10, which is referenced in the 2012 and 2015 IBC and IRC. For more information on the Texas Windstorm Inspection Program, refer to Section 2.2.3 on the Texas Windstorm Program.

Table 2-3: Building Codes in Effect at the Time of Hurricane Harvey for Selected Cities in Texas Impacted by High Winds

City	Building Codes
Fulton	2009 IBC and 2009 IRC
Rockport	2012 IBC and 2012 IRC
Aransas Pass	2012 IBC and 2012 IRC
Corpus Christi	2015 IBC and 2015 IRC
Port Aransas	2015 IBC and 2015 IRC
Woodsboro	None
Holiday Beach	None
Houston	2012 IBC and 2012 IRC
Victoria	2015 IBC and 2015 IRC

IBC = International Building Code, IRC = International Residential Code

2.2.1 International Building Code and ASCE 7

Various editions of the IBC were adopted in the areas impacted by Hurricane Harvey, as indicated in Table 2-3. The 2006 and 2009 IBC primarily reference ASCE 7-05 for determining wind loads for the design of buildings. The 2009 IBC also contains a simplified or alternate procedure for determining wind loads, but the method is based on ASCE 7-05 and results in generally the same loads as ASCE 7-05.

One significant wind load-related difference between the 2006 IBC and the 2009 IBC pertains to the use of wood structural panels as glazed opening protection in wind-borne debris regions. The 2009 IBC requires attachment hardware for wood structural panels used as opening protection to be permanently installed on the building, whereas the 2006 IBC permitted the use of No. 6 or No. 8 screws directly fastened into the wall framing. Also of note, the 2006 IBC and subsequent editions prohibit the use of aggregate, gravel, or stone on roofs in hurricane-prone regions because the roofing material often becomes wind-borne debris.

The 2012 IBC references ASCE 7-10 for determining wind loads for the design of buildings. The wind provisions of ASCE 7-10 were significantly revised from ASCE 7-05.[1] The most notable change was to the wind speed maps. A summary of the changes to the wind speed maps is as follows:

- The wind speed maps were changed to reflect strength design-level values instead of the allowable stress design (ASD) levels in ASCE 7-05 and earlier editions. (The 2012 and 2015 editions of the IBC refer to these strength design-level wind speeds as ultimate design wind speeds, or V_{ult}.)

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[1] A comprehensive discussion of all the changes to the wind provisions in ASCE 7-10 can be found in *Significant Changes to the Wind Load Provisions of ASCE 7-10, An Illustrated Guide,* published by ASCE Press (Stafford, 2010).

- The wind speed maps were provided according to Risk Category, which eliminated the need for Importance Factors to adjust the mean recurrence interval (MRI).
- Wind speeds were updated based on new hurricane data and new analysis of hurricane wind speeds, which resulted in lower design pressures for the hurricane-prone region.

As a result of the updates, wind speeds shown on the maps in ASCE 7-10 are higher than those in ASCE 7-05. However, after using the appropriate strength design/ASD conversions, the design wind loads (pressures) for hurricane-prone regions in ASCE 7-10 are generally lower (significantly lower in some areas) than ASCE 7-05.

Another significant change in ASCE 7-10 that affected wind loads was the re-introduction of the applicability of Exposure Category D in hurricane-prone regions. In ASCE 7-05, Exposure Category D did not apply in hurricane-prone regions. Buildings and other structures classified as being in Exposure Category D in hurricane-prone regions in ASCE 7-10 would qualify as Exposure Category C in ASCE 7-05. The impact on design pressures of being classified as Exposure Category D as opposed to Exposure Category C diminishes as mean roof height increases (design pressure increases approximately 23 percent at a mean roof height of 15 feet and 13 percent at a mean roof height of 100 feet).

One way to realize the impact of the changes to the basic wind speeds in ASCE 7-10 is to convert the strength design-level wind speeds to ASD and overlay the converted wind speeds on the ASCE 7-05 basic wind speed map. Figure 2-2 shows how comparable wind speeds have changed between ASCE 7-05 and ASCE 7-10 for Risk Category II structures. The red contours on the map are the ASCE 7-05 wind speeds (ASD). The blue contours are ASCE 7-10 wind speeds for Risk Category II structures converted to an ASD level. The strength design level wind speeds in ASCE 7-10 are converted to an ASD level by dividing by the square root of the load factor on wind load for strength design in ASCE 7-05 (divided by $\sqrt{1.6}$).

Another way to assess the impacts of the changes to the wind speed maps is to look at changes to comparable design pressures. Because ASCE 7-10 wind speeds are strength design-level, calculated design wind pressures have to be converted to ASD for comparison to ASCE 7-05 (alternatively, the ASCE 7-05 wind pressures could be converted to strength design). The governing equations for determining design wind pressures in ASCE 7-10 have not changed from ASCE 7-05. Similarly, pressure coefficients and other variables used to calculate design wind pressures for buildings did not change in ASCE 7-10 (except for a few clarifications). Therefore, the changes in design pressures can be determined by taking the square of the ASCE 7-10 wind speeds and multiplying it by 0.6 (to convert it to ASD) and then dividing by the square of the ASCE 7-05 wind speed. For Risk Category II buildings sited in Exposure Categories B or C, the percent change in design pressures can be shown as follows:

$$\text{Percent Change in Design Pressures from ASCE 7-05 to ASCE 7-10} = [((\text{ASCE 7-10 Wind Speeds})^2 \times 0.6) \ / \ (\text{ASCE 7-05 Wind Speeds})^2] - 1$$

For areas where Exposure D now applies, an additional factor is needed. As previously mentioned, the effect of changing from a C Exposure to a D Exposure diminishes as the height of the building increases. For buildings with a mean roof height up to 30 feet, the effect of Exposure D is approximately 18 percent higher than Exposure C. Therefore, for buildings with a mean roof height of 30 feet located where Exposure D now applies, the percent change in design pressures from ASCE 7-05 to ASCE 7-10 can be shown as follows:

$$[((\text{ASCE 7-10 Wind Speeds})^2 \times 0.6 \times 1.18) \ / \ (\text{ASCE 7-05 Wind Speeds})^2] - 1$$

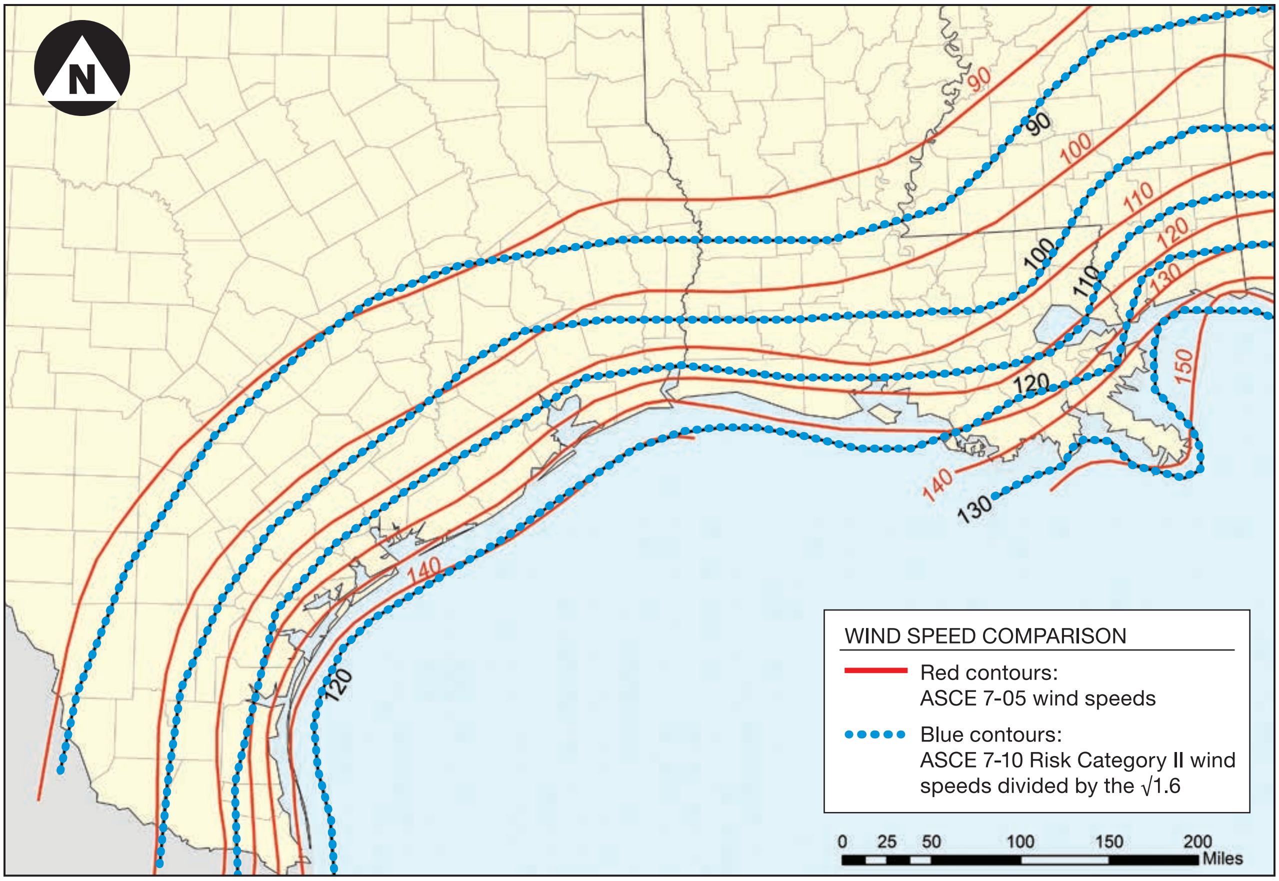


Figure 2-2: Comparison of ASCE 7-05 (red contours) and ASCE 7-10 basic wind speeds for Risk Category II buildings converted to ASD (blue dotted contours)

(SOURCE: MODIFIED FROM STAFFORD, 2010)

Table 2-4 summarizes the percent change in design wind pressures from ASCE 7-05 to ASCE 7-10 for Risk Category II buildings at a mean roof height of 30 feet for select cities impacted by Hurricane Harvey.

Table 2-4: Design Wind Pressures from ASCE 7-05 and ASCE 7-10, Risk Category II Buildings

Location	Basic Wind Speed(a) ASCE 7-05	Basic Wind Speed(a) ASCE 7-10	Percent Change in Comparable Design Pressures from ASCE 7-05 to ASCE 7-10	
			Exposures B and C	Exposure D(b)
Aransas Pass	130	147	-23%	-9%
Corpus Christi	125	143	-21%	-7%
Fulton	129	147	-22%	-8%
Holiday Beach	126	146	-19%	-5%
Port Aransas	135	149	-27%	-14%
Refugio	116	140	-13%	+3%
Rockport	130	147	-23%	-9%
Victoria	119	142	-15%	+1%
Woodsboro	116	140	-13%	+3%

(a) Basic wind speeds were obtained from the Applied Technology Council wind speed database at hazards.atcouncil.org.

(b) Percent change reflects the increase/decrease in design pressures resulting from structures being classified as being in Exposure Category D in ASCE 7-10 as opposed to Exposure Category C in ASCE 7-05.

For example, the ASCE 7-05 basic wind speed for Rockport, TX, is 130 mph (ASD-level). The ASCE 7-10 basic wind speed for Risk Category II buildings in Rockport is 147 mph (strength design level). Although the actual wind speed is higher, when the proper conversions are applied, the ASCE 7-10 design pressures for Risk Category II buildings in Exposures B or C are approximately 23 percent lower than those in ASCE 7-05.

2.2.2 International Residential Code

The IRC addresses environmental loads, such as wind, in a more prescriptive manner so that one- and two-family dwellings can be built without individual designs by architects or engineers being required. However, the use of the prescriptive construction criteria in the IRC is limited. The prescriptive provisions in the 2006 and 2009 IRC apply to areas where the basic wind speed is 100 mph or less. The 2006 and 2009 IRC reference ASCE 7-05, and the wind speed map in the IRC is a reprint of the basic wind speed map in ASCE 7-05. Therefore, where the design wind speed exceeds 100 mph, residential buildings have to be designed in accordance with ASCE 7-05, or in accordance with one of the prescriptive high-wind standards referenced by the 2006 and 2009 IRC, such as the American Wood Council's *Wood Frame Construction Manual* (2001), the American Iron and Steel Institute's AISI S230, *Standard for Cold-Formed Steel Framing: Prescriptive Method for One- and Two-Family Dwellings* (2001, including 2004 supplement; 2007, including Supplement 2 dated 2008), and the International Code Council's SSTD 10, *Hurricane Resistant Construction Standard* (1999; referenced only in the 2006 IRC), and the International Code Council's ICC 600-08, *Standard for Residential Construction in High Wind Regions* (2008; referenced only in the 2009 IRC).

The 2012 IRC took a slightly different approach to ASCE 7-10 than the 2012 IBC. While the 2012 IRC references ASCE 7-10, the wind speed map in the 2012 IRC is an ASD-level version of the ASCE 7-10 wind speed map. In addition, a new map was added that identifies areas where wind design is required (see Figure 2-3). In these areas, the prescriptive provisions of the IRC are not permitted; rather, residential buildings must be designed in accordance with ASCE 7-10 or in accordance with one of the prescriptive high-wind standards. The "Wind Design Required" region in the 2012 IRC corresponds roughly to the areas on the ASCE 7-10 Risk Category II map where the wind speed is 130 mph and greater (in the extreme northeastern areas of the United States and Alaska, it corresponds to 140 mph and greater).

The 2015 IRC also references ASCE 7-10, but uses the wind speed maps from ASCE 7-10, in addition to providing a map identifying regions where wind design is required. Like the 2012 IRC, the "Wind Design Required" region in the 2015 IRC corresponds roughly to the areas on the ASCE 7-10 Risk Category II map where the wind speed is 130 mph and greater (and in the extreme northeastern areas of the United States and Alaska, it corresponds to 140 mph and greater).

2.2.3 Texas Windstorm Program

In 1971, as a response to the devastation caused along the Texas coast by previous hurricanes and by Hurricane Celia (1970), the Texas Legislature established the Texas Catastrophe Property Insurance Association (TCPIA) as an insurer of last resort for those unable to obtain windstorm and hail insurance in the private market. The association was renamed and became the Texas Windstorm Insurance Association (TWIA) in 1997. All insurers who provide windstorm insurance in Texas are required to become members of TWIA. Excess premiums and investment income on those premiums are deposited into the Texas Catastrophe Reserve Trust Fund, which is used to pay for excess losses.

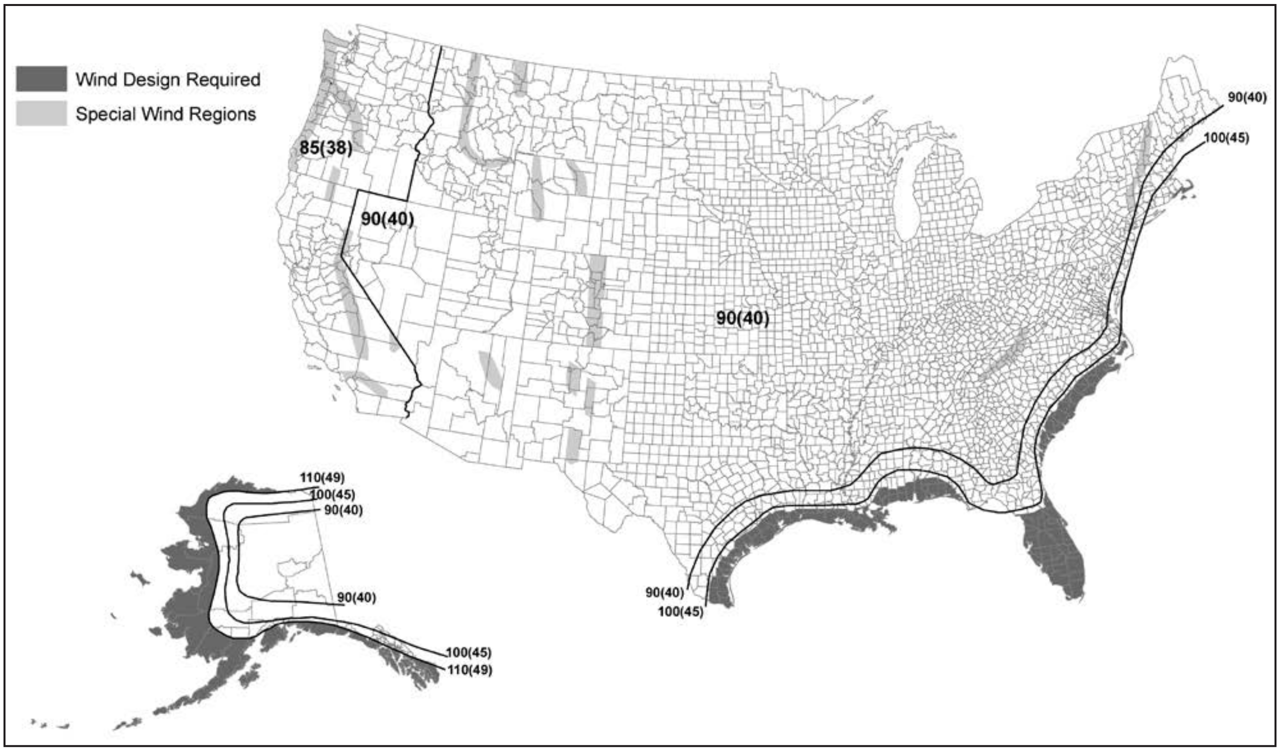


Figure 2-3: 2012 IRC Wind Design Required map

SOURCE: ICC, USED WITH PERMISSION

TWIA operates only in First Tier coastal counties along the 367-mile Texas Gulf Coast, as shown in Figure 2-4. Along with the counties shown in Figure 2-4, TWIA also provides windstorm and hail coverage in certain specifically designated communities in Harris County that are east of State Highway 146. These communities include La Porte, Morgan's Point, Pasadena, Seabrook, and Shore Acres.

2.2.3.1 Texas Department of Insurance

At the same time the TCPIA was established, the Texas Legislature adopted the TCPIA Building Code for Windstorm Resistant Construction, which was based on the wind load provisions of the 1971 Standard Building Code. Various other codes were adopted in later years. Successive hurricanes caused damage that revealed that these code requirements were not being enforced. This lack of enforcement led to the creation of the Windstorm Inspection Program at the TDI in 1988. The Windstorm Inspection Program is currently responsible for providing product evaluations, construction inspection services, and certification that buildings are in accordance with the adopted codes.

2.2.3.2 Basic Tenets of the Texas Windstorm Code

The TDI has adopted various codes for windstorm-related design since the TCPIA was established. In 2003, the TDI adopted the 2000 IRC and 2000 IBC directly rather than modifying the Standard Building Code, as was done previously. In 2005, the TDI adopted

TEXAS DEPARTMENT OF INSURANCE

For more information about the Texas Department of Insurance, visit www.tdi.texas.gov/wind/index.html.

the 2003 IRC and 2003 IBC, and in 2008, the 2006 IRC and 2006 IBC were adopted. TDI has also established a set of revisions to the adopted codes (referred to as the Texas Revisions) that are also required.

Since 1998, the TDI has divided the Texas counties in the Designated Catastrophe Area along the Gulf of Mexico into three zones, described as Inland (II), Inland (I), and Seaward. The TDI adopts different wind speed requirements for each zone that roughly follow the wind speed contours in ASCE 7-05. Figure 2-4 illustrates the three zones, as well as the adopted wind speed requirements applicable to each zone. Notable Texas Revisions to the 2006 IRC and 2006 IBC regarding protection of glazed openings from wind-borne debris are shown in Table 2-5. Additionally, design wind pressures are provided for specific sizes of garage doors for various wind speeds. The Texas Revisions also provide specific requirements for corrosion resistance for Inland II, Inland I, and Seaward areas.

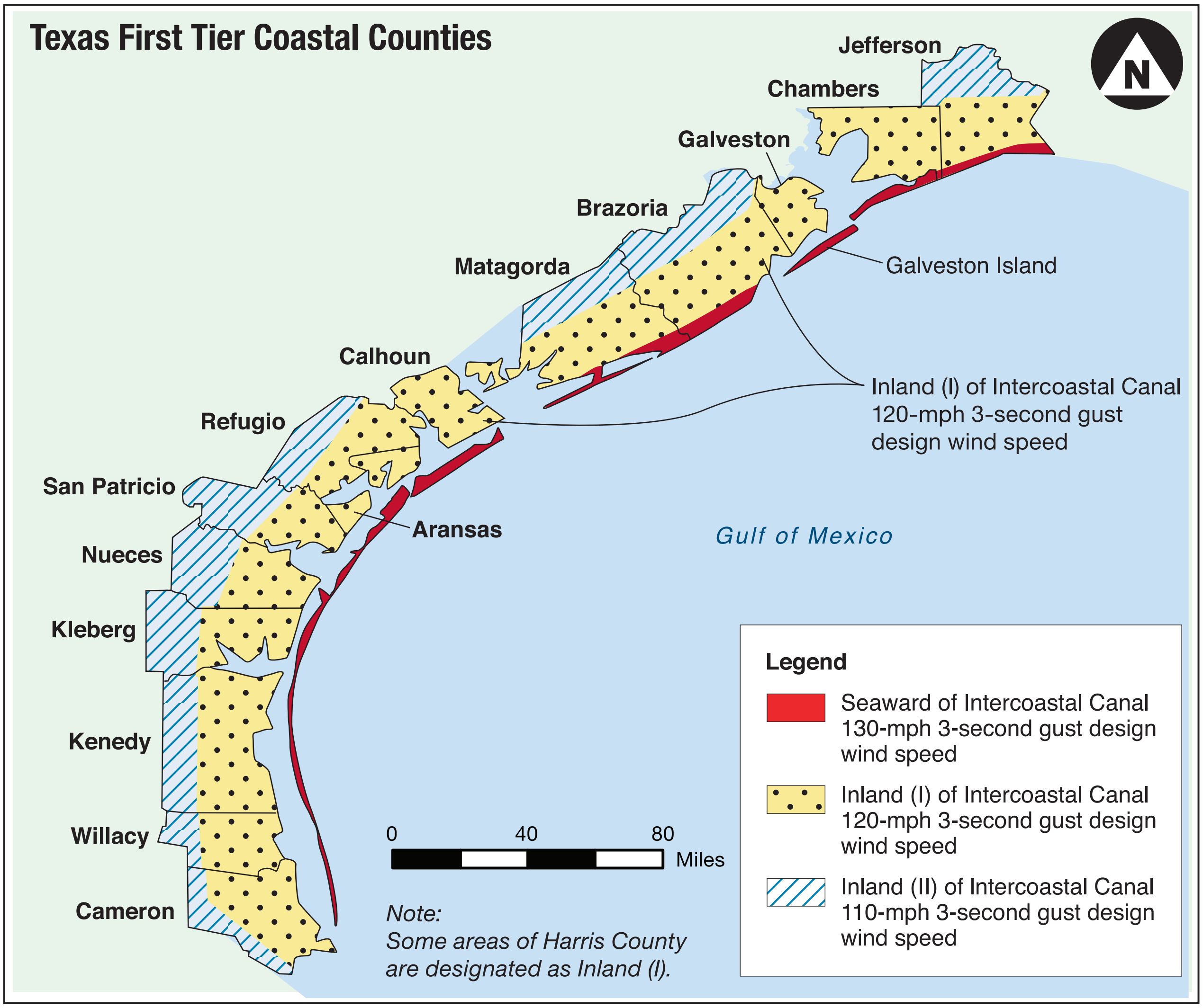


Figure 2-4: Texas Windstorm Designated Catastrophe Areas

ADAPTED FROM: TDI, 2018

The TDI requires building products to be tested to and comply with the test standards and criteria specified in the IRC, the IBC, and the Texas Revisions. Manufacturers who sell products that meet these standards and criteria may request to have their products evaluated by TDI and listed on the TDI website. The TDI also evaluates and lists some types of building products that have passed test criteria specified for the High-Velocity Hurricane Zones in the Florida Building Code.

Table 2-5: Texas Revisions to 2006 IRC and IBC for Protection of Glazed Openings from Wind-Borne Debris

Location	Texas Revisions	
	Opening Protection Requirement	Exceptions
Inland (II)	No protection required	Not applicable
Inland (I)	All glazed openings must be protected with products meeting ASTM 1886 and ASTM 1996, or ANSI/DASMA 115 (Garage Doors)	Exception permits the use of plywood with a minimum thickness of 15/32 inches and maximum span of 8 feet • Limited to one- and two-story buildings • Requires attachments to be designed in accordance with IRC simplified loads, ASCE 7, or the prescriptive attachment method provided • Installation instructions are required to be provided • Attachment is required to be secured to the wall framing
Seaward	All exterior openings (windows, doors, skylights, and garage doors) must be protected with products meeting ASTM 1886 and ASTM 1996, or ANSI/DASMA 115 (Garage Doors)	Exception permits the use of plywood with a minimum thickness of 15/32 inches and a maximum span of 8 feet • Limited to one- and two-story buildings • Installation instructions are required to be provided • Requires panels and attachments to meet ASTM E 1886 and ASTM E 1996 or an “approved impact-resisting standard” • Requires panels to be tested for uniform static wind resistance in addition to wind-borne debris resistance
Wind-borne Debris Regions	Requires skylights in wind-borne debris regions to meet ASTM E 1886 and ASTM E 1996, or AAMA 506, *Voluntary Specifications for Impact and Cycle Testing of Fenestration Products*	None

AAMA = American Architectural Manufacturers Association
ANSI = American National Standards Institute
ASCE = American Society of Civil Engineers
DASMA = Door & Access Systems Manufacturers Association, International
IBC = International Building Code
IRC = International Residential Code

HURRICANE
HARVEY
IN TEXAS

3

Flood-Related Observations

Most of Hurricane Harvey's damage was caused by flooding originating from the historic rainfall in Southeastern Texas and by the storm surge at its three landfalls.

The heavy rainfall caused significant riverine and sheet flow flooding, which resulted in inundation damage to hundreds of thousands of residential and non-residential buildings and billions of dollars in damage across 42 counties. The MAT visited both residential and non-residential buildings and the focus for each was different, as described in the paragraphs that follow.

The mission of the MAT was to assess the performance of residential and non-residential buildings affected by flooding. For residential buildings, the MAT was tasked with identifying neighborhoods containing a mixture of new and old construction, with high participation in the NFIP, for use in a desktop analysis. The desktop analysis assessed the effect of floodplain regulations on flood insurance claims in those neighborhoods. For non-residential buildings, the MAT was tasked with assessing the performance of dry floodproofing mitigation measures installed in buildings within Harris County, including the Texas Medical Center (TMC).

Residential buildings. Within Harris County alone, 154,170 single-family houses and thousands of apartment units, condos, and townhouses flooded. The widespread extent of the flooding revealed a large variability in the performance of residential buildings. The MAT focused on houses within the mapped 1-percent-annual-chance and 0.2-percent-annual-chance event flood hazard areas to determine whether there was any correlation in the flood damage observed and age of the house.

FLOODWAY DEVELOPMENT

In Harris County, 20,000 parcels worth $13.5 billion are located in or along floodways. Approximately 75% of buildings on those 20,000 parcels were built before the first 1.0-percent-annual-chance probability flood elevations for Harris County were published in 1985. About 1,400 structures, on floodway parcels valued at $4.2 billion, have been built in the City of Houston and Harris County since 2008, 7 years after Tropical Storm Allison exposed the City's vulnerabilities to severe rainfall events. After Tropical Storm Allison, a prohibition against construction in the floodway was passed; however, after numerous lawsuits against the ban, Houston eliminated the prohibition on floodway development in 2008.

Non-residential buildings. Within Harris County alone, approximately 15,000 non-residential buildings were flooded. Unlike residential buildings, floodplain management regulations and building codes allow non-residential buildings to be dry floodproofed to protect the building from flood damage. Given the frequency and severity of flooding in Harris County, the practice of dry floodproofing is common in non-residential buildings. In fact, following Tropical Storm Allison in 2001, several million dollars in dry floodproofing projects were funded under the FEMA Public Assistance program as hazard mitigation measures in conjunction with repairs to public buildings. Floodplain management regulations allow non-residential buildings to be dry floodproofed. To receive a dry floodproofing rating credit under the NFIP, the floodproofing measure must protect to a minimum of 1 foot above the BFE. For buildings that were repaired or constructed after Tropical Storm Allison, dry floodproofing protection was implemented to 2 feet above the measured water surface elevation recorded during that event.

The severity and area impacted by Hurricane Harvey resulted in numerous dry floodproofed buildings being exposed to floodwater, allowing the MAT to visit and assess the performance of various dry floodproofing systems. The performance of dry floodproofed buildings the MAT visited in Harris County varied significantly, allowing lessons to be gleaned from both successes and failures of dry floodproofing mitigation.

FLOODPROOFING TERMINOLOGY

Dry floodproofing entails the strengthening a building's foundation, floor, and walls to withstand flood forces while making the structure watertight.

Wet floodproofing entails making utilities, structural components, and contents flood- and water resistant during periods of flooding within the structure.

NFIP TERMINOLOGY

Special Flood Hazard Area (SFHA): The land area covered by the floodwater of the base flood as delineated on NFIP maps. The SFHA is the area where the NFIP's floodplain management regulations must be enforced and the area where the mandatory purchase of flood insurance applies.

Regulatory Floodway: Delineated within the SFHA on NFIP maps; it is the channel of a river or other watercourse and the adjacent land areas that must be reserved in order to discharge the base flood without cumulatively increasing the water surface elevation more than a designated height.

MAT observations. Evaluating buildings to observe performance of residential buildings and dry floodproofed non-residential buildings was one of the MAT's main goals. Although the MAT believes its assessments of buildings described in this chapter are correct, statements made herein are not intended to represent final judgments as to the cause of damage to individual buildings; further investigations by others may refine or alter judgments made by the MAT. Nevertheless, general damage patterns and trends the MAT observed are valid and can be used as the basis for recommendations to improve residential design and construction and non-residential dry floodproofing design and construction.

Chapter organization. The MAT observations of flood-impacted buildings are divided into two main sections: Residential Buildings (Section 3.1) and Non-Residential Buildings with Dry Floodproofing (Section 3.2). Section 3.1 is presented by topic areas identified as of particular concern and Section 3.2 is presented by individual buildings.

3.1 Residential Buildings

The MAT visited select residential buildings (primarily single-family buildings) that were flooded by Hurricane Harvey in Aransas, Harris, and Nueces Counties. The Hurricane Harvey MAT emphasized identifying newly constructed or elevated houses that were adjacent to non-elevated houses with a wide range in age of construction to help evaluate the performance of buildings constructed to minimum floodplain management standards versus those constructed to higher standards. Additionally, the MAT endeavored to identify any areas of building performance in newer construction that could benefit from improvements in existing design and construction requirements.

NIFP CLAIM PAYMENTS

For this report, NFIP claim payments were used as proxies for the estimated cost of repair. The claim payments do not reflect the deductible or items that were not covered under the policy.

Because of limited access and ongoing recovery efforts, most of the residential building performance was studied by analyzing NFIP flood insurance claims information in locations identified from MAT windshield assessments or other damage assessment surveys. The assessment focused on collecting location-specific information, including the flood zone and BFE, the year the residence was built, the foundation type, the estimated flood depth, and the total flood insurance claim payment amount. This information was gathered from a variety of sources. For example, the year built and foundation type (e.g., crawlspace versus slab) was gathered from county parcel data, the flood zone and BFE were collected from the National Flood Hazard Layer, and the flood insurance claim data were collected from the FEMA Federal Insurance Directorate based on closed claims as of June 30, 2018. Building characteristics, particularly the foundation type, were verified based on data collected during windshield assessments.

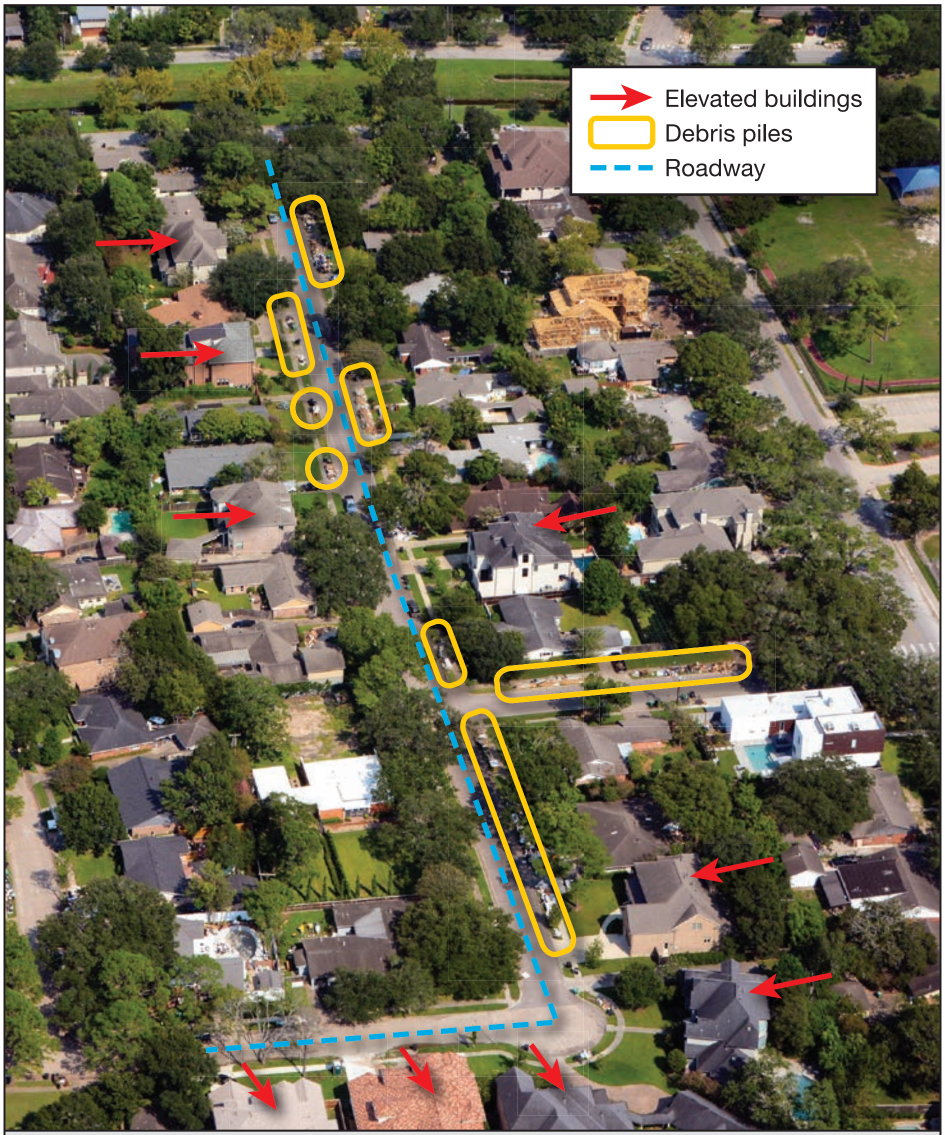
An example of a representative neighborhood visited by the MAT is shown in Figure 3-1, which shows part of an image taken by the Texas Civil Air Patrol on September 6, 2017. The neighborhood pictured had a range of old and new construction slab-on-grade houses and residences elevated on a crawl space. As shown in the figure, the newer elevated houses (shown with red arrows on Figure 3-1) had little to no debris in front of them, whereas the older non-elevated structures had large piles of debris (shown outlined in yellow) in front of them indicating extensive damage to the building and contents. The entire area is in Zone AE based on the FIRM (effective June 2017). Of the 30 parcels along the highlighted route in Figure 3-1 (dashed blue line), 19 had an active flood insurance policy under the NFIP, 16 of the residences were built in the 1950s, and three were built after 2007.

DEBRIS

The MAT observed debris piles as it drove through neighborhoods. The size of the debris piles outside each building is considered an indicator of the extent of building and contents damage.

Figure 3-1: Representative residential neighborhood visited by the MAT [Zone AE]

PHOTO COURTESY OF TEXAS CIVIL AIR PATROL



Neighborhood contains a mixture of older slab-on-grade construction with some new houses on elevated foundations. Note the prevalence of debris piles in front of older construction versus the elevated houses.

Of note:

- Of the 16 residences built before the community joined the NFIP, 12 currently have a closed insurance claim. The average total payment (building and contents) was approximately $181,750. Most of the claims are close to meeting the Substantial Damage 50 percent threshold.
- Two of the three residences built after communities started regulating development in the SFHA had closed claims. One had a total payment of approximately $12,050 and the other was closed without a payment (due to minimal to no damage).

3.1.1 General Observations

Building elevation was a universal indicator of performance: many older buildings built before communities joined the NFIP and began regulating SFHA development were inundated 3 to 6 feet, while newer elevated residential buildings performed much better, in some cases with no inundation and other cases with less than 1 foot of flooding above the lowest floor. Figure 3-2 through Figure 3-5 are representative examples of flood inundation depths, as indicated by HWMs, and damage observed by the MAT.

Figure 3-2:
An approximately 5-foot-high HWM (shown as the dotted red line) observed by the MAT while assessing residential buildings on September 9 in Harris County [Zone AE]

Residential building, built in 2001 in Aransas County, had extensive damage to the ground floor from approximately 3 to 4 feet of surge inundation along with damage from high winds throughout the residence.

Figure 3-3: Residential building located within the Limit of Moderate Wave Action (LiMWA) based on the February 2016 effective FIRM [Zone AE]

Floodwater caused extensive damage (top row) to older construction while, neighboring newer residences in the SFHA sustained little to no flood damage (bottom row).

Figure 3-4: A 54-inch-high HWM on residential buildings in Nueces County [Zone A]

The interior damage shown in the image on bottom right is representative of typical damage observed by the MAT for single-family residences.

Figure 3-5: A 42-inch-high HWM on a house in Harris County built in 1955 [Zone AE]

The one-story apartments in Figure 3-6 were built in phases starting in 2011. The apartments, which are located within the SFHA, were built to the minimum NFIP requirements without any freeboard. During Hurricane Harvey, the apartments were flooded with approximately 6 inches of water; most of the damage likely could have been avoided if the slab foundations had been elevated 1 foot as required by the model building codes and standards. Based on input from the repair contractor, most of the exterior condenser units were not sufficiently inundated to cause damage; however, some did have to be repaired, and in rare circumstances they had to be entirely replaced. One challenge noted by the MAT was the difficulty in repairing the party wall between apartment units. The damaged material was removed, but there is no practical way to replace the inner sheets with new material.

These one-story apartments in Nueces County were inundated by approximately 6 inches of floodwater. The flood damage resulted in extensive repairs to walls and flooring, including the party walls (top right) and to some condenser units (bottom left).

Figure 3-6: Flood damage to Nueces County apartments [Zone AE]

Figure 3-7 illustrates an elevated residence the MAT observed in Harris County. While not many residences were elevated in neighborhoods that the MAT visited, those that were elevated performed better than adjacent, older houses built before communities began regulating SFHA development. The elevated residences were randomly distributed and often surrounded by slab-on-grade structures, allowing a comparison of new and old construction. Figure 3-8 illustrates three houses that were adjacent or immediately across from the elevated residence in Figure 3-7. All four houses are in Zone AE. The elevated residence was built in 2002, while the three slab-on-grade structures were built in 1955. The MAT measured a HWM at 42 inches above the slabs along this street. The homeowner of the elevated residence (shown in Figure 3-7) stated that the water reached the top step of their entrance but did not inundate the habitable space. The elevated residence had a flood insurance claim payment of approximately $18,000 (primarily due to having non-flood damage-resistant materials in the garage and crawlspace), while the three slab-on-grade structures had an average claim payment of $136,000.

Figure 3-7:
This elevated house built in 2002 (HWM, shown as the dotted red line) had much less damage than surrounding older slab-on-grade houses (example shown in Figure 3-8) [Zone AE]

Figure 3-8:
Slab-on-grade house (located across the street from the elevated residence shown in Figure 3-7) has large debris pile [Zone AE]

Flood damage to buildings was not limited to properties in mapped 1.0-percent-annual-chance probability floodplains (SFHA). For example, the elevated Aransas County single-family residence in Figure 3-9 built in 2016 in Zone X had approximately $12,000 in damages due to lack of flood damage-resistant materials below the elevated floor. In Harris County, aerial imagery revealed that about one-third of the county was under water at one point, and approximately half of the inundated area was outside of the FEMA-mapped 0.2-percent-annual-chance probability floodplain and therefore outside the SFHA.

Figure 3-9: Elevated residence built in 2016 with flood damage (approximately $12,000) [Zone X]

The MAT observed recently built houses that met or exceeded the minimum NFIP elevation requirements (but not requirements for enclosures) and had minimal structural damage, but still required some repair to interior finishing. For example, the Zone AE residence in Figure 3-10 was built in 2016 with insufficient flood openings; it appeared to have limited flood damage from the exterior, yet an NFIP insurance claim was filed for this residence. In addition to flood damage related to its elevation, the house had damage to the building envelope from hurricane-force winds, including loss of siding and soffit covering, which may have caused interior damage from leaking around those openings.

Figure 3-10: Relatively new house built in 2016 had limited exterior flood damage, yet interior repairs were required due to flood inundation and penetration of wind-driven rain [Zone AE]

3.1.2 Enclosures Below Elevated Buildings

For floodplain management purposes, an enclosure is a confined area below the lowest elevated floor of a building that is formed by walls on all sides of the enclosed space. Enclosed areas that are used solely for parking of vehicles, building access, or storage are permissible below the lowest elevated floor. However, floodplain management regulations for Zone A/AE require enclosures to be built with flood damage-resistant materials and have openings in walls to allow free entry and exit of floodwater. If an enclosure is not properly constructed with adequate openings (refer to FEMA Technical Bulletin 1, *Openings in Foundation Walls and Walls of Enclosures* [2008d]), it can transfer flood forces to the main structure and possibly lead to structural damage or collapse.

Most of the enclosures the MAT observed were in Aransas and Nueces Counties. Although no damage to enclosures with compliant flood openings was observed, compliance with floodplain management requirements was inconsistent. For example, a recently constructed (2016) single-family residence in Zone AE had a two-car garage enclosure and another enclosure for access to the house. The two-car garage had openings along two sides (top row of images in Figure 3-11), but the enclosure for access to the house had no openings (bottom row of images in Figure 3-11).

Residential building constructed with proper openings for the garage enclosure (top row, indicated by yellow circles), but no opening in the enclosure for access to the house (bottom row).

Figure 3-11: Elevated residence built in 2016 in Aransas County [Zone AE]

FEMA Technical Bulletin 1, *Openings in Foundation Walls and Walls of Enclosures* (2008d), outlines the requirements and guidance for the installation of openings. The Technical Bulletin includes requirements for an enclosure's minimum size, as well as guidance on limiting covers or devices that could impede the free flow of floodwater into and out of the enclosed area. Some enclosures were observed to have the compliant number of openings, but the openings did not necessarily meet all the requirements. For example, the elevated single-family residence built in 2009 in Zone AE shown in Figure 3-12 had an enclosure that appeared to be for storage; it had an engineered opening on one wall, but on the other wall it had a less than 3-inch by 6-inch cutout opening covered by an air vent faceplate with a screen along the interior. The smaller opening was not a compliant flood opening. While the MAT did not identify a HWM in this area, and access was not provided to the interior of this enclosure, the presence of piles of insulation and other garbage in the debris pile adjacent to the elevated residence (upper left image of Figure 3-12) suggests that the interior of the enclosure sustained damage because flood damage-resistant materials were not used.

[A] Elevated house in Nueces County with evidence of non-flood damage-resistant materials in the enclosure (yellow dotted circle identifying debris piles).

[B] An engineered opening (red circle).

[C] A non-compliant flood opening (red circle).

Figure 3-12: Elevated residential building non-compliant flood opening [Zone AE]

In Port Aransas, the MAT observed two elevated houses approximately 300 feet apart along the same street within the SFHA in Zone AE; the two sites experienced the same flood conditions during Hurricane Harvey. One house was built in 1982 and the other in 2014. Both had enclosures below the elevated building, but only the enclosure below the newer house had flood openings. The performance and extent of damage within the enclosure of these two buildings was considerably different, with the enclosure of the older house suffering extensive damage (see Figure 3-13), while the newer house required much less repair (see Figure 3-14).

Figure 3-13: Extensive damage to the enclosure of an older (1982) elevated residence in Port Aransas; the enclosure did not have flood openings [Zone AE]

Figure 3-14:
The enclosure of a newer elevated residence in Port Aransas with compliant flood openings on each side of the house (see insets) suffered only limited damage to its contents [Zone AE]

The MAT observed recently built elevated houses in Nueces County with enclosures that were permitted under the effective 1992 FIRM but whose flood zone determination will likely change based on the preliminary map. The elevated residence in Figure 3-15 had flood openings, but there were not enough openings based on the enclosure size. In addition, based on the preliminary FIRM, this house will be reclassified from Zone AE to Zone VE. Without breakaway walls and based on the enclosure size, the house is susceptible to damage from wave action. Although a HWM was not identified by the MAT during the windshield assessment, preliminary damage assessment and flood insurance claims information obtained by the MAT indicate there was about $3,000 in damage within the enclosure.

Figure 3-15: Elevated residence built in Nueces County in 2016 to Zone AE floodplain management requirements [Zone VE, per updated preliminary FIRM]

3.1.3 Perimeter Wall Foundations (Crawlspace)

Perimeter wall foundations (also called crawlspaces) were present in many of the newer elevated buildings the MAT observed, especially in Harris County. The foundations were predominantly pier and beam construction and ranged from 2 to 6 feet above grade. Like enclosures, crawlspaces must have flood openings to allow the equalization of flood forces. Figure 3-16 shows a representative crawlspace observed by the MAT.

Figure 3-16: Residential crawlspace observed by the MAT in a Harris County house built in 2002 where the insulation along the elevated floor had to be removed [Zone AE]

One common performance issue the MAT observed in crawlspace foundations was the use of non-flood damage-resistant materials, particularly insulation. The MAT observed relatively small piles of debris adjacent to several of the elevated buildings in Harris County, and the observed debris appeared to be non-flood damage-resistant materials likely removed from crawlspaces and garages, as illustrated in Figure 3-17.

Based on MAT observations, some property owners used fiberglass insulation or other non-flood damage-resistant insulation materials below the elevated lowest floor. Use of such materials requires an additional factor of safety be incorporated into the foundation design flood elevation, or freeboard, to reduce the risk of flood damage.

Figure 3-17:
Non-flood damage-resistant materials removed from the crawlspace of the adjacent elevated Harris County building built in 2014 [Zone AE]

3.1.4 Ongoing Slab-on-Grade Elevation Project

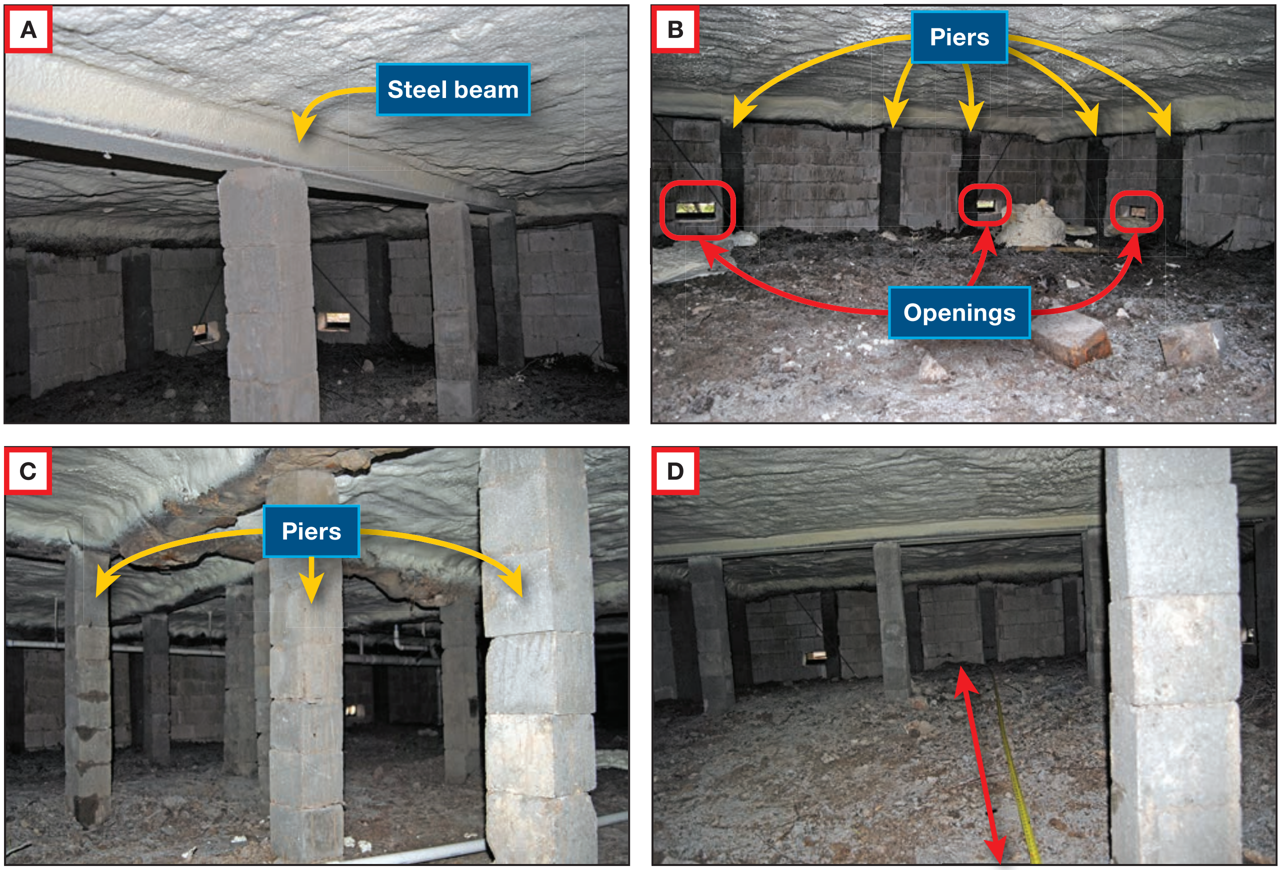
The MAT observed one residential elevation project that was underway at the time Hurricane Harvey struck (see Figure 3-18 through Figure 3-20). The project was located in the SFHA (Zone AE) and was partially funded under FEMA's Hazard Mitigation Assistance programs, and the house was scheduled to be lifted days before Hurricane Harvey made landfall. Because of the storm, the contractor had to put the lift on hold. Damage to the house was significant and resulted in a maximum coverage NFIP claim from Hurricane Harvey.

Because the project was underway at the time the MAT visited, this house offers a case study in elevating a slab-on-grade foundation. The house was elevated more than 4 feet after Hurricane Harvey.

Elevation method and foundation system. The elevated slab is supported by mini-piers consisting of concrete blocks connected to one another with a series of threaded steel dowel rods or other material running through a hole in the center of each block (see Figure 3-18 for representative examples of mini-piers).

The homeowner stated that a structural engineer evaluated the slab and recommended the pier spacing. In some parts of the house a steel beam was used to support the slab to limit the pier spacing, although pier spacing varied greatly. Most spans were approximately 8 to 10 feet; some exceeded 12 feet.

The MAT did not observe any evidence of a continuous load path connection between the piers and the steel beam or the concrete slab to the piers around the perimeter wall. Figure 3-18 shows representative images from the crawlspace illustrating the foundation system.



[A] Recently elevated slab-on-grade foundation, where steel beams were used to support the elevated slab and limit pier spacing.

[B] Piers and openings along perimeter.

[C] Representative pier spacing.

[D] Piers are spaced every 10 feet in the direction of the tape measure.

Figure 3-18: Recently elevated slab-on-grade foundation where steel beams were used to support the elevated slab and limit pier spacing [Zone AE]

Finish. A perimeter wall finish with flood openings (as seen in Figure 3-19) was placed around the base of the elevated houses to provide an aesthetic covering for the raised slab. The homeowner stated that the contractor sprayed the bottom of the slab with closed-cell foam to insulate it. Closed-cell foam was also sprayed throughout all the exterior walls, shown in Figure 3-20. The closed-cell foam was sprayed directly on the existing fiberboard and wood framing adhering the components into an assembly. If the house is elevated above the BFE with sufficient freeboard to make sure that it has minimal flood risk, this approach will likely result in a more energy efficient house. It is important to inspect the fiberboard to make sure that it was not damaged during previous flood events and that the moisture content of the fiberboard is within the manufacturer's recommended limits. If the fiberboard sheathing is damaged and no longer maintains its structural properties, the proposed assembly (which includes the closed cell foam), should be evaluated by an engineer to verify that it can sufficiently resist lateral loads and that the exterior sheathing does not need to be replaced. Although closed-cell foam is considered an acceptable flood damage-resistant material, applying it directly to the existing fiberboard, which is not flood damage-resistant, could be problematic because any trapped moisture from floodwater would be difficult to dry out. Such assemblies, which include porous exterior sheathing materials, could be susceptible to mold growth or other damage that is difficult to inspect and should therefore be avoided in floodprone areas.

Figure 3-19: Exterior of new masonry perimeter foundation wall adjacent to piers supporting the elevated slab [Zone AE]

[A] Closed-cell foam applied to exterior walls.

[B] Closed-cell foam applied to existing fiberboard sheathing.

Figure 3-20: Closed-cell foam was applied to all exterior walls when this slab-on-grade house was elevated

3.1.5 Floodplain Management Requirements versus Damage

The MAT visited neighborhoods similar to that shown in Figure 3-21, where there are side-by-side new and old residences as well as new construction that exceeds the NFIP requirements. Visiting such neighborhoods provided the MAT with a unique opportunity to evaluate the effectiveness of elevating houses to mitigate flood damage.

Figure 3-21:
Example of neighborhood in Harris County where newer elevated residences (house on left was built in 2013) are situated next to older residences (non-elevated older residence on right was built in 1948) [Zone AE]

3.1.5.1 Proof of Benefit of Building Elevation

The MAT was able to identify some situations where adjacent elevated and non-elevated buildings both had active NFIP flood insurance policies before Hurricane Harvey and their claims were closed or paid. Having NFIP claims for adjacent (or nearby) structures allowed the MAT to compare flood damage cost based on current floodplain management requirements as well as design and construction practices. One example is illustrated in Figure 3-22 where the recently constructed elevated residence had approximately $4,000 in damage, while the non-elevated structure had over $96,000.

Figure 3-22:
Example of an elevated residence (left side) next to a non-elevated residence (right side); the elevated house sustained much less damage during Hurricane Harvey

3.1.5.2 Proof of Benefit of NFIP Construction

Most of the neighborhoods visited in Harris County were in two NFIP-participating communities: Bellaire and Houston. Based on the information collected in the field, as well as a desktop assessment of parcel data attributes including year built and foundation type, the MAT identified groups of houses with a high percentage of active NFIP flood insurance policies to compare building performance.

Within the specific neighborhoods visited and analyzed, there were 1,280 active NFIP policies, of which 673 had closed claims from Hurricane Harvey. Table 3-1 provides a summary of these closed flood insurance claims. The distribution was almost evenly split between houses built before (54 percent) and after (46 percent) the communities began regulating SFHA development in 1982. The average claim for houses built after the communities adopted floodplain management regulations was half that compared to those built before.

Table 3-1: Summary of Closed Flood Insurance Claim Data for Neighborhoods Analyzed by MAT

Construction Date	Number of Houses	Average Claim
Before 1982	663	$181,258
After 1982	572	$89,906

Note: 1982 is the year the community adopted floodplain management regulations

SOURCE: CLAIMS BASED ON NFIP DATA THROUGH JUNE 2018 (FEMA, PERSONAL COMMUNICATION) AND YEAR BUILT BASED ON HARRIS COUNTY APPRAISAL DISTRICT REAL AND PERSONAL PROPERTY DATABASE (2018)

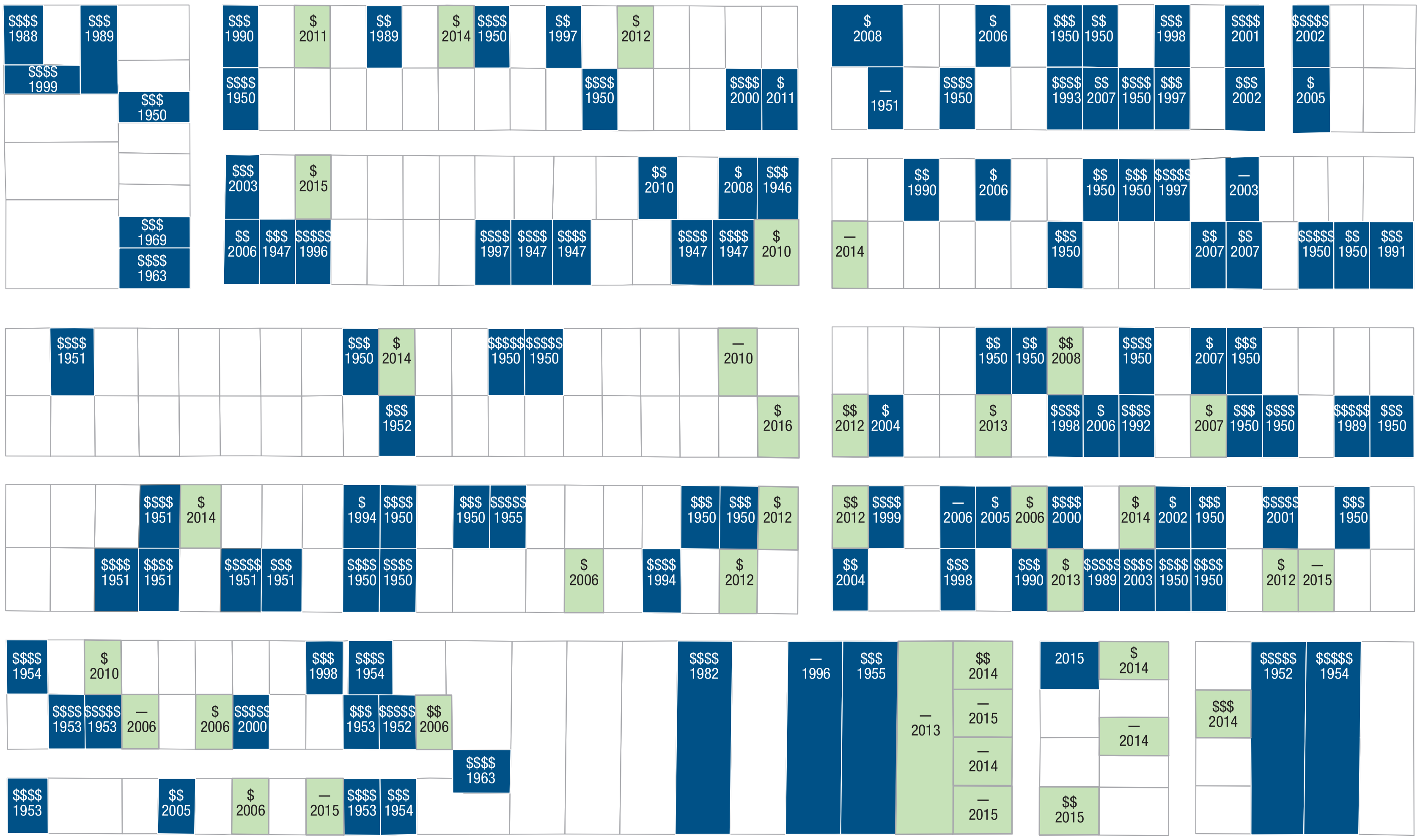
3.1.5.3 Proof of Benefit of NFIP Participation

One residential area associated with the 1,280 NFIP policies the MAT studied consisted of 334 residences, all of which were in Zone AE. This representative neighborhood is illustrated in Figure 3-23. As shown on Figure 3-23, the neighborhood is composed of houses built on slabs and crawlspaces and includes houses of varying ages. The relatively close proximity of these residences provided an opportunity for the MAT to compare residences that were subject to similar flood conditions during Hurricane Harvey and analyze damage (as represented by claim payments) with respect to homeowner maintenance of an active flood insurance policy, presence of a new FIRM, and foundation type.

Effect of Active Flood Insurance Policy

Of the 334 residences, 161 (48 percent) had an active flood insurance policy. The 48 percent rate for having an active flood insurance policy within the SFHA is representative of the neighborhoods analyzed (the overall rate was about 50 percent). At the time this report was written, 157 of the 161 flood insurance policies in this residential area had a closed claim. The average total (building and content) closed claim payment was approximately $98,182. Of the 157 structures with closed claims, 62 were built prior to 1982 and the remaining 95 were built after 1982.

Within this specific neighborhood, the average total claim payment for the houses built prior to when the community began regulating SFHA development was approximately $146,800, whereas those built after 1982 had an average total claim of approximately $66,450 (see Table 3-2).



LEGEND

🟩 **Crawlspace**
■ **Slab**
☐ **No NFIP policy**
Year built

Insurance Claims (data as of June 2018):
— Closed w/o payment
$ 1–10,000
$$ 10,000–50,000
$$$ 50,000–125,000
$$$$ 125,000–225,000
$$$$$ 225,000+

RESULTS

	CLAIM AMOUNTS		FOUNDATION TYPE		YEAR BUILT			
	Quantity	Percent	Crawlspace	Slab	Pre-1982[1]	Post-1982	1982-2000	Post-2000[2]
0	16	10%	13	3	0	16	1	15
$	31	20%	18	13	0	31	1	30
$$	24	15%	6	18	7	17	4	13
$$$	27	17%	1	26	19	8	5	3
$$$$	40	26%	0	40	27	13	11	2
$$$$$	19	12%	0	19	9	10	9	1
Total	**157**	**100%**	**38**	**119**	**62**	**95**	**31**	**64**

[1] Initial FIRM is dated 1981; structures built 1982 and later would comply with NFIP requirements per the initial FIRM.
[2] Updated FIRM for the area studied is dated 1999; structures constructed 2000 and later would comply with updated zone information shown on the 1999 or latest effective FIRM.

Figure 3-23: Distribution of residences analyzed in the representative residential area, as of June 2018

Table 3-2: Summary of Closed Flood Insurance Claim Data for the Representative Residential Area

Description	Houses Built Before 1982	Houses Built After 1982	All Houses
Total number of policies	66	95	161
Total number of closed claims	62	95	157
Average closed building claim	$117,506	$57,034	$80,915
Average closed content claim	$29,924	$9,418	$17,267
Average closed total claim	$146,800	$66,452	$98,182
Claims closed without payment ($0)	0	16	16

SOURCE: CLAIMS BASED ON NFIP DATA THROUGH JUNE 2018 (FEMA, PERSONAL COMMUNICATION) AND YEAR BUILT BASED ON HARRIS COUNTY APPRAISAL DISTRICT REAL AND PERSONAL PROPERTY DATABASE [2018]

Effect of New FIRM on Damage

While the year built relative to the initial adoption of floodplain management regulations was a key indicator in differentiating building performance, the MAT found during its analysis that newer construction built to meet the latest FIRM as well as the latest floodplain management requirements (including freeboard) was an indicator as well.

In the representative neighborhood introduced in the previous subsection, 15 of the 16 claims closed without payment were built in 2001 or later. The average claim for a post-2000 (effective date of previously effective FIRM) residence was approximately $19,335, almost 90 percent less than those built from 1982 through 2000. Table 3-3 shows a summary of claims comparing post-2000 construction to those built from 1982 through 2000.

Table 3-3: Closed Flood Insurance Claim Data for Post-1982 Construction in the Representative Residential Area

Description	Houses Built 1982–2000	Houses Built After 2000	All Houses
Total number of policies	31	64	95
Total number of closed claims	31	64	95
Average closed building claim	$139,514	$17,083	$57,034
Average closed content claim	$24,214	$2,252	$9,418
Average closed total claim	$163,728	$19,335	$66,452
Claims closed without payment ($0)	1	15	16

SOURCE: CLAIMS BASED ON NFIP DATA THROUGH JUNE 2018 (FEMA, PERSONAL COMMUNICATION) AND YEAR BUILT BASED ON HARRIS COUNTY APPRAISAL DISTRICT REAL AND PERSONAL PROPERTY DATABASE [2018]

Representative Neighborhood – Effect of Foundation Type on Damage

One additional indicator of building performance found during the MAT's analysis was the foundation type. Buildings constructed on crawlspaces had significantly lower claims than those with a slab-on-grade foundation. The average claim for a house with a crawlspace was approximately $8,800, about 93 percent less than those built on a slab. Table 3-4 shows a summary of the flood insurance claims based on foundation type.

Table 3-4: Closed Flood Insurance Claim Data for Slab-on-Grade versus Crawlspace Construction in the Representative Residential Area

Description	Slab-on-Grade	Crawlspace	All
Total number of policies	123	38	161
Total number of closed claims	119	38	157
Average closed building claim	$104,042	$8,490	$80,915
Average closed content claim	$22,670	$347	$17,267
Average closed total claim	$126,712	$8,837	$98,182
Claims closed without payment ($0)	3	13	16

SOURCE: CLAIMS BASED ON NFIP DATA THROUGH JUNE 2018 (FEMA, PERSONAL COMMUNICATION) AND YEAR BUILT BASED ON HARRIS COUNTY APPRAISAL DISTRICT REAL AND PERSONAL PROPERTY DATABASE [2018]

3.2 Non-Residential Buildings with Dry Floodproofing

Unlike residential buildings, non-residential buildings can use dry floodproofing to protect the building from flooding. Many non-residential buildings in Harris County have dry floodproofing measures installed to prevent damage from the frequent flooding experienced in the county. With its record-breaking rainfall amounts, Hurricane Harvey tested dry floodproofing measures installed at buildings throughout Harris County.

One goal for the MAT was to evaluate the performance of these measures to assess which methods worked and which did not, and why. To accomplish this goal, the MAT visited private commercial buildings, government buildings, and the TMC in Harris County. Table 3-5 lists the buildings visited that are described in this report (the MAT visited some non-residential buildings not described herein) and the pertinent subsection number.

Table 3-5: Facilities and Buildings Assessed by MAT in Harris County

Facility Name	MAT Section	Private Commercial	Government	NFIP Flood Zone
Harris County Jail	3.2.1.1		X	Zone AE
Harris County Criminal Justice Center	3.2.1.2		X	Zone X
Jury Assembly Building	3.2.1.3		X	Zone X
Harris County Civil Courthouse	3.2.1.4		X	Zone X
City of Houston Public Works	3.2.2		X	Unshaded Zone X
Wortham Theater and Underground Parking and Tunnel Complex	3.2.3	X		Zone AE
Energy Corridor Office Building #1	3.2.4	X		Zone X
Energy Corridor Office Building #2	3.2.5	X		Unshaded Zone X
Houston Galleria Office Tower	3.2.6	X		Unshaded Zone X
Four Leaf Towers	3.2.7	X		Unshaded Zone X
Starbucks at 4660 N. Braeswood	3.2.8	X		Zone AE
Texas Children's Hospital	3.2.9.1	X		Zone X
The University of Texas MD Anderson Cancer Center	3.2.9.2		X	Zone AE and Zone X(a)
Harris Health System Ben Taub Hospital	3.2.9.3		X	Zone X
Baylor College of Medicine	3.2.9.4	X		Zone X
CenterPoint Energy Grant Substation	3.2.9.5	X		Zone AE
Thermal Energy Corporation (TECO) Paul G. Bell, Jr. Energy Plant	3.2.9.6	X		Zone AE

Note: All buildings are located on the Harris County Community FIRM panels

(a) The MD Anderson Cancer Center has numerous buildings on the TMC campus, with some of the buildings located in Zone AE and others located in Zone X.

MAT = Mitigation Assessment Team; NFIP = National Flood Insurance Program

KEY DRY FLOODPROOFING TERMINOLOGY

Flood Barrier: The physical barrier, composed of opening protection, floor slab, and wall system, that separates floodwater from the dry floodproofed portion of the building.

Opening Protection: A cover, shield, or door that covers a window, doorway, loading dock access, or other opening in a building wall or floor. Sometimes called "closure device."

Active: A dry floodproofing opening protection system that requires human intervention to install the physical barrier. These systems are effective only if there is enough warning time to mobilize the labor and equipment necessary to implement them and then safely evacuate.

Passive: A dry floodproofing opening protection system that does not require human intervention to deploy the physical barrier.

Floodwall: A constructed barrier of flood-damage-resistant materials to keep water away from or out of a specific area. Floodwalls surround a building and are typically offset from the exterior walls of the building; some floodwalls can be integrated into the building envelope. Floodwalls are considered a component of the overall flood barrier.

Flood Entry Point: Any opening, joint, gap, crack, low point, or other location through or over which floodwater can enter the dry floodproofed area.

Substantially Impermeable: According to USACE, a wall is considered substantially impermeable if it limits water accumulation to 4 inches in a 24-hour period (USACE, 1995). In addition, sump pumps are required to control any seepage, and flood-resistant materials must be used in all areas where seepage is likely to occur. As stated in FEMA's Technical Bulletin 3, FEMA adopted the USACE's standard for defining substantially impermeable. ASCE 24 is the minimum requirement; it is possible to achieve lower seepage rates, which is strongly encouraged by FEMA, particularly in new construction.

General Observations

The performance of dry floodproofing measures was highly variable, ranging from effective to complete failure. However, the dry flood proofing systems evaluated that performed well (or failed) shared similar characteristics. In buildings where the dry floodproofing failed, critical building systems located in basements and first floors were damaged and rendered inoperable. In addition to failures, the MAT observed numerous instances of "near misses." In these cases, the dry floodproofing measures or human intervention prevented widespread flood damage, but if flood levels had been only slightly higher or if building managers had not taken action before the onset of flooding, many of these successes would have

TROPICAL STORM ALLISON COMPARED TO HURRICANE HARVEY

Similar to Hurricane Harvey, Tropical Storm Allison lingered over eastern Texas for 5 days before travelling eastward toward North Carolina and Virginia. In Houston, total rainfall from Tropical Storm Allison was recorded between 5 and 35 inches; east of Houston, some areas recorded rainfall totals that exceeded 40 inches.

By comparison, all of Harris County received a minimum of 25 inches of rain, with a maximum of 54 inches of rain, during Hurricane Harvey. For additional information, refer to Chapter 1.

been failures. Table 3-6 summarizes the key observations by the MAT on the performance of dry floodproofing systems and the amount of downtime and damage that occurred at the buildings visited by the MAT.

Owners of the buildings visited understood their vulnerability based on their location on the FIRM and as a result of having sustained flood damage from Tropical Storm Allison (or from more recent flooding events such as the Memorial Day Flood in 2015 or the Tax Day Flood in 2016). Most of the buildings that the MAT visited initiated dry floodproofing mitigation measures and annual preparedness training performed by their employees in response to the damage sustained during Tropical Storm Allison in 2001.

FEMA MITIGATION FUNDING

Many of the Harris County buildings, TMC buildings, and the Theater District received a FEMA Public Assistance (406 mitigation) grant after Tropical Storm Allison to install dry floodproofing measures to protect against future events.

Organization of Non-Residential Dry Floodproofing Observations

The remainder of this section first describes MAT observations related to planning and implementation of dry floodproofing systems, followed by the observed damage and performance of dry floodproofing systems organized by building or facility, rather than by damaged component. The presentation of the information is ordered by grouping together buildings based on their location within Harris County. Building locations are grouped into the following areas:

- Downtown Houston (Sections 3.2.2 to 3.2.4)
- Energy Corridor (Sections 3.2.5 and 3.2.6)
- Houston Galleria (Section 3.2.7 and 3.2.8)
- Brays Bayou Watershed (Section 3.2.9)
- Texas Medical Center (TMC) (Section 3.2.10)

The following information is presented for each location visited: brief discussion of the building(s) and the flood risk at the site, dry floodproofing mitigation measures in place prior to Hurricane Harvey, the performance of the building during Hurricane Harvey and its effect on operations, and a summary of observations by the MAT.

NAVD 88

All flood elevations in this section are referenced to the North American Vertical Datum of 1988 (NAVD 88).

3.2.1 Planning and Implementation of Dry Floodproofing Systems

Most of the buildings visited as part of the field investigation had well-organized and thorough emergency operations plans on how to prepare the building and implement dry floodproofing measures before the arrival of severe weather.

Buildings that survived Hurricane Harvey with minimal impact had building managers who had learned from previous failures and instilled a culture of preparedness and redundancy. These building managers reported holding annual training exercises to ensure that building engineering and maintenance staff knew how to deploy dry floodproofing measures and that institutional knowledge was shared with everybody responsible for protecting the building. The annual exercises

Table 3-6: Dry Floodproofing Key Observations Crosswalk with Report Section

Key Observations	Report Section																
	3.2.2.1	3.2.2.2	3.2.2.3	3.2.2.4	3.2.3	3.2.4	3.2.5	3.2.6	3.2.7	3.2.8	3.2.9	3.2.10.1	3.2.10.2	3.2.10.3	3.2.10.4	3.2.10.5	3.2.10.6
Building managers instilled a culture of preparedness and have extensive emergency operations plans									✓	✓		✓	✓				✓
Flood damage-resistant materials were not used below the DFE	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓			
Freeboard was above code-recommended values										✓	✓					✓	✓
Freeboard based on previous events instead of tied to an MRI flood event	✓	✓				✓	✓	✓									
Independent verification of dry floodproofing systems performed								✓	✓	✓			✓			✓	✓
Material not designed to resist hydrostatic forces used in the flood barrier						✓	✓										
Successful performance of passive flood barriers							✓	✓	✓				✓				
Redundant dry floodproofing systems were in place						✓		✓	✓	✓		✓	✓		✓	✓	✓
Seepage occurred around pipe penetrations and though cracks in walls	✓	✓		✓		✓		✓	✓						✓		
Stormwater piping issues resulted in flood damage						✓							✓	✓	✓		
Dry floodproofing system considered to be Substantially impermeable				✓				✓	✓	✓	✓				✓	✓	✓
Submarine door or floodgate seepage issue or failure occurred		✓				✓											
Sump pump not provided to remove seepage through flood barriers	✓	✓	✓	✓		✓	✓				✓		✓	✓			
Water flowed in utility/electrical conduits	✓							✓					✓		✓		

DFE = design flood elevation
MRI = mean recurrence interval

had the added benefit of allowing participants to identify broken or missing components in the dry floodproofing system. After Hurricane Harvey, these same building managers had meetings about lessons learned and how their emergency management plan and training should be modified as a result.

EMERGENCY OPERATIONS PLANS

All emergency operations plans start with a clear understanding of the flood hazard, identifying where floodwater may originate and how it can enter the building. As a best practice, these plans should be updated or refined every year after failures or successes are identified with the intent of minimizing the impact flooding has on the building. Texas Recovery Advisory 1, *Dry Floodproofing: Planning and Design Considerations* (2018g), included in Appendix A, provides an overview of flood vulnerability assessments and how to use the information obtained.

Preparation for the potential impact of Hurricane Harvey started a week before the storm made landfall. Long-range forecasts showed the potential of a hurricane in the Gulf of Mexico, which is often the trigger for implementing emergency operations plans for buildings in Texas. Preparation activities included filling the fuel tanks of the backup generators, emptying dumpsters, cleaning up trash and debris from around the building, checking sump pumps and renting back up pumps in case of failure, and verifying that backflow preventers were functioning. Some building owner and operators went as far as to stockpile common building materials, such as drywall, to speed up recovery efforts after an event, since those supplies are often in short supply after an event.

The timing for when facility managers began to deploy active opening protection depended on the size of the building. Deployment in larger buildings began 2 days before Hurricane Harvey made landfall, whereas managers of smaller buildings waited until the day before or after Harvey made landfall. Buildings with passive opening protection had the option to either let the barrier function as designed or manually open the barrier.

The buildings visited by the MAT that were located in Unshaded Zone X and critical government facilities that could not be fully evacuated had teams of building engineers or maintenance staff positioned on upper floors during Hurricane Harvey to respond to any issues with the dry floodproofing systems. In at least three cases, building engineers and maintenance staff were able to respond to issues, minimizing damage or preventing a catastrophic failure in the dry floodproofing system.

3.2.2 Judicial and Correctional Facilities – Downtown Houston

Several Harris County judicial and correctional facilities are located near downtown Houston. Many are within ¼ mile of where White Oak Bayou flows into Buffalo Bayou (see Figure 3-24). The MAT visited eight judicial and correctional buildings in the area. The four buildings discussed herein both sustained flood damage and had sources of floodwater entry into the building that were examples of overall issues with the dry floodproofing design. Three of the four facilities—the Criminal Justice Center, Jury Assembly Building, and the Civil Courthouse—are clustered within 300 feet of each other; the fourth, the Harris County Jail, is approximately 1,200 feet to the north.

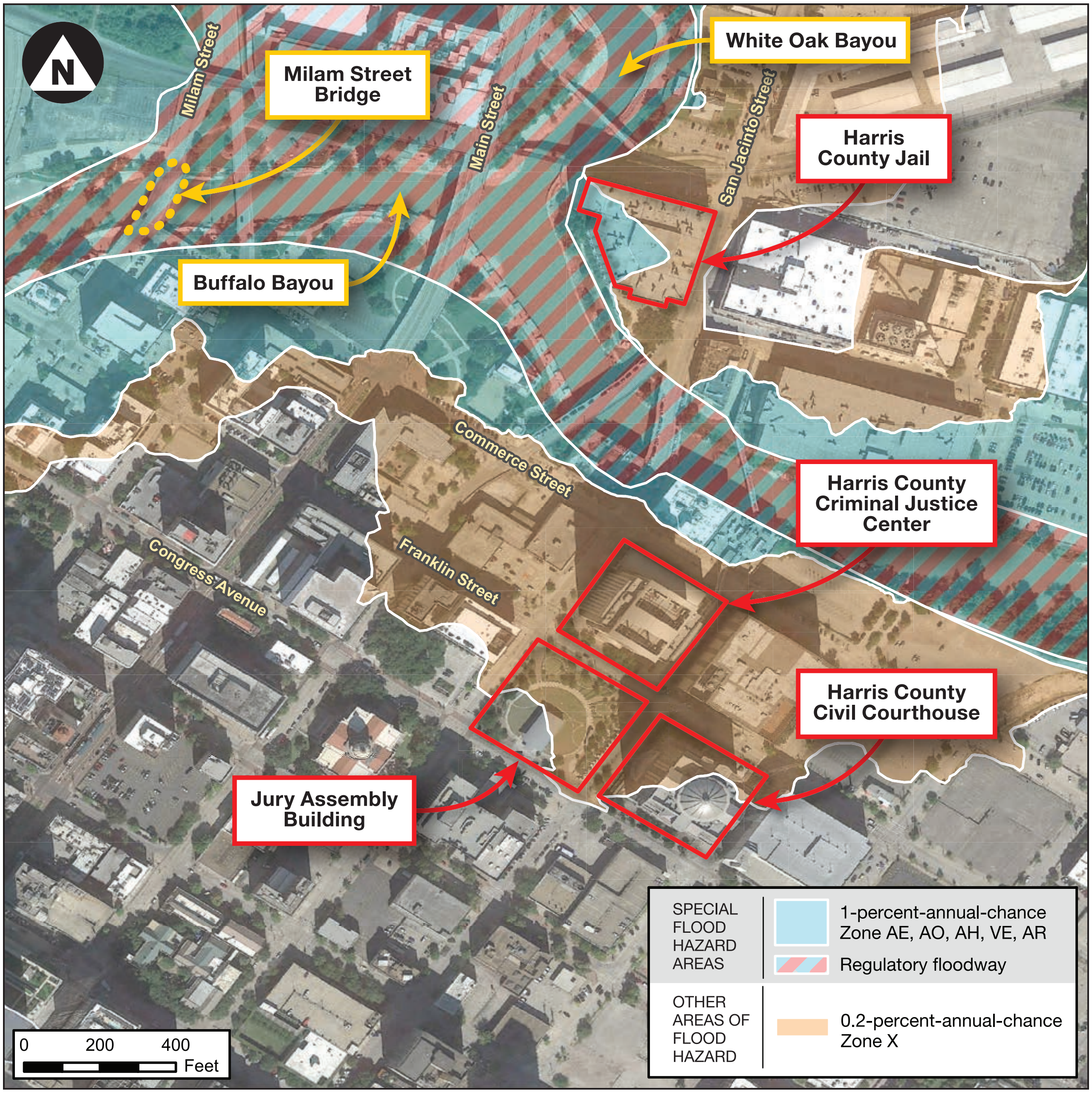


Figure 3-24: Map of Downtown Houston showing the confluence of White Oak Bayou with Buffalo Bayou, and the four Harris County facilities visited by the MAT discussed in this subsection

A HCFCD stream gage is located near the Milam Street Bridge (see Figure 3-24) approximately 900 feet upstream of the confluence of the White Oak and Buffalo Bayous. The Milam Street gage is the closest stream gage to, and is just upstream of, the four Harris County buildings discussed in this section and is 2,100 feet downstream of the Wortham Theater (see Section 3.2.3).

Historic Flood Levels at Harris County Judicial and Correctional Facilities in Houston

Historic flood levels were compared to published flood elevations to determine the approximate MRIs for those events at the Milam Street Bridge stream gage. The HCFCD had determined the flood elevations for various MRIs, as shown in Table 3-7. Table 3-8 shows the highest flood levels recorded by the Milam Street Bridge gage for the six largest severe weather and flooding events within the last 20 years and their approximate MRIs. Based on the Milam Street Bridge stream gage, the recorded HWM of 37.8 feet for Hurricane Harvey was the highest recorded event, but was less than a 0.2-percent-annual-chance event.

Table 3-7: Flood Levels, Probabilities, and Associated Recurrence Intervals at the Milam Street Bridge

Milam Street Flood Elevations for Various Flood Events				
Annual Chance of Exceedance	10%	2%	1%	0.2%
Mean Recurrence Interval (years)	10	50	100	500
Flood Elevation (feet)	27.1	32.6	35.6	41.3

Table 3-8: Summary of Data Based on Milam Street Bridge Gage

Event	Maximum Flood Elevation (feet)	Approximate MRI[a] (years)	Percent Annual Chance of Exceedance
Harvey (2017)	37.8	197	0.5
Allison (2001)	35.9	117	0.85
Memorial Day (2015)	31.3	33	3
Fran (1998)	30.4	26	3.8
Tax Day (2016)	28.7	16	6.3
Ike (2008)	27.8	13	7.7

(a) The MRIs (mean recurrence intervals) were determined using regression analysis whereby a best-fit curve was selected to model the data and then compared to the published flood elevations. A logarithmic curve was selected, which produced a coefficient of determination (R^2 value) of 99.8 percent.

SOURCE: HCFCD, 2018A

3.2.2.1 Harris County Jail – 701 N. San Jacinto Street, Houston, TX

HARRIS COUNTY JAIL

FIRM = Zone AE

BFE = 34 feet

(see Figure 3-26)

Harris County Jail is a 650,000-square-foot, seven-story building with an additional basement level located in downtown Houston near the confluence of White Oak Bayou and Buffalo Bayou. Originally a cold storage warehouse constructed in the 1920s, the building was heightened by two stories and opened as a correctional facility in 1991. Per the FIRM effective in 1985, the area was classified as Zone AE; however, whether any measures were taken to mitigate the flood risk to the building as part of the conversion from a cold storage warehouse to a correctional facility is unknown. The building site is exposed to flooding from the White Oak and Buffalo Bayous and is located in Zone AE with a BFE of 34 feet. The west elevation of the building is adjacent to the regulatory floodway (see Figure 3-25). Figure 3-26 shows the building's location on the effective FIRM.

The building's first floor is approximately 4 feet above grade on the south, east, and north. The basement is near grade on the west. An underground inmate tunnel connects the Harris County Jail to other correctional facilities and government buildings to the southeast.

Figure 3-25:
Harris County Jail as viewed from the Main Street Bridge

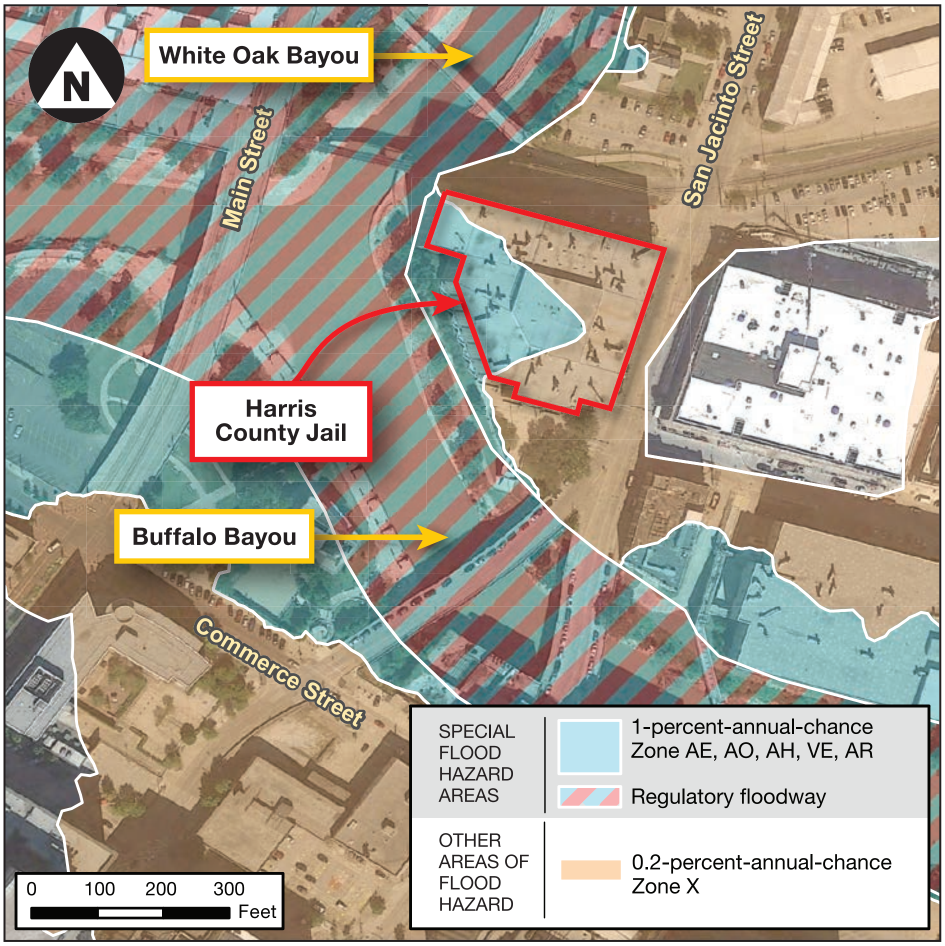


Figure 3-26:
FIRM for Harris County Jail in the City of Houston

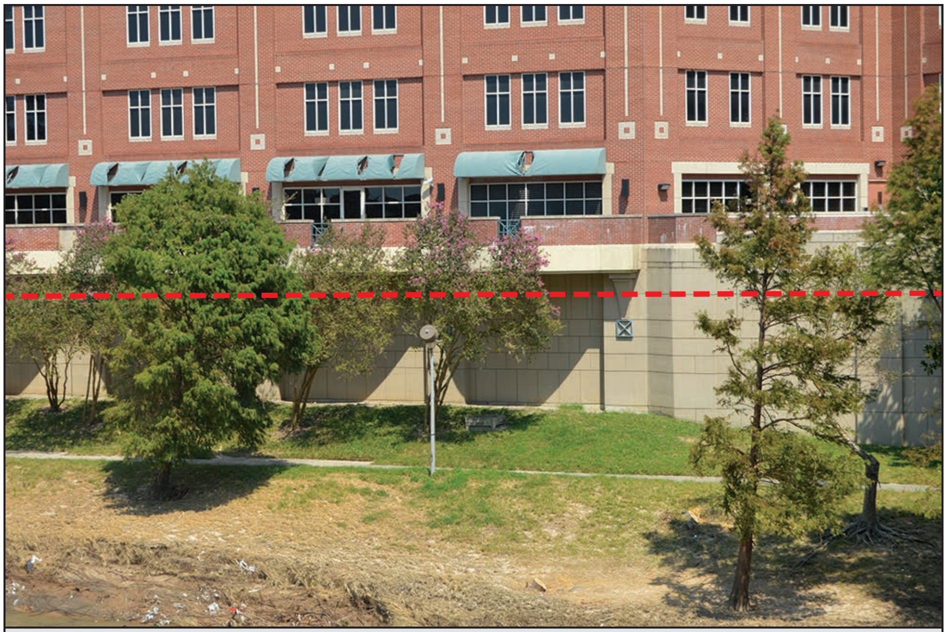
Dry Floodproofing Mitigation Measures

At the time of the MAT, the Harris County Jail did not have any dry floodproofing mitigation measures to provide protection from flooding. The first floor elevation is above the mapped 0.2-percent-annual-chance flood elevation. Given the nature of the building's function, there are few openings in the building (though the basement level has utility penetrations and a connection to the inmate transfer tunnel).

Performance during Harvey

Hurricane Harvey's extreme rainfall caused both the Buffalo and White Oak Bayous to overtop their banks. Water from the White Oak Bayou flowed around the north and east sides of the building, effectively creating an island of the jail. Data from the Milam Street Bridge stream gage approximately 900 feet upstream indicate flood levels reached 37.8 feet during Harvey (see Table 3-8). At the jail, staff reported water was 2 feet deep on N. San Jacinto Street (see Figure 3-27), which is nearly 18 feet above the elevation of the basement floor. To the west (see Figure 3-28), water levels in the bayou were reported to be 6 feet lower, or approximately 12 feet above the basement floor. The jail was not evacuated before the storm.

Figure 3-27:
View of east wall of jail along N. San Jacinto Street where water levels reached the top of the concrete wainscot (red line)

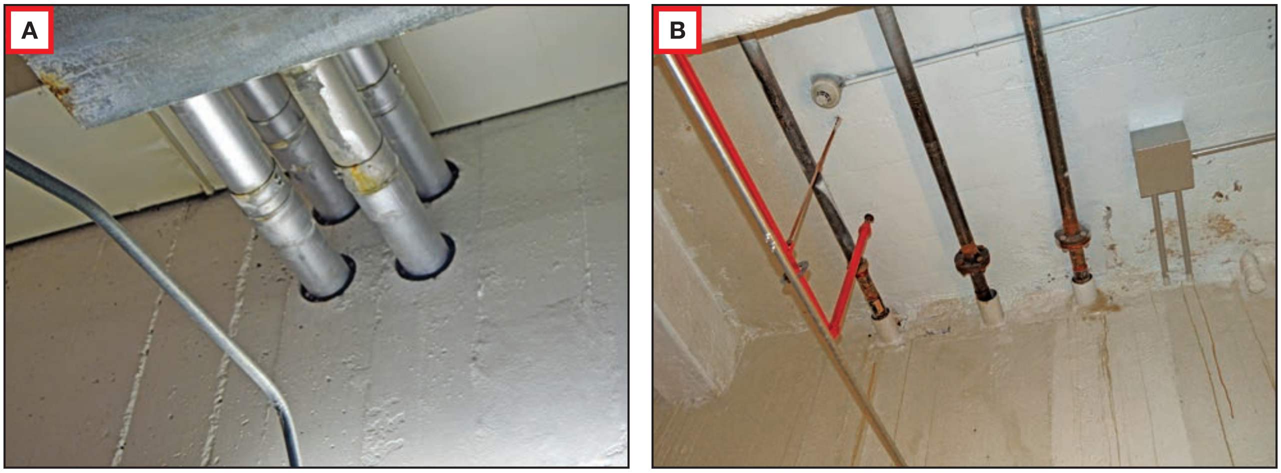


The approximate HWM (red line) was reported by jail staff. Staff reported that water flowed down the interior surface of this wall.

Figure 3-28:
View of west side of the jail along White Oak Bayou

Basement. Staff reported that the building experienced "excessive seepage." Water was described as flowing in sheets down the basement walls and flowing through the joint between the basement walls and the basement floor. Water entry was described as being dispersed throughout, but there were several areas where water entry was concentrated and flowed freely into the basement, particularly where utilities penetrated the basement walls. One area of concentrated floodwater entry was where electrical conduits containing communication cabling penetrated the east wall of the basement (see Figure 3-29 and Figure 3-30); the communication conduits originate in a below-grade communications vault on N. San Jacinto Street. Concentrated floodwater flow also entered where water service piping and gas piping enter the basement. Water stains and corrosion patterns suggest that water flowed around water and gas piping but through electrical conduits.

Figure 3-29:
Location of below-grade communication vault (red circle) on N. San Jacinto Street



[A] Water flowed through and around communication conduits that penetrate the east wall of the basement from N. San Jacinto Street.

[B] Water flowed around piping penetrations in the north wall of the basement.

Figure 3-30: Concentrated floodwater entry points

The water from seepage and the utility penetrations collected in the lowest areas of the basement, reaching a depth of up to 8 inches in places. This depth of floodwater was within inches of overtopping the base of critical equipment, including the electrical service switchboard (see Figure 3-31), which was elevated slightly on a short concrete service slab, and the Houston Lighting and Power (now Reliant) electrical vault.

Figure 3-31: Maximum water depth at the electrical service equipment

Water did not flow freely into openings in the building's exterior, but floodwater appeared to have risen within inches of a ventilation grate in an alley along the north side of the building (see Figure 3-32) that provides combustion air and ventilation for the building's emergency generator. Rainwater falling though this grill collected in the vaults and seeped into the standby generator room located in the basement, but did not reach the generator itself.

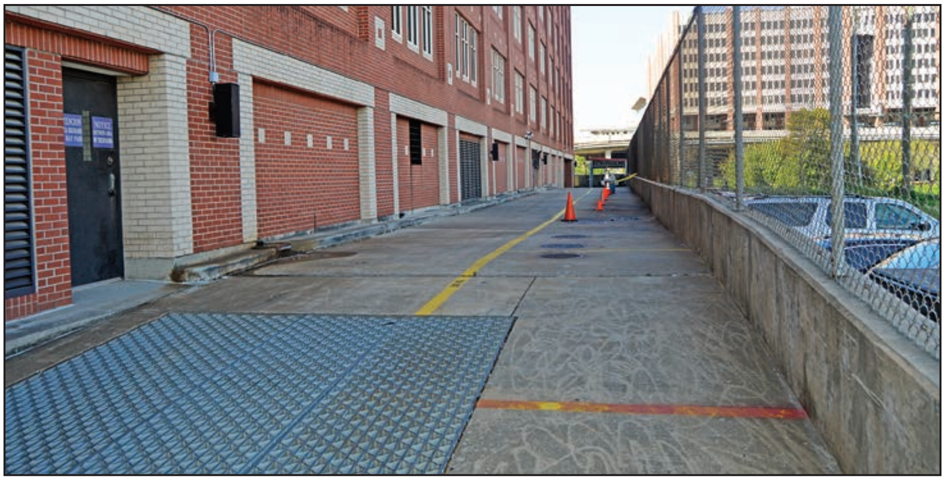


Figure 3-32:
At-grade ventilation grill on north side of the building that was not inundated

Inmate transfer tunnel. Floodwater also entered the building's perimeter through an inmate transfer tunnel (see Figure 3-33). At its highest level, floodwater depths where the tunnel enters the jail exceeded 5 feet and nearly filled the tunnel. When water levels rose in the inmate transfer tunnel and began to flow into the building, staff placed heavy furniture next to the door in an attempt to resist flood loads. However, the barricades were insufficient, and the door failed during the flood. Fortunately, the point where the tunnel connects to the jail is below the basement, so large volumes of floodwater did not flow into the basement itself.

Staff installed temporary sump pumps and attempted to remove floodwater that entered the building. They reported that efforts were hampered because no low areas or sump pits existed where pumps could be placed to more effectively remove floodwater.

Figure 3-33:
Inmate transfer tunnel door

View from lowest floor of jail looking toward the pedestrian tunnel. The door was barricaded but failed during the flood. The red line shows the approximate flood level.

Effect on operations. During Hurricane Harvey, the basement spaces (containing the medical facilities, print shop, and electrical rooms) were not occupied. The use of flood damage-resistant materials in the basement allowed normal function to resume after the floodwater receded and the water in the basement was removed.

Summary of MAT Observations

- The Harris County Jail is located in Zone AE, adjacent to the floodway, and has a BFE of 34 feet. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24.
- The below-grade portions of the building were not substantially impermeable and allowed floodwater to enter the building in areas where floodwater rose above the basement floor.
- Water entered the basement through joints between construction materials, such as between basement walls and footings and basement walls and upper floors. Construction drawings were not available to confirm this, but the MAT suspects that construction details such as waterstops to limit migration of fluids across construction joints were not used.
- The amount of floodwater that entered along any given length of construction joint was likely limited, and per-foot flowrates were likely modest; however, the total length of construction joints in the building that were exposed to floodwater allowed enough water to enter the building to disrupt operations and threaten critical equipment.
- Water entered the basement around or through utility penetrations. The number of water entry points was relatively low, but flowrates in those that existed were relatively high.
- There were no sump pits located in the lowest portion of the basement where floodwater flow could be concentrated, resulting in a large amount of floodwater accumulating within the building basement before it could be removed.
- Even though floodwater entered the building, the use of flood damage-resistant materials in the basement limited the disruption to operations after floodwater receded.

3.2.2.2 Harris County Criminal Justice Center – 1201 Franklin Street, Houston, TX

HARRIS COUNTY CRIMINAL JUSTICE CENTER

FIRM = Shaded Zone X

(see Figure 3-34)

Constructed in 1999, the Harris County Criminal Justice Center is a 20-story building, with an additional basement level, located northeast of the intersection of Franklin Street and San Jacinto Street about a block and a half south of Buffalo Bayou. The main entrance to the building is on Franklin Street (south side of building), and smaller public entrances are on San Jacinto Street (west side) and Caroline Street (east side). Service entrances are along San Jacinto Street and Commerce Street (north side) and the former Harris County Jail is to the east. The building is in Shaded Zone X outside of the SFHA but exposed to the 0.2-percent-annual-chance flood (see Figure 3-34). Figure 3-35 shows the Criminal Justice Center as viewed from the intersection of Franklin Street and San Jacinto Street.

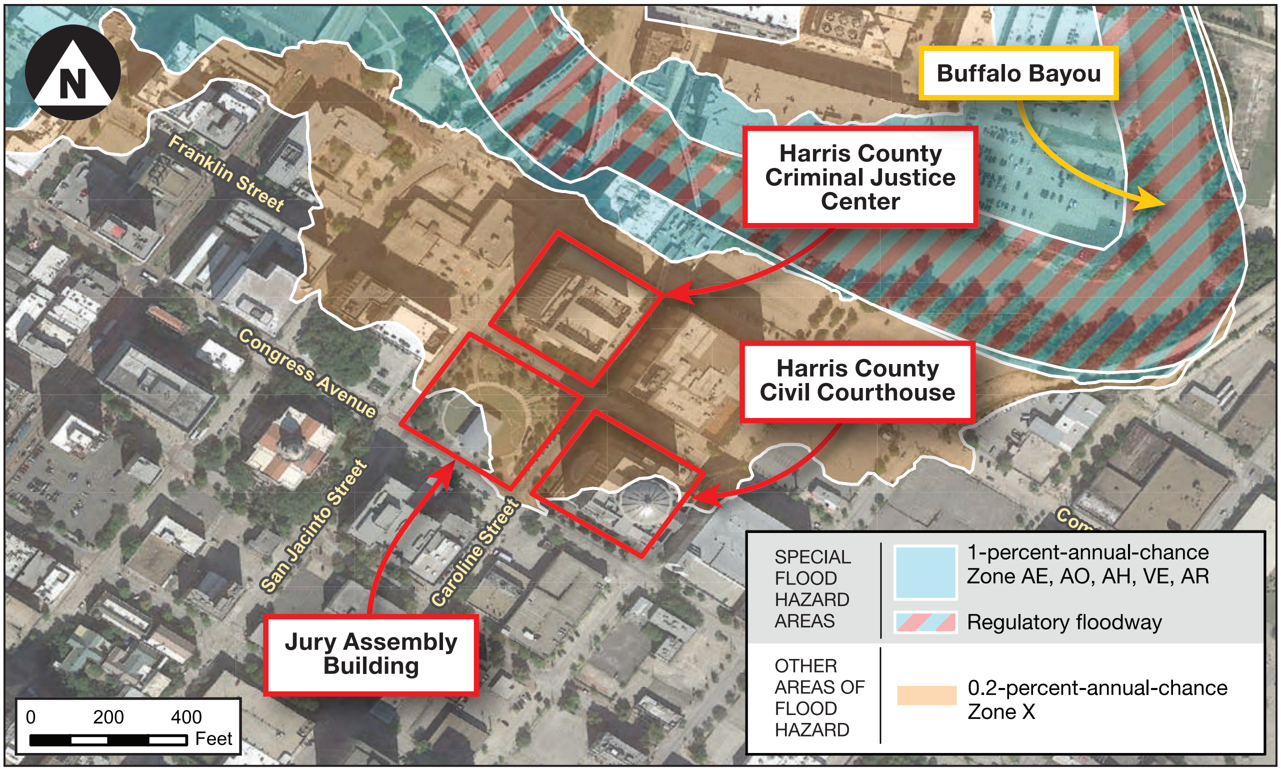


Figure 3-34: FIRM for Harris County buildings on south side of Buffalo Bayou in the City of Houston

Figure 3-35: Harris County Criminal Justice Center viewed from the southwest

The first floor of the building is approximately 2 feet above street level along Franklin Street and is slightly higher above street level on the west and north. The building is constructed over a basement that extends one level below the first floor, with the south wall of the basement extending beyond the footprint of the first floor.

Between 2009 and 2012, an underground pedestrian tunnel was constructed that connects the Harris County Criminal Justice Center to the Jury Assembly Building, the Harris County Civil Courthouse, and the Harris County Juvenile Justice Center, all located to the south. As part of the construction of the pedestrian tunnel, submarine doors were installed where the tunnel ties into the basement of the Harris County Criminal Justice Center, to the Jury Assembly Building, and the Harris County Civil Courthouse.

Dry Floodproofing Mitigation Measures

Shortly after Harris County Criminal Justice Center's dedication in 1999, Tropical Storm Allison (June 2001) struck. Floodwater from Tropical Storm Allison entered the building and destroyed critical equipment, much of it located in the basement level. Damage was extensive, exceeding $11.1 million, and repairs reportedly took nearly a year to complete. A design flood elevation (DFE) was established at an elevation 39 feet, 3 feet above the reported Tropical Storm Allison HWM. The mitigation involved adding 13 flood shields, each 3.5 feet tall, at all first-floor openings around the building; elevating critical equipment, such as the main electrical service equipment, several feet above the basement floor; and installing a backflow prevention valve in the main sanitary sewer lateral. The entrance to the underground parking area at the southeast corner of the building was elevated and fitted with an automatic floodgate at the top of the ramp (see Figure 3-36). If floodwater reaches the gate, buoyant forces of the water raise the gate into position.

FEMA MITIGATION FUNDING

Approximately $3.1 million in FEMA Public Assistance Program mitigation funding was used for the repairs.

Figure 3-36: Flood shield that automatically deploys as waters rise at ramp to underground parking garage

The building has a sanitary sewer lift system that serves plumbing fixtures in the basement. Those fixtures are below the elevation of the sewer line lateral, which exits the building near the basement ceiling. Sewage from the basement fixtures is collected in a sanitary sewer sump, which contains two lift pumps that discharge into the sanitary sewer lateral. Both pumps are equipped with check valves that prevent sewage from flowing back into the sump (see Figure 3-37).

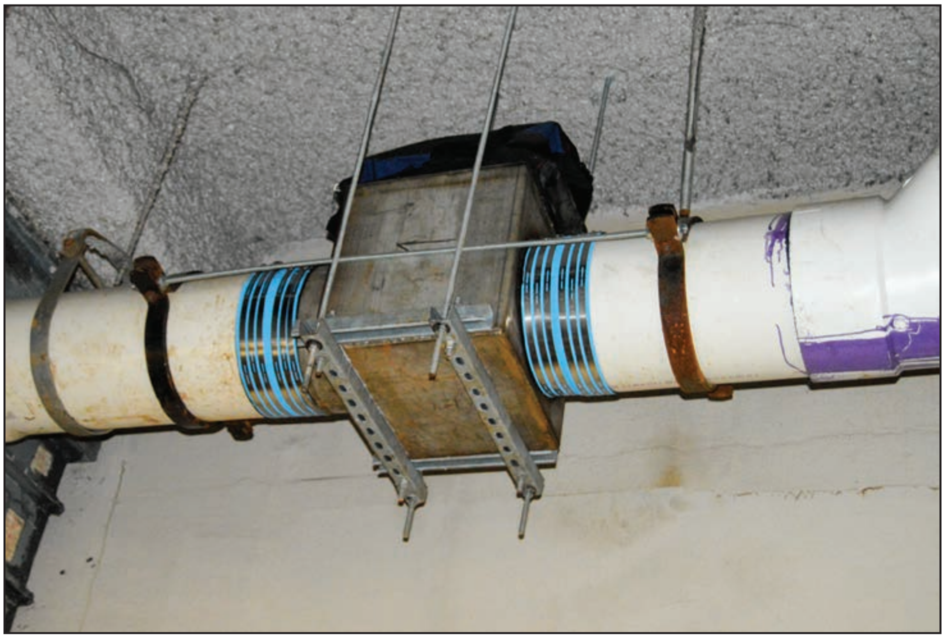


Figure 3-37: Check-valve in sanitary sewer lateral

The building has a separate system to collect and discharge groundwater and stormwater from underground portions of the building. Water from drains in the basement floor and in the underground parking garage collects in the stormwater sump. Like the sanitary sewer lift pumps that serve the basement plumbing fixtures, the stormwater sump has two pumps that discharge into the municipal stormwater sewer lateral.

Performance during Harvey

In preparation for Hurricane Harvey, staff deployed all of the flood shields and closed the submarine doors to the pedestrian tunnel with emergency staff remaining in the building during the hurricane.

Water from the Buffalo Bayou overtopped its banks, spilling into the streets of Downtown Houston. Because of the slight hills in the area around the Harris County buildings, floodwater depths in the street ranged from no floodwater accumulation in the street at the intersection of Franklin Street and Austin Street to the east of the Criminal Justice Center to approximately 4 feet at the intersections of Franklin Street with San Jacinto Street, Commerce Street, and Caroline Street, to the north, west, and south of the Criminal Justice Center.

Flood shields. The flood shields functioned as intended and prevented water from entering the building where they were installed. Flood shields along Franklin Street were exposed to approximately 2.5 feet of flooding (see Figure 3-38), leaving approximately 1 foot of freeboard for the shield. Shields along San Jacinto and Commerce Streets were exposed to slightly deeper floodwater.

Figure 3-38:
View of the Criminal Justice Center from the southeast with approximate depth of flooding indicated by dotted red line

Pedestrian tunnel. The pedestrian tunnel network connecting the Harris County Criminal Justice Center with the Jury Assembly Building, Harris County Civil Courthouse, and the Harris County Juvenile Justice Center was fully inundated with floodwater.

Basement. Emergency staff reported that floodwater entered the basement around the submarine door that separates the pedestrian tunnel from the Criminal Justice Center. Videos taken during the flood show that water entered around the frame of the submarine door, not past the pneumatic seals. Water flow was concentrated around the bolt penetrations that secure the door frame to the adjacent wall (see Figure 3-39). The video shows that leakage was significantly more intense near the bottom of the door, where hydrostatic pressures would be greatest.

Figure 3-39: Floodwater seepage at submarine door

Submarine door separating the pedestrian tunnel from the Criminal Justice Center; red arrows indicate bolt penetrations where water entered the basement from the tunnel.

Staff also reported that water entered where the south wall of the basement meets the basement ceiling. They described water as flowing freely down that wall. That portion of the basement extends beyond the footprint of the first floor, so floodwater along Franklin Street rushed over the basement ceiling in that area. Although construction drawings were not available, the MAT suspects that construction details such as waterstops to limit migration of fluids across construction joints were not used. Not using such waterstops is common for buildings not designed to retain fluids. Because much of the flood mitigation was completed for the building after original construction, installing features to reduce the permeability of the basement would be difficult.

Water depths in the basement reached 12 inches. Floodwater did not reach the critical equipment that had been elevated after Tropical Storm Allison (see Figure 3-40) but did cause widespread damage to the lower portions of interior partitions and finishes. Most of the areas exposed to floodwater were not constructed with flood damage-resistant materials.

Figure 3-40: Floodwater did not reach critical equipment that was elevated after Tropical Storm Allison

However, floodwater did reach electronic equipment that controls the domestic water booster pumps and caused the booster pumps to over-pressurize the domestic water system. As a result, pneumatically controlled domestic water valves failed on the 17th floor.

First floor. Sewage flowed out of plumbing fixtures on the first floor. In some portions of the first floor, flood depths of approximately 1 inch were reported. Much of the first floor was contaminated by effluent, necessitating the removal of the lower portions of drywall to allow the area to be cleaned and disinfected (see Figure 3-41).

Effect on operations. During the MAT visit 2½ months after Harvey made landfall, the facility was still undergoing repairs and will remain unoccupied until repairs are complete. Prior to the MAT's site visit, the booster pump controls had been elevated. Wall finishes on both the first floor and basement had been removed and had yet to be replaced.

Figure 3-41:
Wall finishes were removed from the first floor as a result of sewage leakage

Summary of MAT Observations

- The Harris County Criminal Justice Center is located in Shaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- The mitigation actions taken after Tropical Storm Allison, dry floodproofing 3 feet above the Tropical Storm Allison HWM to elevate to 39 feet, were effective at reducing flood damage. Since readings from the local stream gage suggest that flood levels during Hurricane Harvey were nearly 2 feet higher than during Tropical Storm Allison, the damage would likely have been more extensive if mitigation actions had not been completed.
- The primary area of water entry appeared to have been limited to (or at least concentrated in) an area where the basement extends beyond the footprint of the first floor. In that area, the ceiling of the basement and the top of the basement wall were exposed to floodwater.
- During Hurricane Harvey, the network of pedestrian tunnels connecting the Criminal Justice Center to the Jury Assembly Building and other Harris County-operated buildings in the area was fully inundated with water (refer also to Section 3.2.1.3). A submarine door located between the basement of the Criminal Justice Center and the pedestrian tunnel leaked at many of the bolted connections securing the door to a concrete masonry unit (CMU) wall.
- Significant flood damage resulted from the inability of the building's drain waste and vent system to function during Hurricane Harvey. As a result, much of the damage to the building was caused by internal sources, not floodwater or effluent that originated outside of the building. MAT observations suggest that flooding caused sewage levels in the municipal system to rise to a level that prevented effluent from being discharged from the building. The

building was occupied, and effluent was likely being generated. Without the ability to drain, effluent rose in the drain waste and vent piping until it reached the level of the first floor plumbing fixtures. At that point, effluent flowed out of those fixtures and contaminated the building interior. The backflow valve installed on the sewer line after Tropical Storm Allison likely prevented municipal system sewage from back-flowing into the building but could not prevent effluent generated within the building from overflowing out of the lowest gravity-fed fixtures. Plumbing fixtures in the basement are several feet below those on the first floor, but they do not rely on gravity to discharge effluent and are isolated from the gravity-fed portions of the system by the check valves on the discharge piping of the sewer lift pumps.

- Approximately 12 inches of water accumulated in the basement. The MAT was not able to determine how long the floodwater was present in the basement, but if design flood conditions persisted for at least 3 days, the seepage the building experienced would meet ASCE 24 criteria for requiring a structure to be substantially impermeable (which limits seepage to 4 inches during a 24-hour period). Because the basement was not equipped with sump pumps to remove the seepage that occurred, the requirements of ASCE 24 were not met to consider this building substantially impermeable.
- The portions of the building interior exposed to floodwater were not constructed with flood damage-resistant materials, and damaged materials had to be removed and replaced. Damage prevented the building from being functional for several months.

3.2.2.3 Jury Assembly Building – 1201 Congress Street, Houston, TX

JURY ASSEMBLY BUILDING

FIRM = Shaded Zone X

(see Figure 3-34)

The Jury Assembly Building is a one-story building, with an additional basement level, constructed between 2009 and 2012 (see Figure 3-42). It is situated on a small hill due south of the Criminal Justice Center and due west of the Civil Courthouse, and lies approximately 700 feet south of Buffalo Bayou (see Figure 3-24 for placement relative to other Harris County buildings). The Jury Assembly Building has one 5,000-square-foot floor above grade and one 30,000-square-foot floor below grade. The below-grade portion of the building contains four large auditoriums for potential jurors. The building is in Shaded Zone X outside of the SFHA but exposed to the 0.2-percent-annual-chance flood.

The upper floor of the Jury Assembly Building is approximately 13 feet above the first floor of the Criminal Justice Center (refer to Section 3.2.1.2).

The building is connected to an underground pedestrian tunnel that provides access to the Criminal Justice Center to the north, the Civil Justice Center to the east, and the Juvenile Justice Center to the south. It is also connected to an underground utility tunnel that contains steam, condensate, and supply and return chilled water lines that originate in a central plant one block to the south. The central plant provides heating and air conditioning to several judicial buildings in the area, including the Harris County Jail, Harris County Criminal Justice Center, Jury Assembly Building, and Harris County Civil Courthouse.

The basement walls of the Jury Assembly Building are reinforced concrete. They encompass the entire underground portion of the building, including a utility vault. The underground electrical utility vault is located at the southeast corner of the building. The vault was installed and operated by Houston Lighting and Power (now called Reliant). The vault can be accessed from within the

Figure 3-42:
Jury Assembly Building viewed from the south

Jury Assembly Building (see Figure 3-43) and from an at-grade access cover above the vault. Because of its proximity to the Jury Assembly Building, the MAT assumes the electrical utility vault contains transformers that supply the building. Based on its size as indicated on the architectural drawings, it may also contain electrical distribution equipment that supplies the area. The electrical utility vault is separated from the Jury Assembly Building auditorium by fire-rated masonry walls. The basement walls contain an access door to the electrical utility vault, which is not designed to resist floodwater (see Figure 3-43).

Figure 3-43:
Door to the electrical utility vault, which is not designed to prevent floodwater entry

Dry Floodproofing Mitigation Measures

Two submarine doors isolate the underground portion of the Jury Assembly Building from the underground pedestrian tunnel (see Figure 3-44). A third submarine door separates the Jury Assembly Building from the underground utility tunnel. Like the submarine doors in the Criminal Justice Center, each door is equipped with two seals, valves to inflate them, and gauges that indicate the air pressure within the seals.

The building is equipped with two sanitary sewer lift pumps that collect effluent from basement plumbing fixtures and pump it to the municipal sewer system. Each pump is equipped with a check valve on its discharge line to prevent backflow.

The building has a separate system to collect and discharge groundwater and stormwater. Water from drains in the basement floor and the surface drain that collects roof runoff accumulates in the stormwater sump. Like the sanitary sewer lift pumps, the stormwater sump has two pumps that discharge into the municipal storm sewer. The stormwater collection system has an electrically operated valve placed in the line that collects roof runoff. The pump controls automatically close the valve if water levels in the stormwater sump exceed a preset level. These controls prevent stormwater inflow from exceeding the capacity of the discharge pumps.

Both the sanitary sewer pumps and the stormwater pumps are powered from an automatic standby generator. The generator is located on a mezzanine above the ground level floor, above the elevation for a 1-percent-annual-chance flood event.

Figure 3-44: Submarine door separating the Jury Assembly Building from the underground pedestrian tunnel

Performance during Harvey

Staff reported that prior to floodwater levels rising, the three submarine doors connected to the underground tunnels were closed with pairs of inflated pneumatic seals. On one of the doors, one of the seals failed to maintain air pressure, but the other seal maintained pressure and was able to form a watertight seal.

In the areas around the Jury Assembly Building, HWMs were several feet below the first floor elevation. Additionally, floodwater approached, but did not reach, the at-grade access cover of the utility vault.

Pedestrian tunnels. The pedestrian tunnel network connecting the Jury Assembly Building with the Harris County Criminal Justice Center, Harris County Civil Courthouse, and the Harris County Juvenile Justice Center was fully inundated by floodwater.

Basement. Floodwater reached a depth of nearly 8 feet in the basement, nearly submerging that level of the building. Floodwater did not reach the ceiling of the basement, but nearly all interior finishes, wiring, and equipment, was submerged. Cleaning and decontamination were ongoing during the MAT site visit. The basement was flooded even though floodwater did not rise to the elevation of the entrances to the Jury Assembly Building; the MAT was not able to identify the source of the basement flooding.

Effect on operations. During the MAT visit 2.5 months after Harvey made landfall, the facility was still undergoing repairs and will remain unoccupied until repairs are complete.

Summary of MAT Observations

- The Harris County Jury Assembly Building is located in Shaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- The damage to the interior was to materials that were not flood damage-resistant.
- The building experienced a failure of measures designed to prevent floodwater entry. The MAT could not definitively determine how floodwater entered the building. Since stream gage data suggest that Hurricane Harvey caused flooding in the area that far exceeded design conditions, even properly designed flood control systems could have been overwhelmed. During the MAT site visit, the submarine doors were intact and there was no indication of structural failures in the basement walls, ceilings, floors, or other portions of the flood protection boundary. At the time of the site visit, the MAT verified that the check valves on the stormwater pumps were functioning even though the controls for the pumps had been destroyed by floodwater. There was no indication that floodwater entered the basement from above or reached the first floor of the building. No ceiling tiles were damaged in the basement, suggesting that water entered from the floor. Security video from inside the building shows water slowly rising but does not show the source of flooding, so the exact failure mode could not be determined.
- The MAT observed a floor drain in the electric utility vault that may have been a possible floodwater entry point. The floor drain in the electrical utility vault connects to the floor

drains in the pedestrian tunnel that runs under Franklin Street on the opposite side of the submarine door. When the pedestrian tunnel became fully inundated with floodwater, water could have backflowed through the floor drain into the electrical utility vault. The electric utility vault is within the flood protection boundary, and any drain not isolated by a check valve or other means to prevent storm water from backflowing through the drain is a potential point of floodwater entry. Staff reported that after floodwater receded and the building could be entered, they found the door to the electrical utility vault open.

Investigation of this door by the MAT indicated that the door deformed, bowing slightly outward toward the interior of the Jury Assembly Building. The depth of flooding within the basement level of the building closely correlates with the observed HWMs on Franklin Street between the Criminal Justice Center and the Jury Assembly Building, suggesting that floodwater flowing into the basement of the Jury Assembly Building was able to equalize with floodwater near the building.

3.2.2.4 Harris County Civil Courthouse – 201 Caroline Street, Houston, TX

HARRIS COUNTY CIVIL COURTHOUSE

FIRM = Shaded Zone X

(see Figure 3-34)

Constructed between 2003 and 2005 and dedicated in 2006, the Harris County Civil Courthouse is an 18-story building, with an additional basement level, located east of the intersection of Congress Street and Caroline Street, one block southeast of the Jury Assembly Building (see Figure 3-24 for placement relative to other Harris County buildings). The main entrance to the building is on Caroline Street and is approximately 8 feet above the street level. The building is constructed over a basement that extends one level below the first floor. The building is approximately 650 feet south of Buffalo Bayou and is situated in the Shaded Zone X, outside of the SFHA, but exposed to the 0.2-percent-annual-chance flood. Figure 3-45 shows the Civil Courthouse when viewed from the southwest.

Figure 3-45:
Harris County Civil Courthouse viewed from the southwest

Like several other judicial buildings in the area, the Civil Courthouse connects to an underground pedestrian tunnel that provides access to the Jury Assembly Building, the Criminal Justice Center, and the Juvenile Justice Center. The elevation of the pedestrian tunnel is approximately 6 feet below the basement floor level of the Civil Courthouse; a corridor with a ramp extends from the basement level of the building to the pedestrian tunnel.

Dry Floodproofing Mitigation Measures

Because the Civil Courthouse was constructed after Tropical Storm Allison, the building contains several design features that reduce its vulnerability to floods. These include:

- **Submarine door.** A submarine door isolates the pedestrian tunnel from the corridor that extends from the basement of the Civil Courthouse (see Figure 3-46).
- **Floodgate.** An automatic floodgate (see Figure 3-47) at the top of the vehicle access ramp to protect an underground garage that is on the same level as the basement.
- **Elevation.** Electrical and heating, ventilation, and air conditioning (HVAC) equipment is elevated to keep it away from floodwater:
  - The electrical service equipment is located on the first floor. It is placed on concrete slabs that elevate it nearly 18 inches above the first floor level.
  - Electrical equipment is “top fed,” meaning conduits and bus ducts enter and exit the top of the electrical service and distribution equipment rather than extending below the electrical equipment where flood risks are greater.
  - Standby power for the facility, the two pad-mounted transformers that supply power to the building, and the utility company’s distribution equipment are elevated several feet above street level.
  - Much of the central HVAC equipment is elevated above flood levels because it is located on the building’s penthouse level.

Figure 3-46: Submarine door that separates the Civil Courthouse basement from the underground pedestrian tunnel

Figure 3-47:
Automatic floodgate at ramp to basement parking garage

Performance during Harvey

Floodwater from Hurricane Harvey surrounded the Civil Courthouse, but was approximately 8 feet below the elevation of the first floor (see Figure 3-48). Floodwater did not reach the automatic floodgate at the ramp for the parking garage below the building and the gate did not deploy.

Pedestrian tunnel. The pedestrian tunnel network connecting the Harris County Criminal Justice Center with the Jury Assembly Building, Harris County Civil Courthouse, and the Harris County Juvenile Justice Center was fully inundated with floodwater. Floodwater from the pedestrian tunnel entered the corridor that extends from basement to the pedestrian tunnel. The submarine door separating the building from the tunnel was submerged; flood depths in the corridor at the submarine door approached 8 feet, reaching a depth that allowed floodwater to overcome the ramp and spill into the basement of the courthouse (see Figure 3-49). Building engineers identified the unsealed conduit and utility penetrations in the flood barrier wall

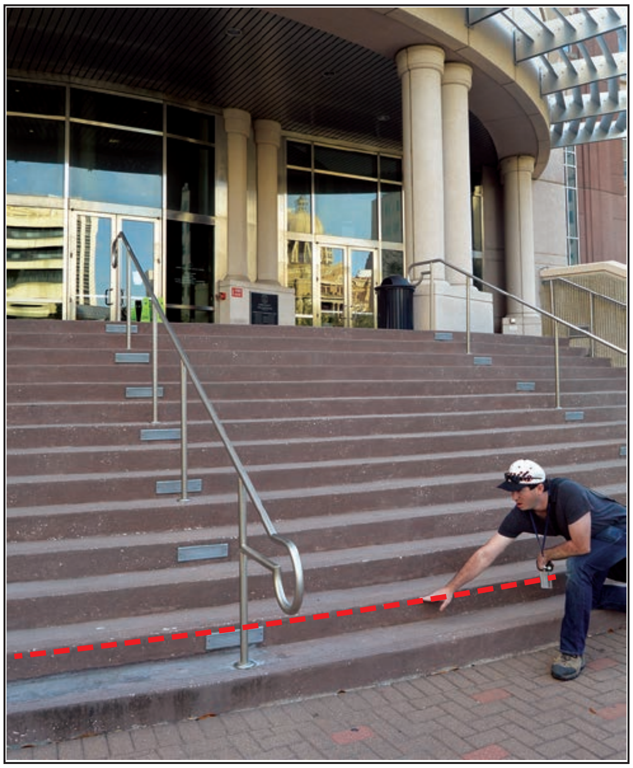


Figure 3-48:
Flood level at the Civil Courthouse during Hurricane Harvey (red dotted line)

Figure 3-49:
Civil Courthouse corridor

[A] A corridor connects the basement of the Civil Courthouse to the pedestrian tunnel.

[B] The corridor is separated from the tunnel by a submarine door. The red line shows the floodwater level in the tunnel.

that separates the basement corridor from the utility tunnel as likely floodwater entry points (see Figure 3-50). The penetrations were sealed after the flooding, prior to the MAT visit. Insufficient information exists to confirm that unsealed penetrations were the only sources of floodwater entry, but they did at least contribute to floodwater entry and resulting damage.

Unsealed penetrations (yellow dotted circles, left) that were repaired before the MAT visit allowed the subgrade tunnel to fill with water (yellow double arrow, right); the penetrations (left) are on the other side of the door at the end of the tunnel (red circle, right)

Figure 3-50:
Floodwater entry through unsealed penetrations

PHOTOGRAPH ON THE RIGHT COURTESY OF FACILITIES AND PROPERTY MAINTENANCE, HARRIS COUNTY ENGINEERING DEPARTMENT.

Basement. Within the courthouse basement, water levels reached approximately 4 inches deep. Floodwater completely filled the elevator pits, which extend below the level of the basement. The pits remained full until staff could return to pump out the water. Floodwater damaged interior finishes in the basement, but during the MAT's site visit, repairs were nearly completed.

Effect on operations. Flood damage limited building function for several weeks after the event while repairs were completed.

Summary of MAT Observations

- The Harris County Civil Courthouse is located in Shaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- Flood damage from Hurricane Harvey was relatively limited and generally involved non-critical components such as interior finishes. The damage to the interior was to materials that were not flood damage-resistant.
- The flooding in the building resulted, in part, from a failure to maintain the integrity of the flood barrier. While most penetrations that the MAT observed in the flood barrier had been sealed and were apparently effective at preventing or limiting floodwater entry, other penetrations were not sealed and allowed floodwater to enter the building.

3.2.3 City of Houston Public Works Building - 611 Walker Street, Houston, TX

Constructed in 1968, the City of Houston Public Works Building is a 27-story office building, with two below-grade levels, located in Downtown Houston and east of Buffalo Bayou. The main entrance is located on the south side of the building along Walker Street (see Figure 3-51).

PUBLIC WORKS BUILDING

FIRM = Unshaded Zone X

(see Figure 3-52)

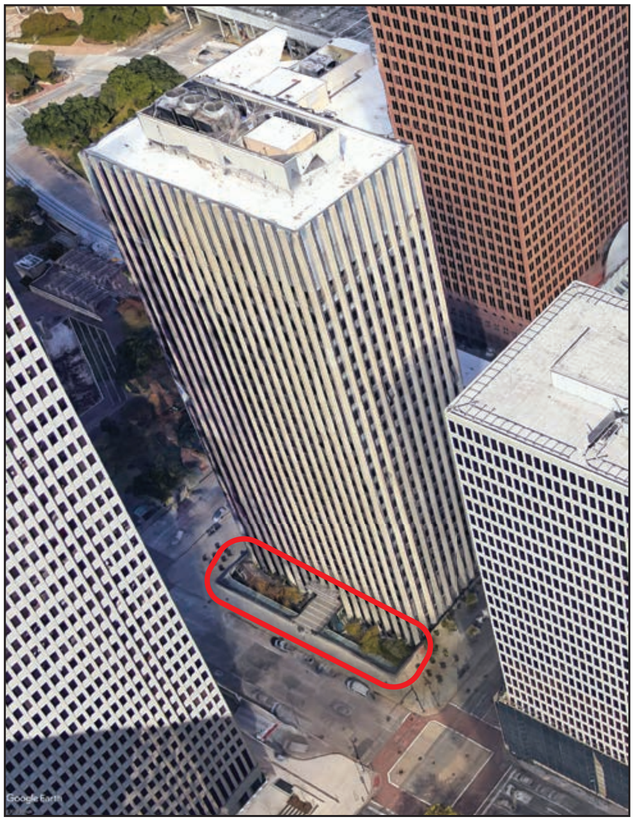


Figure 3-51:
City of Houston Public Works Building; red outline denotes an open-air courtyard on the south side of the building

The deepest below-grade level contains the MEP systems for the building. The first below-grade level, one level below street level, contains an open-air courtyard on the south side of the building and the access from the Downtown Houston tunnel network that connects most of the buildings in Downtown Houston to one another (see red outline on Figure 3-51). The Downtown Houston tunnel network at the public works building is located on the south side of the building running in a west-to-east direction. The west side of the tunnel connects to the Tranquility Park Parking Garage and the rest of the Downtown Houston tunnel network. The Public Works Building is located in Unshaded Zone X, approximately 600 feet from the nearest regulated floodplain (see Figure 3-52).

During Tropical Storm Allison in 2001, the Public Works Building flooded (as with many others in Downtown Houston) when the Tranquility Park Parking Garage became inundated and water flowed into the connecting Downtown Houston tunnel network (see Figure 3-53).

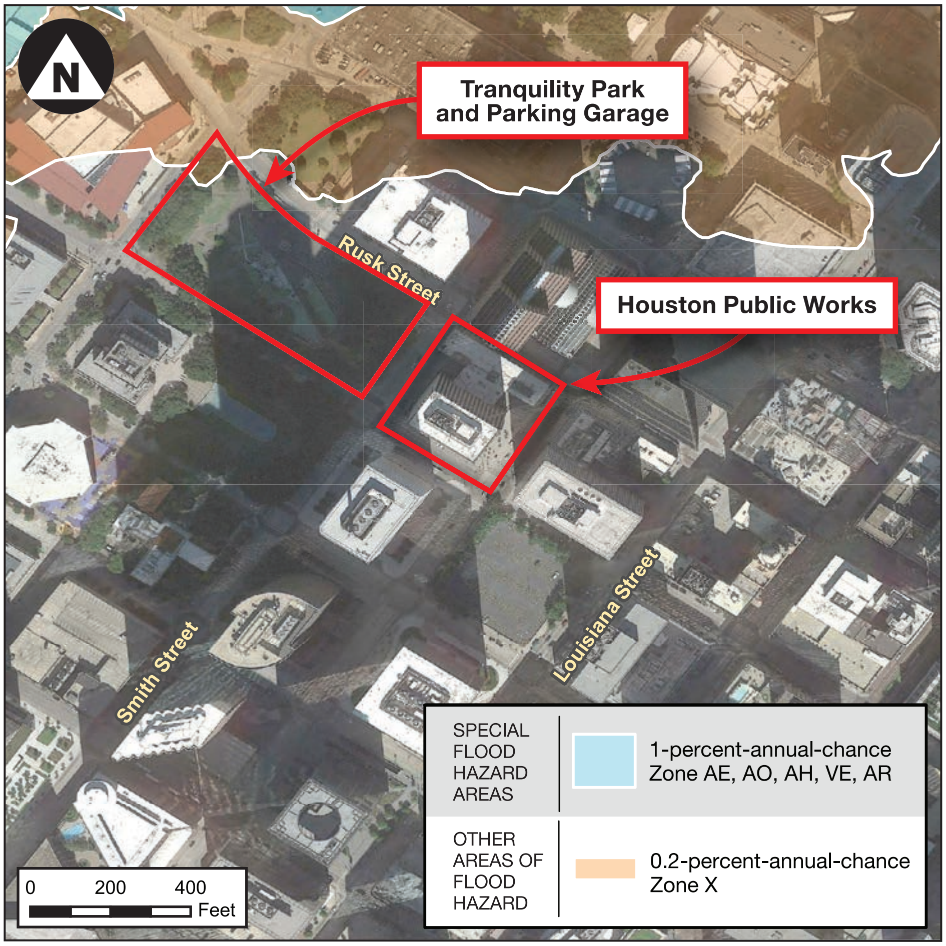


Figure 3-52: FIRM for the City of Houston Public Works Building

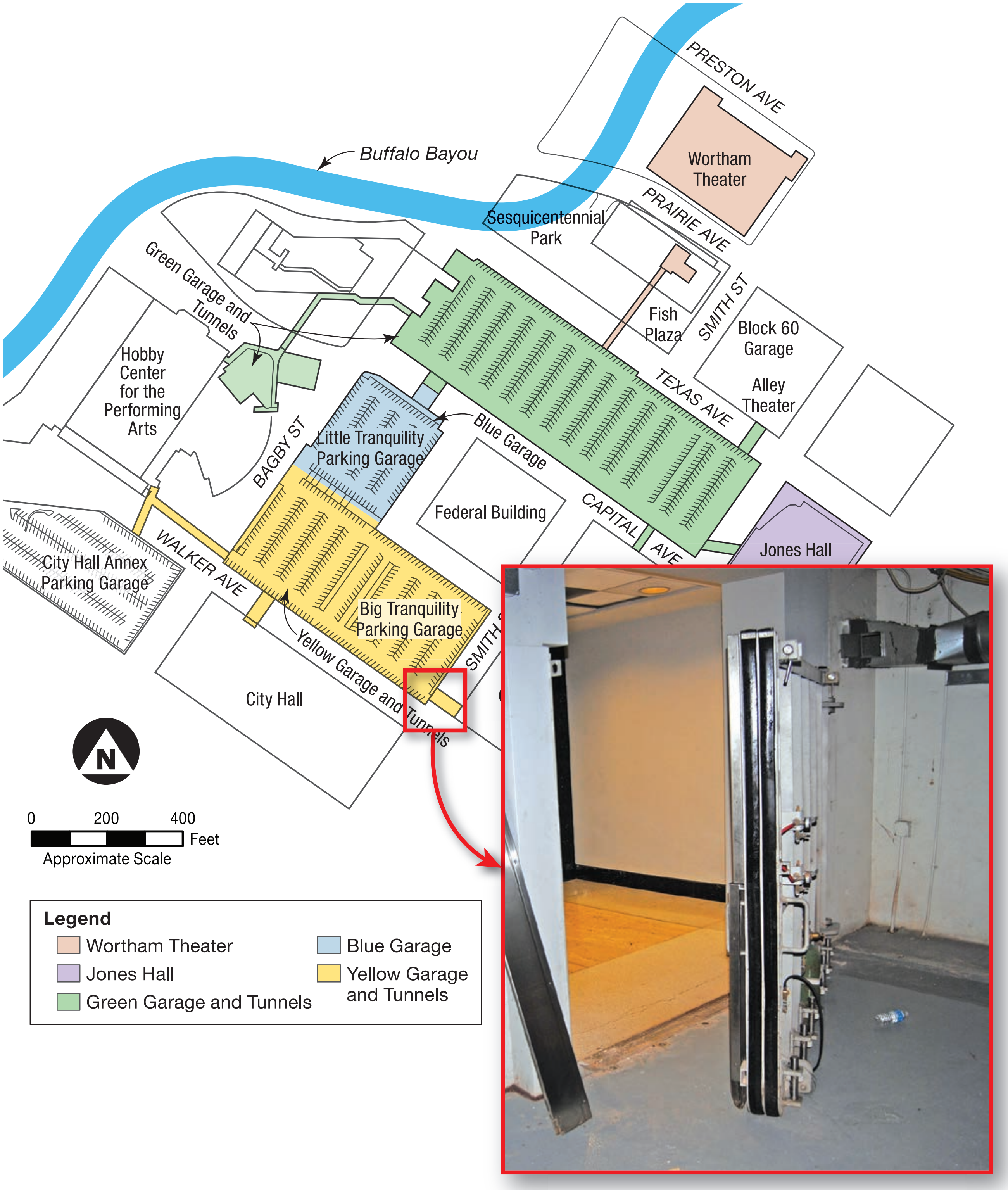


Figure 3-53: Tranquility Park Parking Garage and tunnel network (left); partial-height flood door installed in the tunnel network (right)

MAP SOURCE: HOUSTON FIRST, USED AND MODIFIED WITH PERMISSION

Dry Floodproofing Mitigation Measures

In response to Tropical Storm Allison in 2001, a partial-height flood door was installed in the tunnel network on the east side of Tranquility Park Parking Garage, approximately 50 feet away from the basement entrance to the Public Works Building (see Figure 3-53). The MAT did not observe any redundant flood barriers in the tunnel network beyond this barrier.

Performance during Harvey

During Hurricane Harvey, this area of Downtown Houston received approximately 30 to 35 inches of rain, but floodwater from Buffalo Bayou did not extend far enough from its banks to reach the Public Works Building.

Basement. The rain stripped a considerable amount of leaves from the trees and plants in the open-air courtyard. The fallen vegetation, mixed with trash that was blown into the courtyard, clogged the floor drains in the courtyard, which then caused stormwater to flow into the lower of the two levels of the Public Works Building, damaging interior finishes.

Tranquility Park Parking Garage. The Tranquility Park Parking Garage was completely inundated as a result of numerous breaches in the flood barriers from the Theater District and connected parking garages (refer also to Section 3.2.3). The partial-height flood door shown in Figure 3-53 is 74 inches tall; the water reached a maximum height of 70.75 inches, nearly overtopping it.

Effect on operations. Because of stormwater flooding, both basement levels of office space lost their useful function for several months while damage to interior finishes were repaired.

Summary of MAT Observations

- The Public Works Building is located in Unshaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- Although the Public Works Building was spared catastrophic losses by the successful performance of the partial-height flood door located at the entrance to the Tranquility Park Parking Garage, as with many other buildings in Downtown Houston, no additional protection measures were in place to prevent the full inundation of the tunnel network and connecting basements if the water had reached its full 74-inch height. If this partial-height flood barrier had been overtopped, the damage that occurred in 2001 from Tropical Storm Allison would have recurred, flooding a large portion of the pedestrian tunnel network, the basement of the Public Works Building, as well as the basements of numerous other buildings.

3.2.4 Theater District and Underground Parking and Tunnel Complex

THEATER DISTRICT

FIRM = Zone AE

BFE = 36 to 37 feet

(see Figure 3-54)

The Theater District is located along the east bank of Buffalo Bayou in Downtown Houston. The Theater District includes the Alley Theater, Jones Hall, Hobby Center for the Performing Arts, Houston Ballet, Bayou Place, Wortham Theater and underground parking garages. Because of the recovery efforts being conducted at the time of the MAT deployment, the MAT was only able to assess the performance of dry floodproofing components at the Wortham Theater, Green Parking Garage, Little Tranquility Park Parking Garage, and Tranquility Park Parking Garage.

The Theater District has buildings that are located in the regulatory floodway, Zone AE, Shaded Zone X, and Unshaded Zone X. The Wortham Theater is located in Zone AE, with a BFE of 37 feet. Figure 3-54 shows the FIRM for the Theater District area and the approximate locations of the flood breaches discussed in this report (each breach is numbered uniquely for discussion purposes).

The Theater District buildings are connected to a network of below-grade parking garages that are connected to one another via a pedestrian tunnel network. The pedestrian tunnel network also ties into the Downtown Houston tunnel network via a tunnel extending from the east end of the Tranquility Park Parking Garage and the south end of the Civic Center Parking Garage adjacent to Jones Hall. As shown on Figure 3-54, the Wortham Theater is located on the north side of the

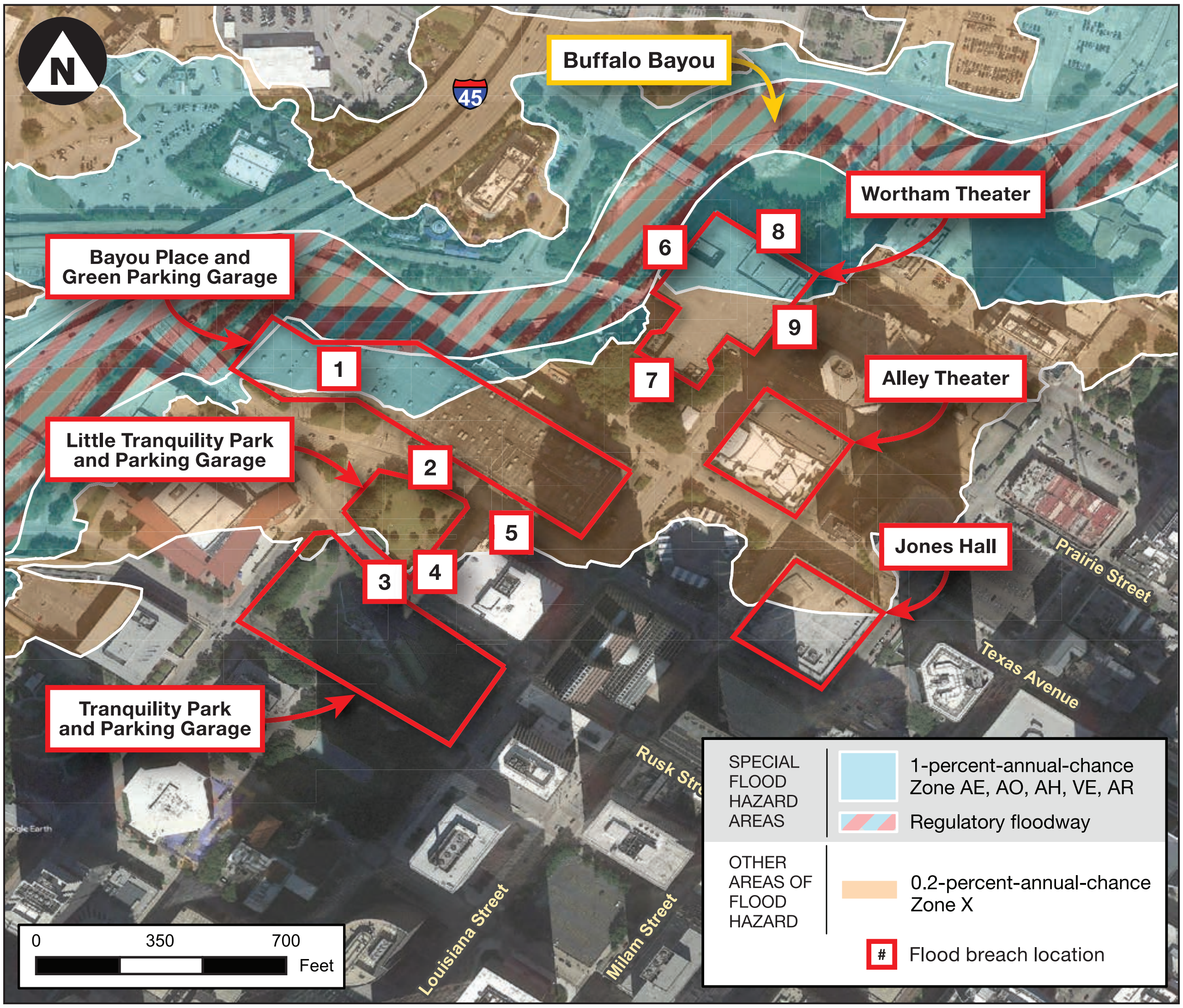


Figure 3-54: FIRM for the Theater District; approximate locations of flood breaches are shown (uniquely numbered from 1 to 9)

Theater District and the Alley Theater and Jones Hall are located to the south and east of the Wortham Theater.

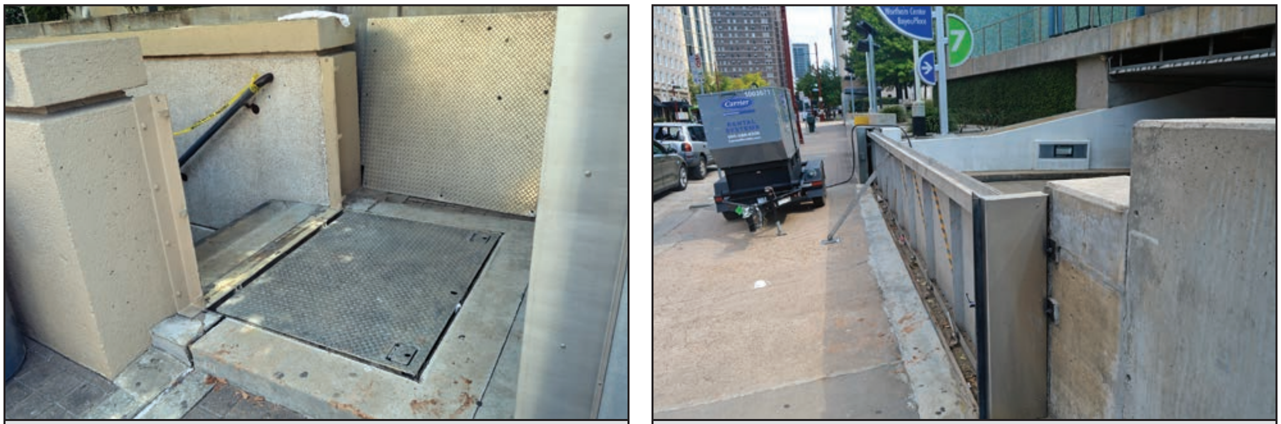
The Wortham Theater, located at 501 Texas Avenue, is a 437,500-square-foot facility that was constructed in 1987. It has an extensive basement level that contains rehearsal areas, costume storage, facilities to construct stages and sets, and dressing rooms. The at-grade and above-grade portions of the theater contain the stage, seating, and means to enter the theater, as well as other amenities such as restrooms and concessions. Extending south from the Wortham Theater and connected via a pedestrian tunnel is the Civic Center (also known as the Green Parking Garage), which is located beneath the Bayou Palace Complex. Further south are the Little Tranquility Park Parking Garage and the Tranquility Park Parking Garage. From the Tranquility Park Parking Garage, pedestrian tunnels extend to Houston City Hall, the City Hall Annex, and 611 Walker Building which includes the City of Houston Public Works Department.

3.2.4.1 Dry Floodproofing Mitigation Measures

During Tropical Storm Allison in 2001, the Theater District, including the Wortham Theater and the surrounding underground parking complex and pedestrian tunnels, was severely flooded. In response, numerous floodgates were installed at entrances to the Wortham Theater, street entrances for vehicles into the parking garages, at pedestrian entrances into the parking garages, and between different parking garage sections. Six submarine doors and 38 floodgates were installed in the Theater District to protect against future flooding (see Figure 3-55 for examples of floodgates installed at pedestrian and vehicle entry points to the below-grade parking garages). All of the gates installed are active systems, meaning they must be manually set in place prior to an event.

FEMA MITIGATION FUNDING

Mitigation measures in the Theater District were installed using approximately $1.2 million of funding provided under FEMA's Public Assistance Program for hazard mitigation (e.g., 406 Hazard Mitigation).



Floodgate protecting pedestrian access to the underground Green Parking Garage.

Floodgate protecting vehicle access to the underground Green Parking Garage.

Figure 3-55: Examples of the floodgates installed to protect the Theater District and underground tunnels and parking garages

The elevation of the floodgates was reportedly selected to provide protection from a flood event that would cause flood levels 2 feet higher than those experienced during Tropical Storm Allison, or approximately 39.3 feet, but were not tied to a recurrence interval for Buffalo Bayou.

3.2.4.2 Performance during Harvey

Hurricane Harvey was the most severe event to impact the Theater District Complex in terms of HWM, exceeding the HWM of Tropical Storm Allison by approximately 2.0 feet. During Hurricane Harvey, the estimated HWM at the Wortham Theater was 39.63 feet based on a HWM surveyed along Preston Street. The FIS for the Prairie Street Bridge crossing of Buffalo Bayou indicates that the 0.2-percent-annual-chance flood elevation is 41.8 feet and the 1-percent-annual-chance flood elevation is 36.15 feet, making the severity of Hurricane Harvey an approximately 0.36-percent-annual-chance probability event.

During Hurricane Harvey, floodwater entered the Wortham Theater, Alley Theater, the basement of Jones Hall, and the Green, Little Tranquility Park, and Tranquility Park parking garages. In total, staff reported that approximately 270 million gallons of water was pumped out of the Theater District.

Breaches in the Dry Floodproofing System

In preparation for Hurricane Harvey, the floodgates protecting the Theater District were deployed starting on Thursday, August 24 and completed on August 25. Eventually the water of Buffalo Bayou overtopped the majority of the floodgates installed to protect the Wortham Theater and entrances into the underground parking and tunnel complex. Prior to the overtopping of the floodgates, nine significant breaches occurred in the dry floodproofing system. Figure 3-56 shows a map of the underground portions of the Theater District and the approximate locations of the nine flood breaches.

Breach No. 1: Foundation Wall Infill Patch

Breach No. 1 is believed to be the first breach in the dry floodproofing system and was one of the largest in the Theater District, occurring in the foundation wall of the Green Parking Garage, beneath Bayou Place. The Green Parking Garage is an extensive three-level underground parking garage. During a past construction or capital improvement project, a large opening had been cut through the foundation wall of the garage to provide temporary access. After the project was completed, the 6-foot by 6-foot opening was infilled with metal stud framing and gypsum wall board, but not reconstructed with substantially impermeable material or with sufficient strength to reestablish the foundation wall load path.

The foundation for Bayou Place consists of a deep foundation system using drilled concrete piers and grade beams. The floor system for Bayou Place consists of precast concrete that spans between the grade beams. The foundation system includes a cavity between the precast concrete floor and the soil within which plumbing and stormwater pipes are supported from the precast concrete using pipe hangers.

The roof stormwater drain network collects water and conveys the stormwater to a system of interior stormwater drain lines that are suspended from the precast concrete floor system. These stormwater drain lines discharge into Buffalo Bayou. On the west side of Bayou Place, along the east bank of Buffalo Bayou, one of the roof stormwater drains had disconnected from the stormwater drain line

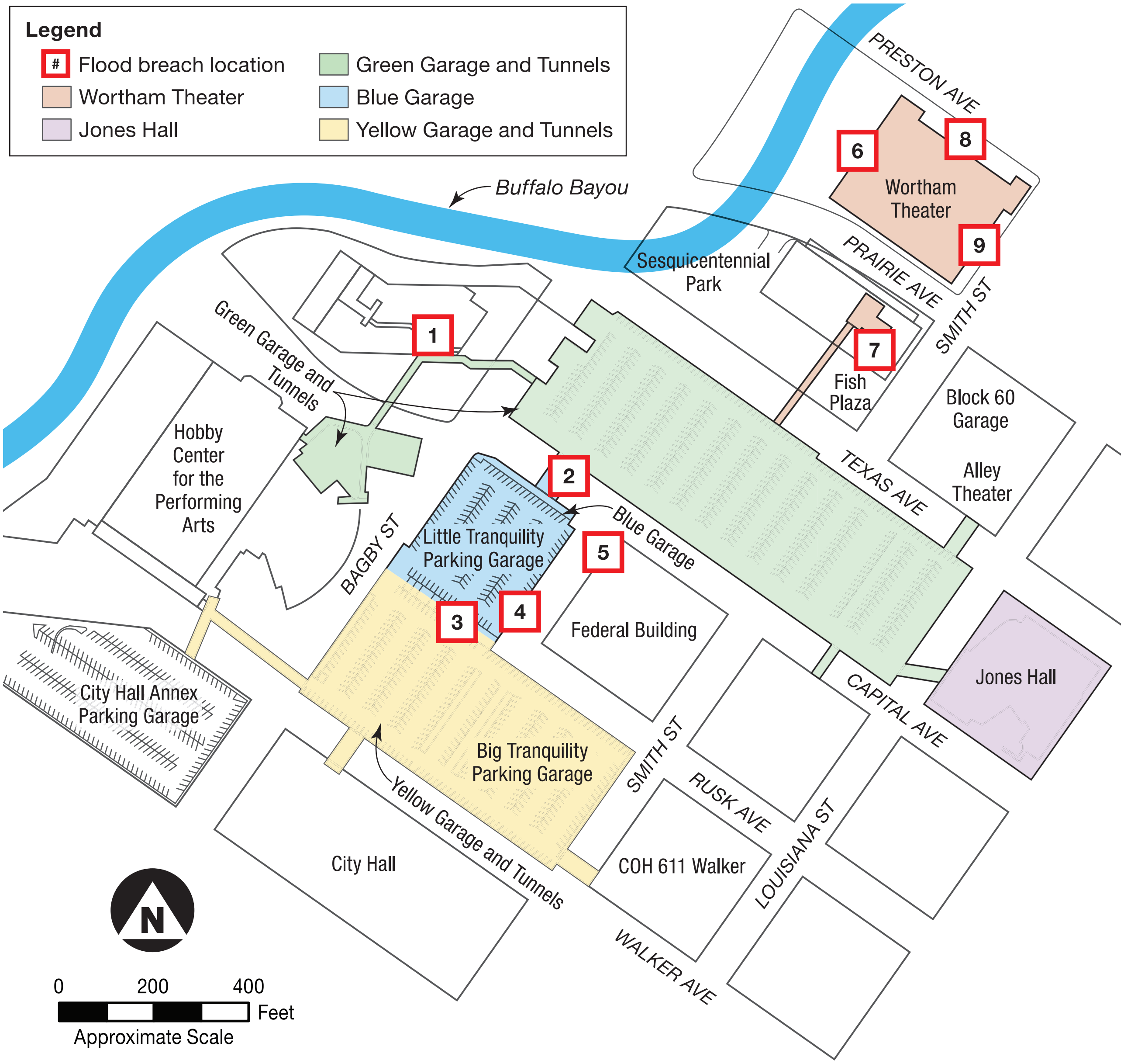
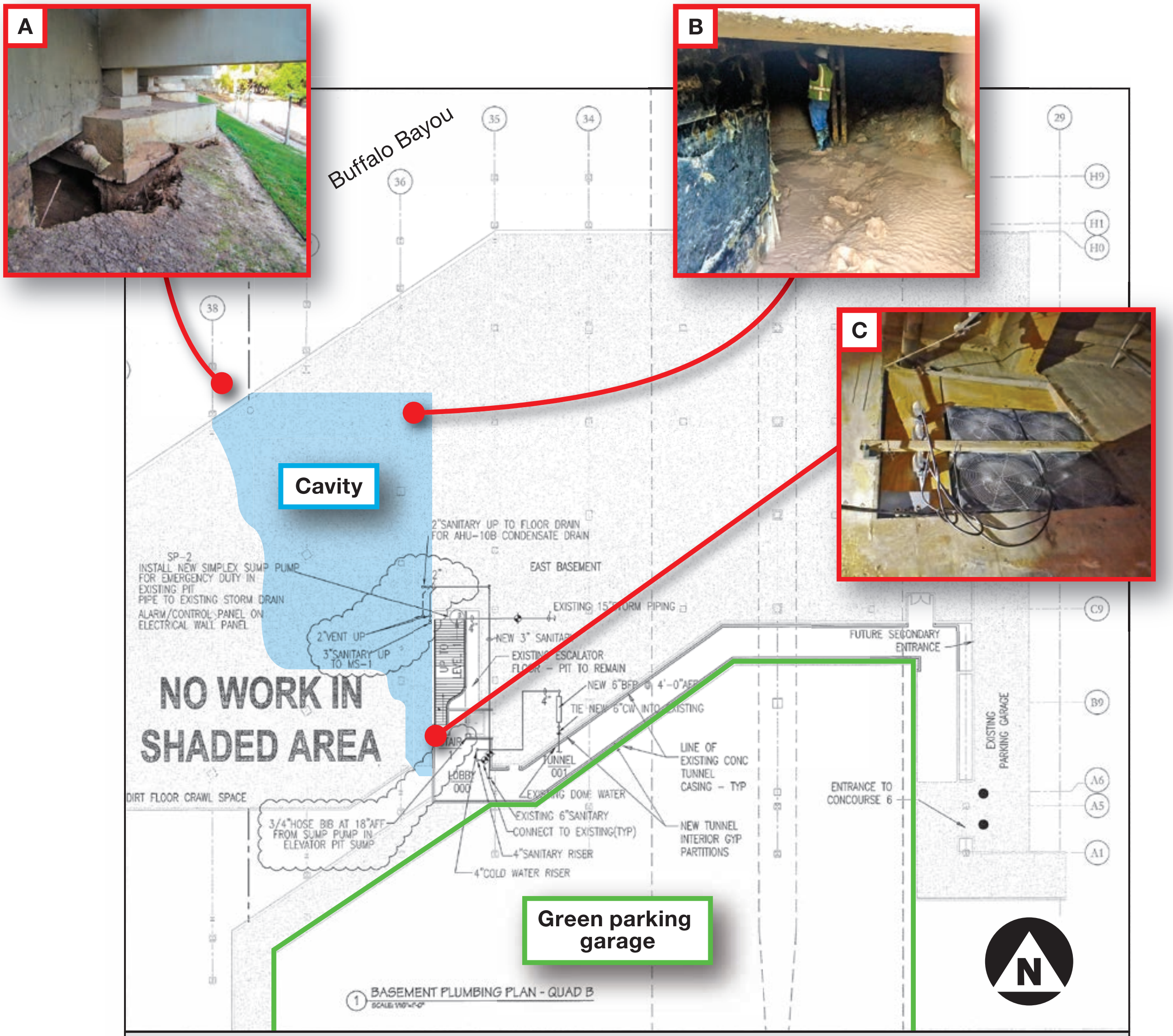


Figure 3-56: Underground components of the Theater District, parking garage network, and tunnels are shown in relationship to the approximate locations of the nine significant flood breaches that occurred

MAP SOURCE: HOUSTON FIRST, USED AND MODIFIED WITH PERMISSION

at the top of the bank of Buffalo Bayou; when this disconnection occurred is unknown. During Hurricane Harvey, the significant amount of stormwater flow eroded the bank of Buffalo Bayou at the location of the disconnected pipe, exposing the cavity beneath the floor slab. When the floodwater in Buffalo Bayou reached the level of the exposed cavity, floodwater filled the cavity and resulted in hydrostatic pressure against the patched 6-foot by 6-foot opening infilled with metal stud framing and gypsum wall board. The bottom of the 6-foot by 6-foot opening was at elevation 26.50 feet, while the HWM of Buffalo Bayou was reported to reach 38.63 feet. Since the infill patch was not constructed from substantially impermeable material, nor did it have adequate structural capacity to re-establish the load path in the foundation wall, the infill patch in the foundation wall failed due to the hydrostatic forces, resulting in the complete inundation of the Green Parking Garage (see Figure 3-57).



[A] Soil erosion caused by disconnected storm drain.

[B] Cavity beneath Bayou Place that was formed by floodwaters from Buffalo Bayou.

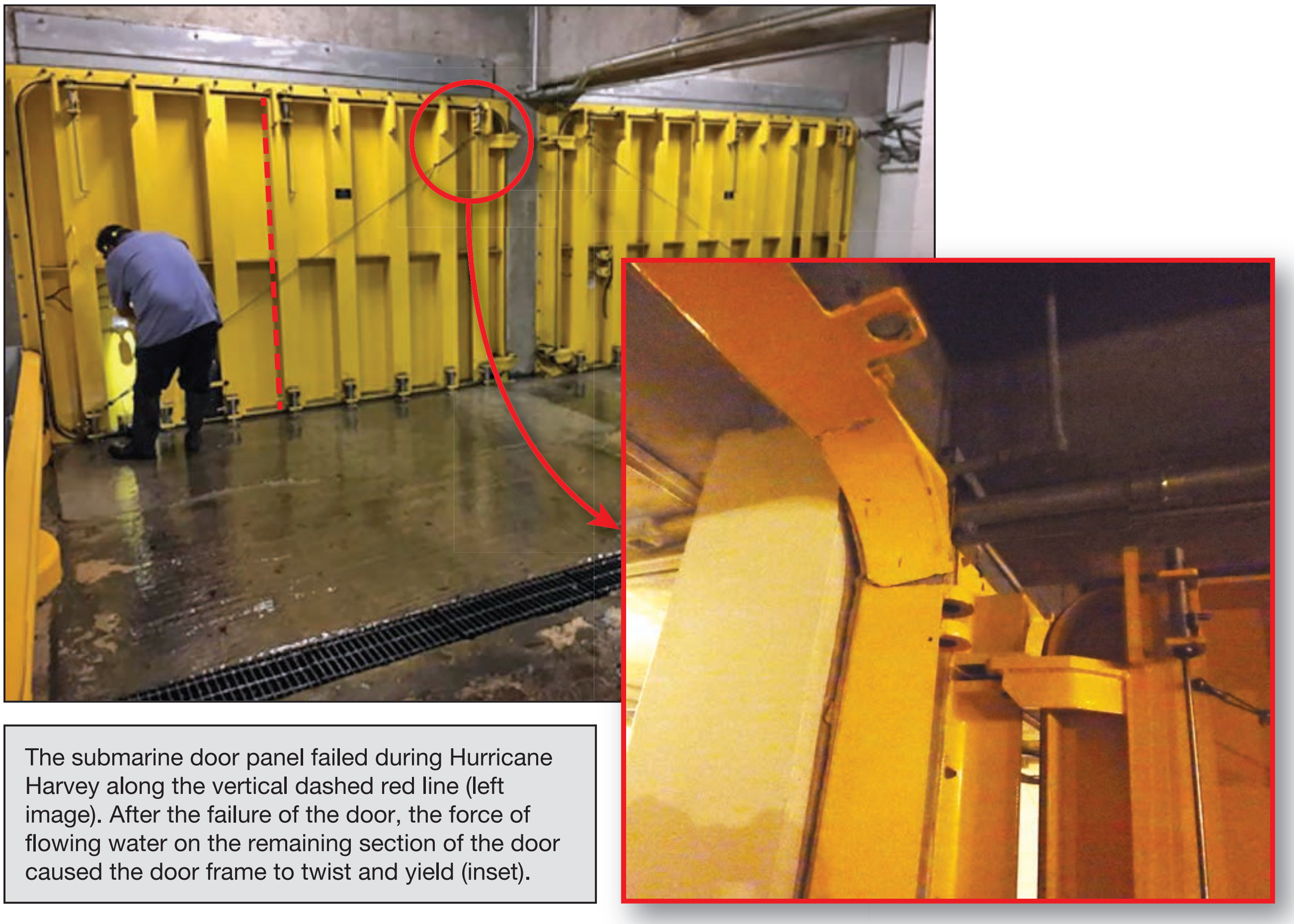
[C] The 6-foot by 6-foot opening cut into the foundation wall of the Green Parking Garage that was filled in with metal stud framing and gypsum wall board.

Figure 3-57: A disconnected pipe allowed stormwater to enter the cavity under the Green Parking Garage floor slab, resulting in the complete inundation of the garage

Breach No. 2: Submarine Door

Breach No. 2 occurred at the submarine door that isolates the Little Tranquility Park Parking Garage and Tranquility Park Parking Garage from the underground structures to the north. Both of these garages are three-level underground parking garages located beneath the parks bearing the same name. As the floodwater from Breach No. 1 filled the Green Parking Garage, it eventually reached the submarine door shown in Figure 3-58.

The loading from the floodwater caused the submarine door to experience a structural failure in the midpoint of the steel face plate adjacent to a vertical stiffening rib, leaving half of the submarine door remaining intact in the door frame (see Figure 3-59 and Figure 3-60). The water elevation in Buffalo Bayou when the submarine door failed is not known. The failure of this submarine door resulted in the complete inundation of the Little Tranquility Park Parking Garage and Tranquility Park Parking Garage.



The submarine door panel failed during Hurricane Harvey along the vertical dashed red line (left image). After the failure of the door, the force of flowing water on the remaining section of the door caused the door frame to twist and yield (inset).

Figure 3-58: Submarine doors on the road that connects the Green Parking Garage to the Little Tranquility Park Parking Garage being deployed in preparation for Hurricane Harvey

PHOTOGRAPH COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING

[A] Remaining section of the submarine door shown in Figure 3-58 after its failure.

[B] Both halves of the submarine door shown in photo A after its failure.

[C] Failure of the door panel along a weld (outlined in red).

Figure 3-59: Submarine door shown in Figure 3-58 after its failure

PHOTOGRAPHS COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING

Floodwater inundating the Little Tranquility Park Parking Garage and Tranquility Park Parking Garage eventually reached the floodgate that protects the Downtown Houston tunnel network—that floodgate did not fail and successfully prevented additional flooding in the tunnel network (refer to Section 3.2.3 and Figure 3-55 for more information).

Breach No.3: Glass Block Wall

Breach No. 3 occurred when the floodwater on the streets in the area continued to rise, eventually cresting a small hill that surrounds Little Tranquility Park. Inside Little Tranquility Park, a glass block wall had been installed to fill the gap between a concrete walkway and the bottom of the overpass for Rusk Street. When Little Tranquility Park began to fill with floodwater, the glass block wall was loaded by hydrostatic forces. With no structural capacity to resist hydrostatic forces, the wall collapsed, resulting in a second floodwater entry point into the underground parking garage network (see Figure 3-60).

Figure 3-60: Glass block wall that failed when exposed to floodwater pressures (left); floodwater entering through Breach No. 3 (right)

RIGHT PHOTOGRAPH COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING

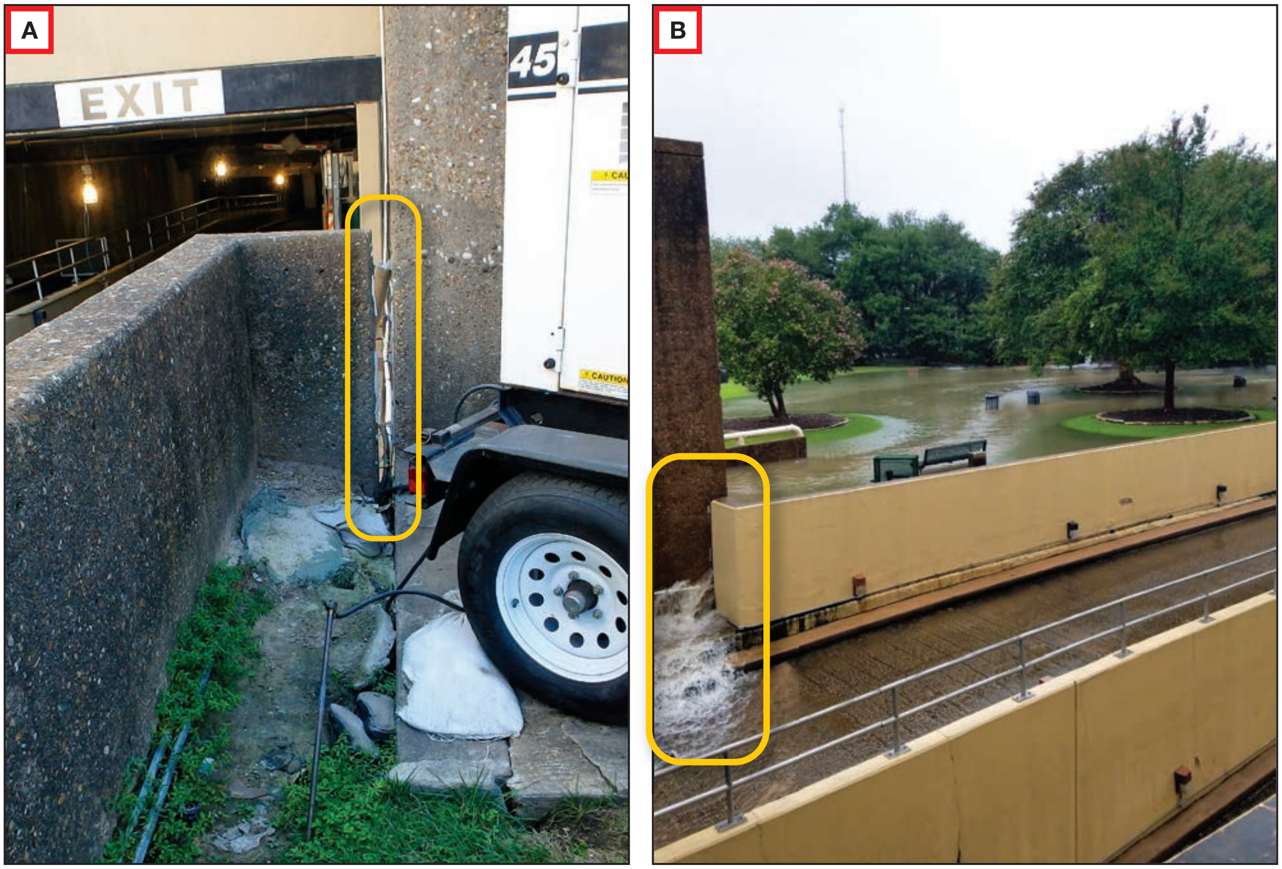
Even if the submarine door between the Green Parking Garage and Little Tranquility Park Parking Garage had remained intact (Breach No. 2), this breach of the glass block wall still would have resulted in the complete inundation of both the Little Tranquility Park Parking Garage and the Tranquility Park Parking Garage.

Breach No. 4 and 5: Tranquility Parking Garage Vehicle Ramp 3

Breaches No. 4 and No. 5 both occurred at vehicle ramp 3 to the Tranquility Park Parking Garage. Vehicle ramp 3 is protected from flooding with retaining walls, acting as floodwalls, on the east and west side with a floodgate across the top of the ramp to the south.

West side of ramp. Breach No. 4 occurred on the west side of the vehicle ramp. This retaining wall abuts the wall and foundation for a stairwell and elevator shaft that provides access to Little Tranquility Park Parking Garage, but is not physically connected to the wall. Over time, the top of the retaining wall has deflected, opening a 2-inch-wide gap between the edge of the retaining wall and the foundation wall that allowed water to enter the parking garage (see Figure 3-61).

East side of ramp. Breach No. 5 occurred along the east side of the Tranquility Park Parking Garage vehicle ramp 3. Prior to Hurricane Harvey, a portion of the retaining wall and stairwell that led from a Federal Building to the Tranquility Park Parking Garage had been temporarily demolished to accommodate construction at the Federal Building. When Hurricane Harvey struck, the construction was not complete, and floodwater was able to enter the parking garage (see Figure 3-62). At the time of the MAT site visit, the opening in the retaining wall had been repaired.



[A] Gap between a retaining wall and foundation wall of the Little Tranquility Park Parking Garage (yellow outline); the cables running through the gap were placed there after Hurricane Harvey.

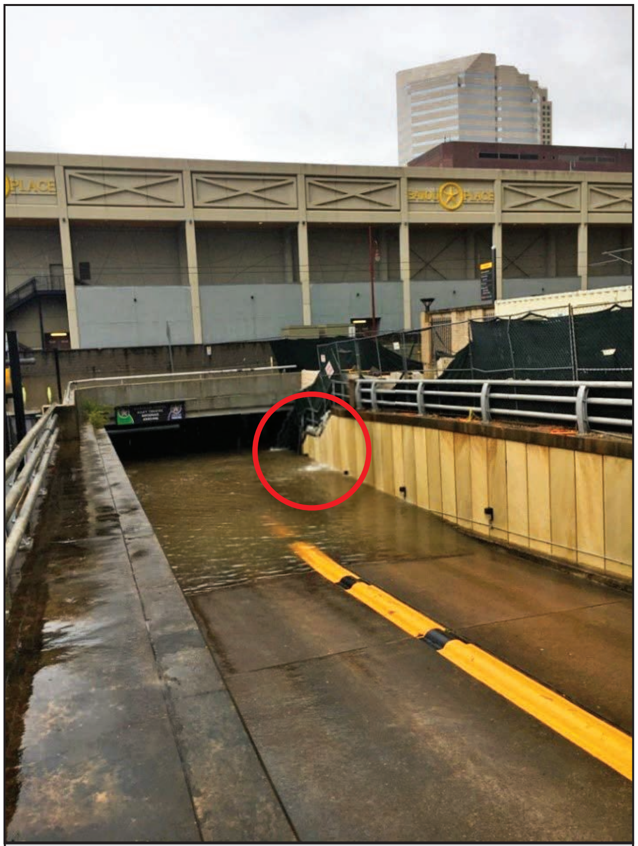
[B] Photo taken during Hurricane Harvey shows floodwater entering the Little Tranquility Park Parking Garage though the gap (yellow outline).

Figure 3-61: Floodwater entry point at a gap in a retaining wall

RIGHT PHOTOGRAPH COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING

Figure 3-62: Floodwater entry point at demolished retaining wall section

PHOTOGRAPH COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING



Water flowed into the Tranquility Park Parking Garage vehicle ramp 3 from a demolished section of a retaining wall (red circle); this photo was taken after floodwater in the area had partially receded.

Breach No. 6: Seepage through Wortham Theater Building Envelope

Breach No. 6 consists of numerous points of water seepage through the building envelope and through two floodgates on the west side of the Wortham Theater, along the bank of Buffalo Bayou.

Seepage through foundation. Water reportedly entered though an unsealed joint between the top of the concrete foundation and the reinforced masonry wall with granite façade, shown in Figure 3-63, and in locations where there was a separation between waterproofing and the foundation wall. The HWM of Buffalo Bayou was approximately 6 feet above this joint in the building envelope.

Floodgates. On the west side of the Wortham Theater there are two emergency exits protected by sliding floodgates. The top of these floodgates, which have an elevation of 39.30 feet, were overtopped by floodwater when it reached its maximum elevation of 39.63 feet. However, even before the floodgates were overtopped, leaks in the seals of the floodgates, coupled with the lack of a seepage collection system, allowed water to infiltrate the building (see Figure 3-64).

Figure 3-63:
Unsealed joint between the concrete foundation wall and reinforced masonry wall with granite façade where significant seepage into the Wortham Theater occurred

Figure 3-64:
Floodgate protecting emergency exit along Buffalo Bayou

RIGHT PHOTOGRAPH COURTESY OF CARLOS GUTIERREZ, CSF CONSULTING

[A] Floodgate protecting an emergency exit along the west side of the Wortham Theater along Buffalo Bayou.

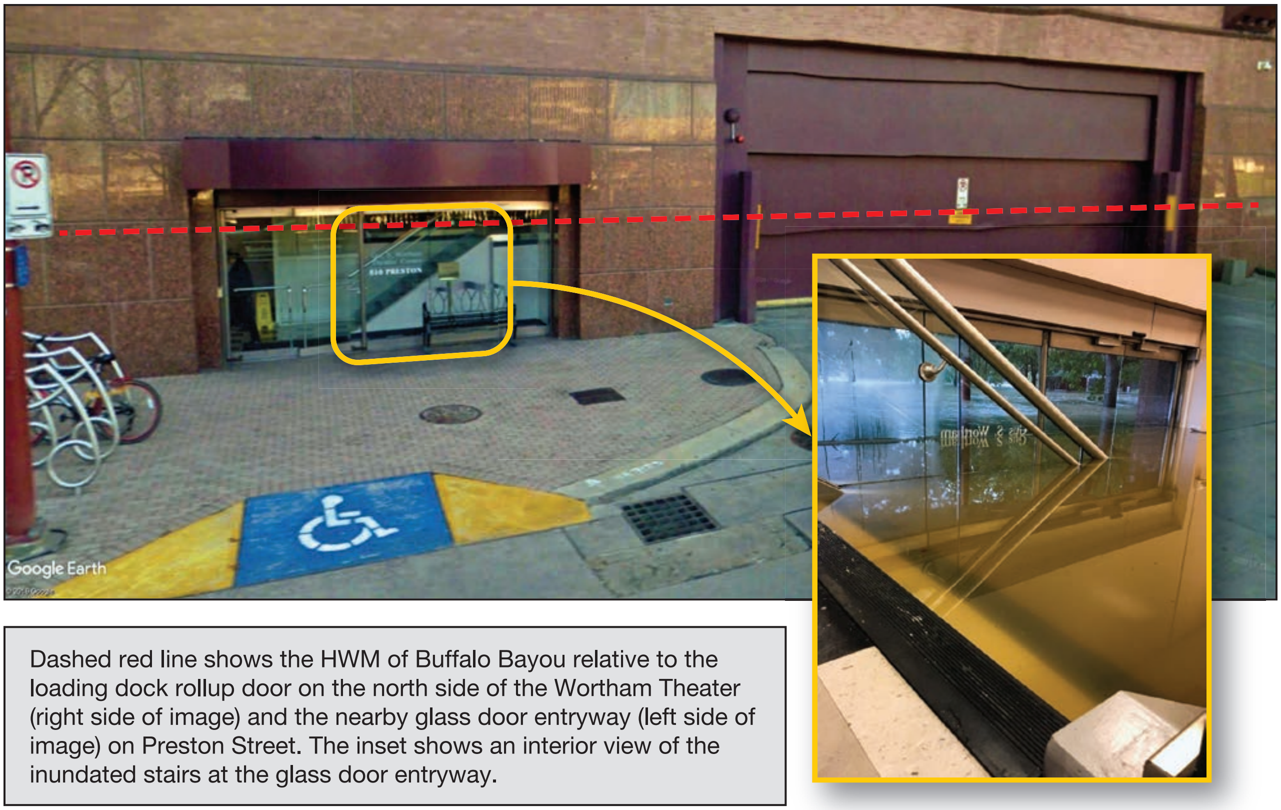
[B] Before the floodgates were overtopped, floodwater seeped through the floodgate seals during Hurricane Harvey.

Breach No. 7 and 8: Seepage Though Glass Doors

Fish Plaza glass door entrance. Breach No. 7 occurred through the glass doors that make up the entryway to the Wortham Theater from Fish Plaza, located along Texas Street. Floodwater inundated Fish Plaza and seeped around the edges of the glass doors into the building. Once inside the building, the water began to flow down a stairwell to the basement and collected in the tunnel that connects the Wortham Theater to the Green Parking Garage. This tunnel has a submarine door (see Figure 3-65) that isolates the Wortham Theater from the Green Parking Garage, which was fully inundated with water from Breach No. 1. The tunnel inside the Wortham Theater eventually filled up to the tunnel ceiling and up to the first landing in the stairwell. The water that filled this tunnel section was the combination of the water that was able to seep around the glass doors and floodwater from the Green Parking Garage. This tunnel section contains a trench drain that was located behind a sheetrock wall, which connects to floor drains in the Green Parking Garage. When the Green Parking Garage became fully inundated, floodwater backflowed within this trench drain, bypassing the submarine door, and filled the tunnel.

Figure 3-65:
Submarine door that isolates the Wortham Theater from the Green Parking Garage

Preston Street glass door entrance. Breach No. 8 occurred at a glass door entryway along Preston Street, on the north side of the Wortham Theater. Breach No. 8 highlights the difficulties associated with establishing and maintaining a continuous barrier to prevent the entry of floodwater at the Wortham Theater. Although the majority of building entrances below the established DFE were protected by a floodgate, not all of the entrances were protected. A large rollup garage door for the loading dock located on the north side of the Wortham Theater was protected by a floodgate, but a glass door entryway 20 feet to the east did not have any installed dry floodproofing protection measures (see Figure 3-66). Inside the glass door entryway is a small vestibule and a short staircase leading up to the main lobby, which is approximately 3.5 feet above the street level. During Hurricane Harvey, floodwater entered the building at the glass door entryway, overtopped the stairs, and flowed into the Wortham Theater.



Dashed red line shows the HWM of Buffalo Bayou relative to the loading dock rollup door on the north side of the Wortham Theater (right side of image) and the nearby glass door entryway (left side of image) on Preston Street. The inset shows an interior view of the inundated stairs at the glass door entryway.

Figure 3-66: Floodwater entry point though glass door entryway

Breach No. 9: Missing Floodgate

Breach No. 9 occurred on the east side of the Wortham Theater, along South Smith Street, at an emergency exit. This emergency exit, while located below the DFE, was not protected with a floodgate (see Figure 3-67). A similar emergency exit, located 50 feet to the north, at a similar elevation, was fitted with a floodgate that successfully kept floodwater from entering the building.

Miscellaneous Ground-Level Floodwater Entry Points

In addition to the nine breaches described in detail, floodwater entered the area protected by dry floodproofing mitigation measures at other ground-level entry points.

Floodgates. Of the 16 pedestrian and vehicle entrances into the garages, two locations did not have floodgates installed. The other 14 entrances were protected by floodgates, but they were all overtopped due to the depth of the floodwater in the Theater District. Additionally, two of the floodgates at pedestrian entrances had issues with their seals, allowing significant seepage prior to overtopping.

Unsealed penetrations. In the Wortham Theater, floodwater seeped into the building through unsealed pipe and conduit penetrations through the walls and ceiling of below-grade areas and through cracks in walls and ceilings of below-grade areas.

Figure 3-67: Emergency exit door along the east side of the Wortham Theater; the red line indicates the approximate HWM during Hurricane Harvey

Effect on Operations

During the MAT visit 2½ months after Hurricane Harvey made landfall, the cleanup and debris removal stage of recovery was ongoing. The Wortham Theater partially reopened on September 26, 2018, a little more than 1 year after Hurricane Harvey. The parking garages took approximately 3 months after Hurricane Harvey to resume regular operation but took approximately 16 months to be fully restored.

3.2.4.3 Summary of MAT Observations

Theater District and Garages

- The Theater District contains buildings that are located in the regulatory floodway, Zone AE, Shaded Zone X, and Unshaded Zone X. The Wortham Theater is located in Zone AE, with a BFE of 37 feet. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- The DFE, which is the water surface elevation of Tropical Storm Allison plus 2 feet of freeboard, was not correlated to a recurrence interval-based flood elevation such as the 1-percent-annual-chance probability event or 0.2-percent-annual-chance probability flood elevation. Although many dry floodproofing systems installed in Houston after Tropical Storm Allison used this metric, the floodplain profile of the different watersheds in Houston are not the same. Two feet of freeboard in a wide floodplain such as Brays Bayou provides a significant level of protection, whereas 2 feet of freeboard provided in the narrower and more restricted floodplain of Buffalo Bayou does not provide the same level of protection.

After Hurricane Harvey, HoustonFirst, the managers of the Houston Theater District, hired an independent engineering consultant to perform a comprehensive flood vulnerability assessment. The summary report, developed by CSF Consulting, L.P. on the events of Hurricane Harvey and findings, is titled Tropical Storm Harvey Flood Investigation (2018). To protect the Houston Theater District from future flooding events, HoustonFirst is evaluating the benefits and costs of three different potential DFEs: the Hurricane Harvey HWM plus 1 foot of freeboard, the 0.2-percent-annual-chance event flood elevation plus 1 foot of freeboard, and the 0.2-percent-annual-chance event flood elevation plus 2 feet of freeboard.

3.2.5 Energy Corridor Office Building #1

Constructed in the early 1980s, this office building complex located in the Energy Corridor near Buffalo Bayou consists of a 28-story high-rise tower, on the west side of the complex, that connects to a five-story building in the center of the complex (see Figure 3-68). On the east side of the complex is a nine-level parking garage. The five-story building has an additional basement level containing a loading dock. The loading dock can be accessed via a vehicle ramp constructed on the north side of the complex, between the parking garage and five-story building. Some portions of the parking garage are within the Shaded Zone X (see Figure 3-69), but most of the complex is located in Unshaded Zone X.

BUILDING #1

FIRM = Unshaded Zone X

(see Figure 3-70)

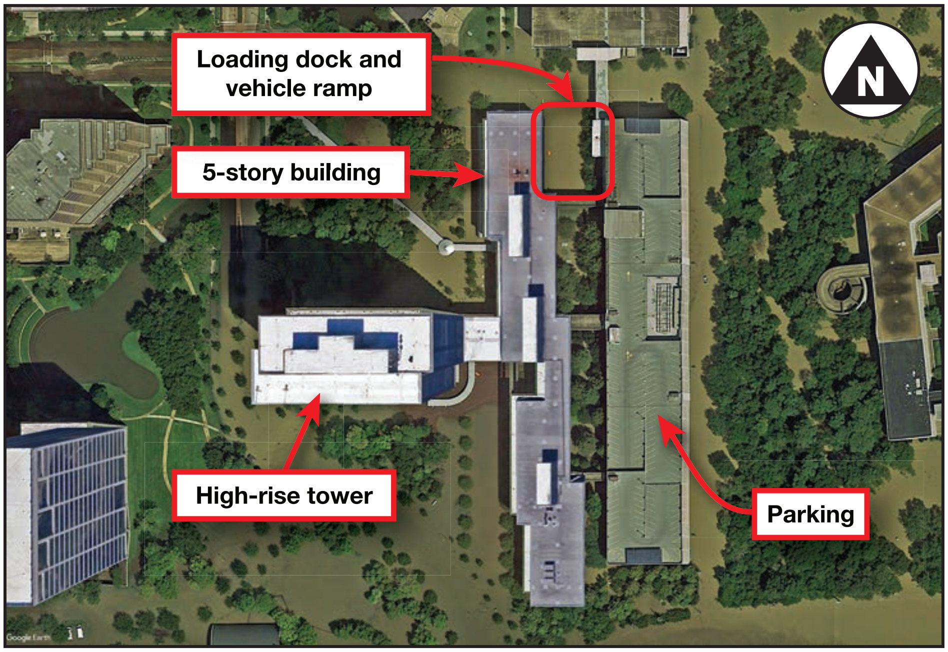
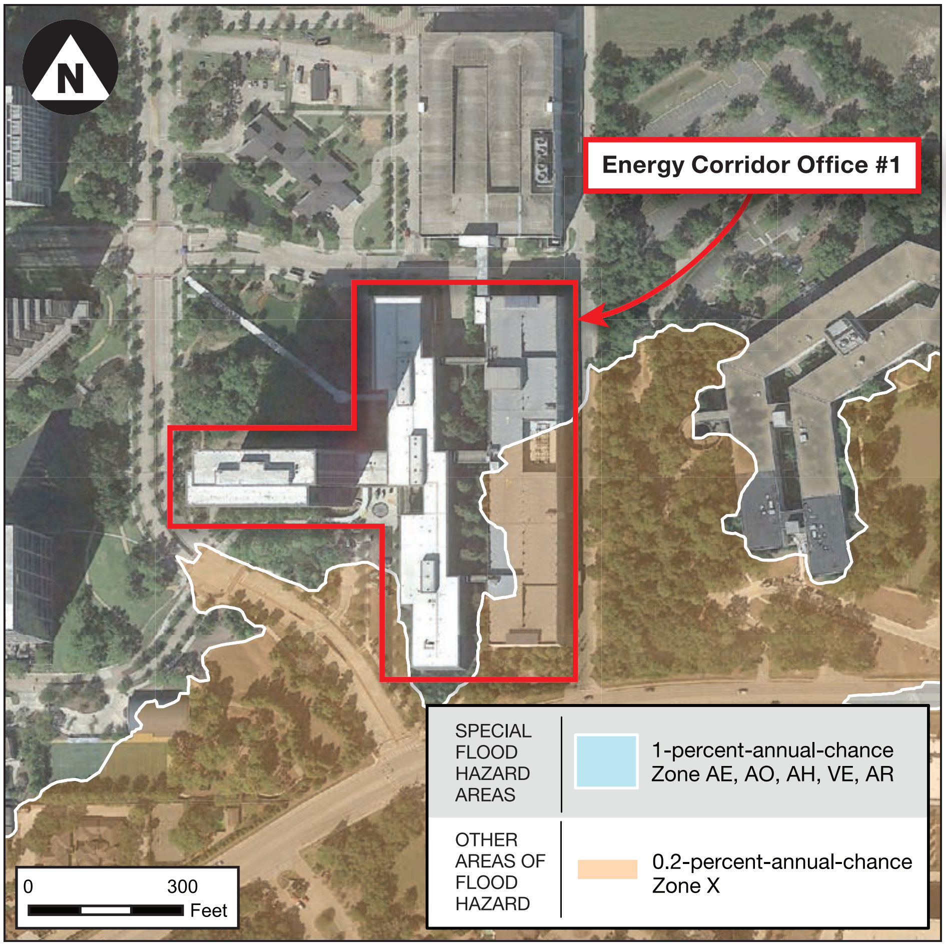


Figure 3-68: Aerial image of Energy Corridor Office Building #1 (taken on August 30, 2017) showing floodwater around the office complex

Figure 3-69:
FIRM for the Energy Corridor Office Building #1



Dry Floodproofing Mitigation Measures

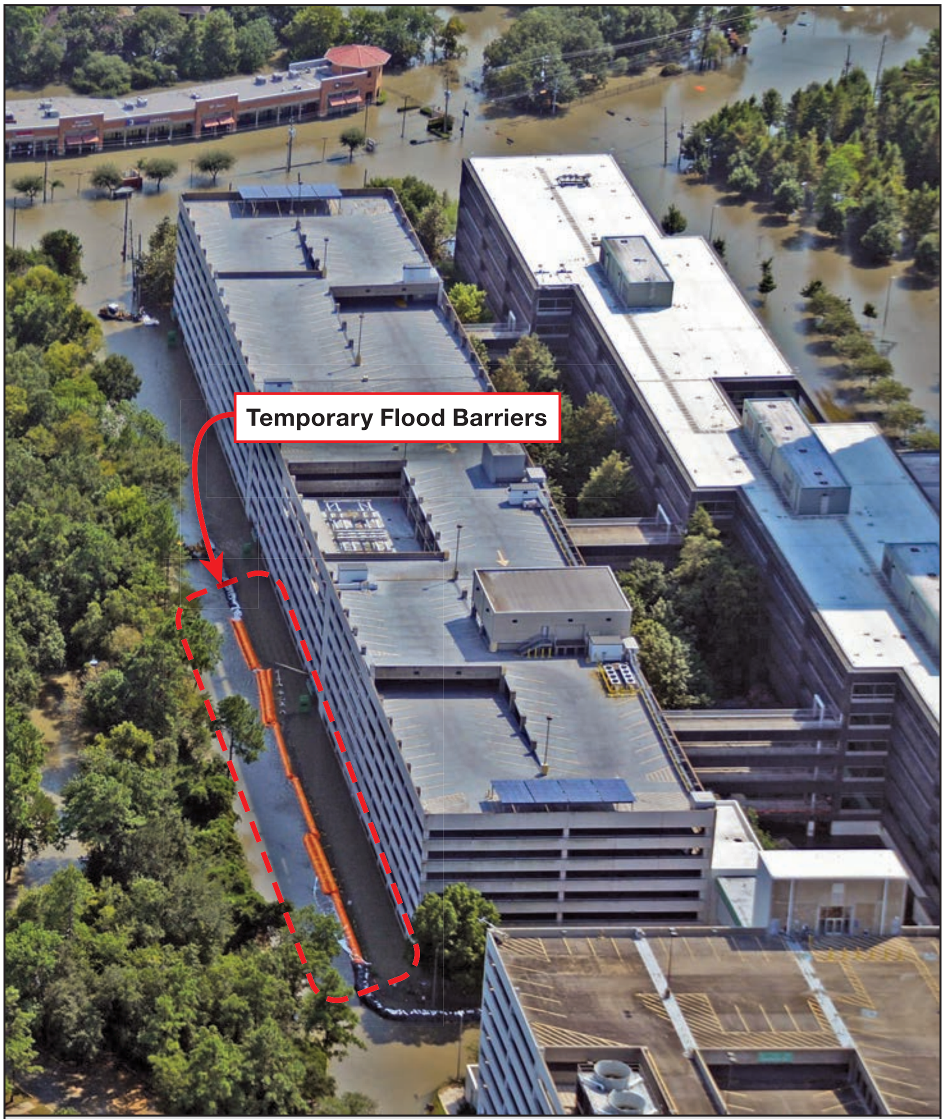
These office buildings have not sustained significant flood damage in the past, but have experienced several minor flooding events caused by stormwater sheet flow flooding collecting in the loading dock. As a result, a passive floodgate was installed to protect the loading dock from sheet flow entering from the street. The passive floodgate was tied into a concrete wall on each side of the loading dock, forming a flood barrier along the north side of the office building complex. In anticipation of flooding associated with Hurricane Harvey, temporary flood barriers composed of water-filled bladders were installed along the eastern portion of the parking garage.

Performance during Harvey

During Hurricane Harvey, the area around the Energy Corridor Office Building #1 complex experienced minor flooding cause by stormwater that receded as bands of heavy rainfall passed by. However, the building experienced significant flooding on August 29, 2017, 4 days after Harvey made landfall. On August 28, the U.S. Army Corps of Engineers (USACE) was forced to start releasing water from Addicks Reservoir and Barker Reservoir to prevent a catastrophic failure of the dams. The Addicks and Barker Reservoirs mark the northern and western boundary of the Energy Corridor. Both reservoirs discharge into Buffalo Bayou, which runs through the southern portion of the Energy Corridor. After the release, a flood gage along Buffalo Bayou at the Dairy Ashford Road

Bridge located approximately 2 miles downstream from the Energy Corridor indicated a HWM of 76.90 feet on August 30, which exceeds the 0.2-percent-annual-chance flood elevation of 74.70 feet by 2.2 feet.

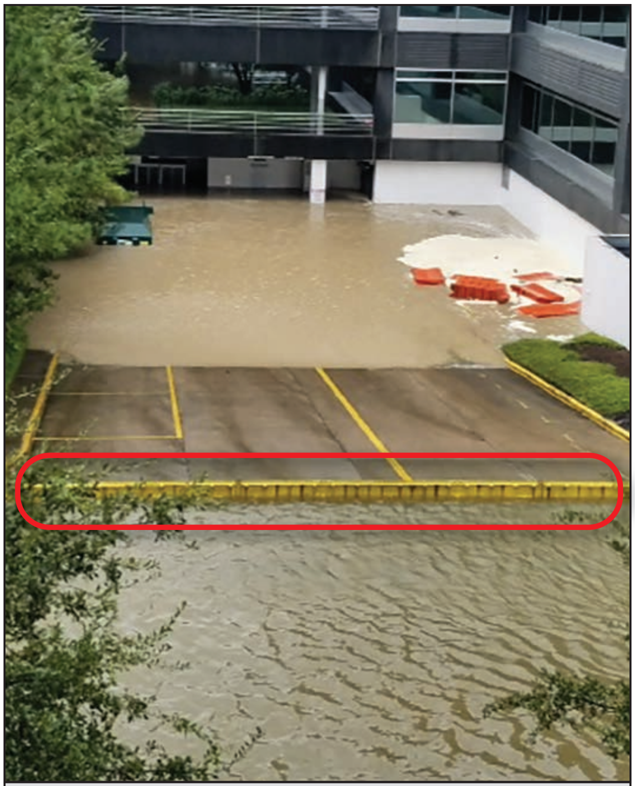
Parking garage. In anticipation of Hurricane Harvey, temporary flood barriers were installed along the eastern portion of the parking garage to protect the complex from floodwater that would approach from the southeast. However, as the floodwater rose, the temporary flood barriers were overtopped, allowing water to flow into the parking garage (see Figure 3-70). As the parking garage filled with water, its walls were overtopped and floodwater started to fill the loading dock area. The automatic passive floodgate protecting the loading dock deployed as designed when floodwater reached the north side of the building complex (see Figure 3-71).



Orange temporary flood barriers are visible along the east side of the complex, but are submerged along the southeast corner of the parking garage where the grade elevation is lower.

**Figure 3-70:
Civil Air Patrol photo showing the east side of the parking garage**

Figure 3-71: Deployed passive floodgate at the top of the loading dock ramp (red outline)



Water from the parking garage filled the loading dock from the left; orange temporary flood barriers are shown floating in the floodwater at right.

Office building basement. An at-grade vault on the north side of the five-story building once provided access to a below-grade ventilation opening for an electrical room whose components were relocated during a project several years prior to Harvey. The opening in the foundation wall was filled in with unreinforced masonry. When floodwater entered the vault, the unreinforced masonry wall failed as a result of the hydrostatic loading, allowing water to enter the basement and fully inundate it.

Office building first floor. Floodwater from Hurricane Harvey eventually reached 1.2 feet above the first floor of both the five-story building and the 28-story high-rise tower, damaging interior finishes on the first floors.

Effect on operations. During the MAT visit 2½ months after Harvey made landfall, this complex was still undergoing repairs and still unoccupied and will remain so until repairs are complete.

Summary of MAT Observations

- The Energy Corridor Office Building #1 is located in Unshaded Zone X, while the parking garage is located in Shaded Zone X. All of the buildings are located outside of the SFHA and thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.

- The passive floodgate was installed to protect against stormwater sheet flow from flooding into the loading dock. It was not designed for an event as severe as Hurricane Harvey, which exceeded the 0.2-percent-annual-chance event. The passive gate performed as designed and was not overtopped.
- Floodwater entered the dry floodproofed area behind the passive floodgate by overtopping an unidentified low point in the office building complex via the parking garage and by overloading an unreinforced masonry wall used to infill a below-grade wall penetration to an unused utility vault.
- When protecting existing buildings, understanding the potential source of flooding is critical. The entire flood barrier should be set to the same elevation without any low points that can lead to overtopping, and all components of the flood barrier should be capable of resisting the hydrostatic forces associated with the DFE.

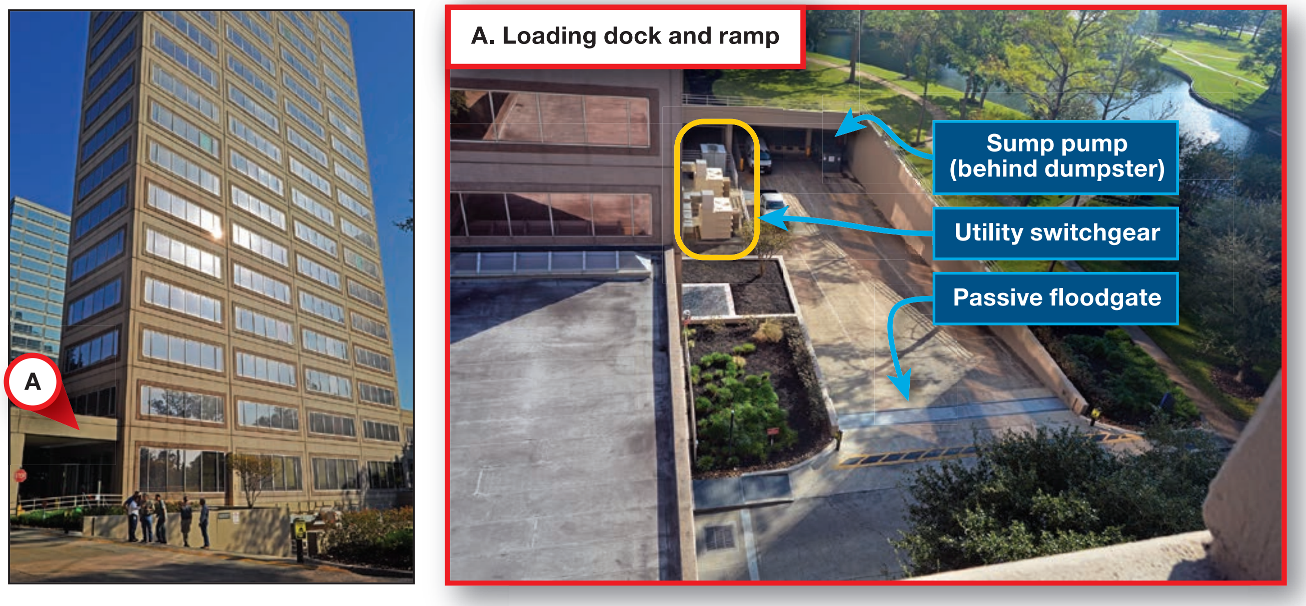
3.2.6 Energy Corridor Office Building #2

Constructed in the early 1980s, this office building located in the Energy Corridor near Buffalo Bayou is a 17-story commercial office building with an additional basement level containing a loading dock. The loading dock is accessed via a vehicle ramp constructed on the south side of the building. A passive floodgate is installed at the top of the loading dock ramp (see Figure 3-72). A majority of the building systems (MEP components, potable water supply pumps,

BUILDING #2

FIRM = Unshaded Zone X

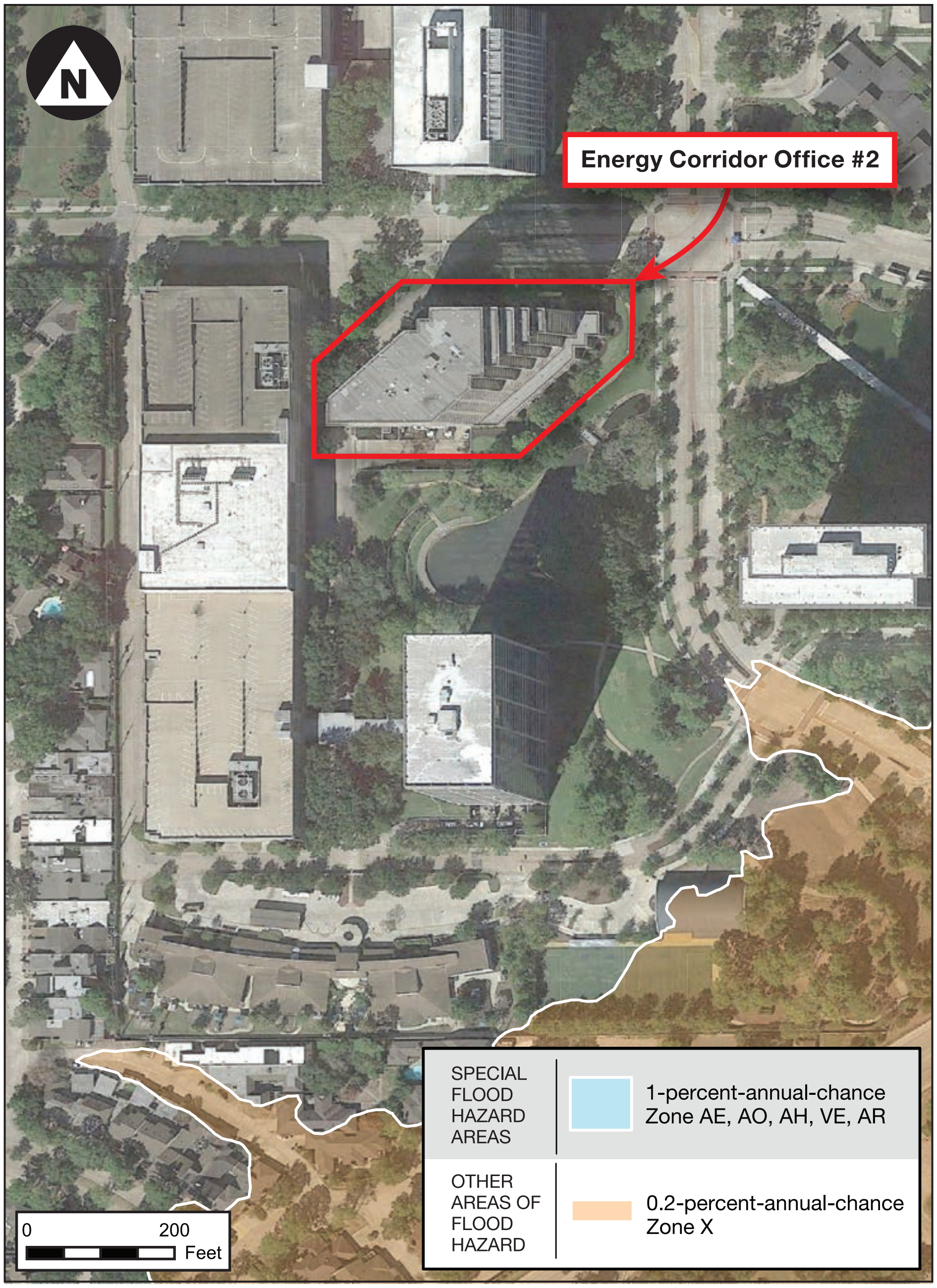
(see Figure 3-74)



[A] The passive floodgate is shown at the top of the ramp, the utility switchgear is on the left side of the loading dock, and the pond is in the background to the right.

Figure 3-72: Energy Corridor Office Building #2 (left image) and loading dock and ramp (right image) fire suppression equipment, and backup generator and fuel) are located in a mechanical room in the basement; a ventilation vault is located on the north side of the building to provide ventilation for this equipment. There are two pad-mounted transformers in the loading dock area and a switchgear with conduits that run into an electrical manhole located in the street beyond the loading dock ramp. The office building is located in an Unshaded Zone X, approximately 0.1 mile from the nearest regulated floodplain (see Figure 3-73).

Figure 3-73: FIRM for Energy Corridor Office #2



Dry Floodproofing Mitigation Measures

This office building sustained significant flood damage when a severe thunderstorm in 2009 resulted in the complete inundation of the basement and loading dock (see Figure 3-74) and has experienced several minor flooding events caused by stormwater sheet flow collecting in the loading dock. As a result, a passive floodgate was installed at the top of the loading dock ramp to prevent stormwater sheet flow from flooding the loading dock. Within the loading dock is a large sump pump, with a connection for a redundant pump, to remove any rainwater that may collect at the base of the loading dock; the water is discharged over the wall into a pond. The passive floodgate and the sump pump are shown on Figure 3-72).

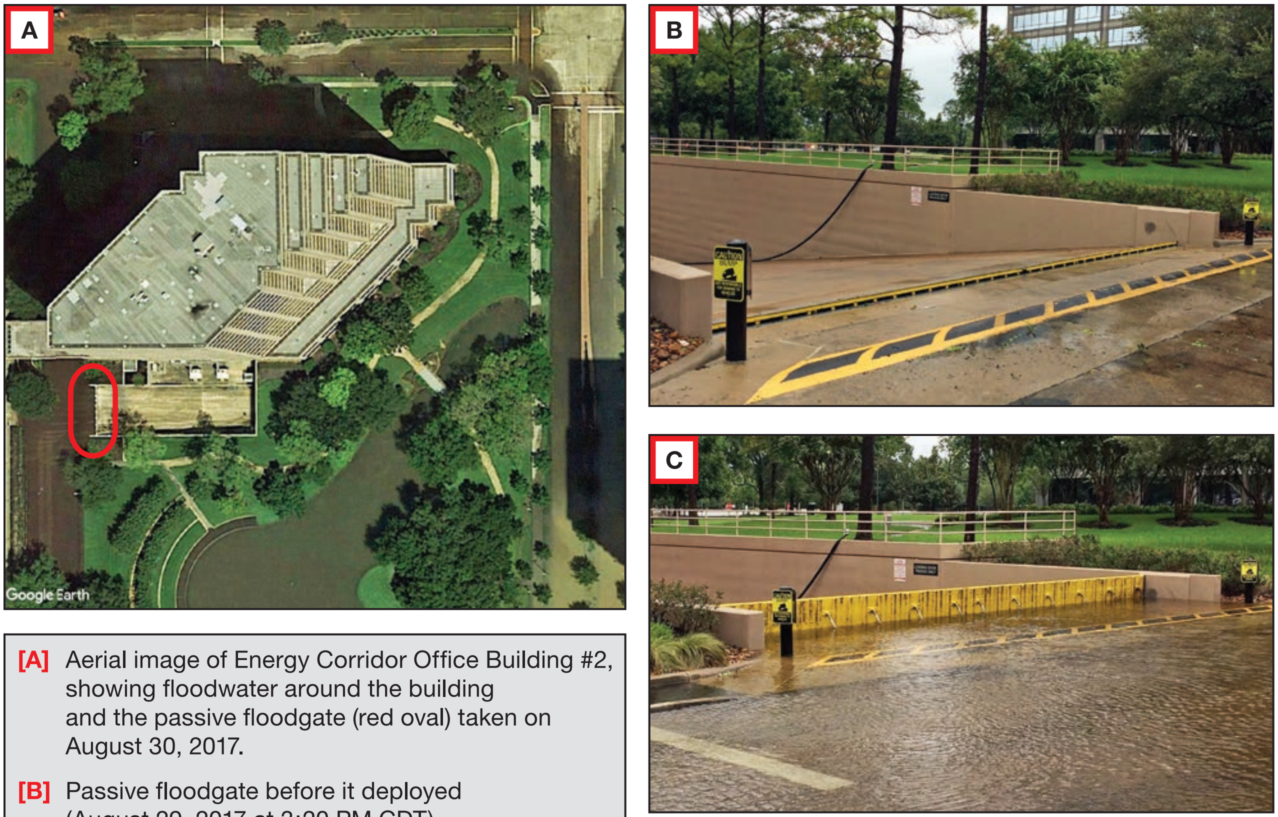
Additionally, a 1-foot-tall concrete curb wall was installed on the top of an existing ventilation vault that provides ventilation to the MEP systems located in the basement mechanical room. The new wall elevation matches the wall height at the loading dock and that of the passive floodgate.

Figure 3-74: Flooding of the loading dock during a severe thunderstorm in 2009

Performance during Harvey

During Hurricane Harvey, the area around the Energy Corridor Office Building #2 experienced minor flooding cause by stormwater that receded as bands of heavy rainfall passed by, but experienced significant flooding on August 29, 2017, 4 days after Harvey made landfall. On August 28, the USACE was forced to start releasing water from Addicks Reservoir and Barker Reservoir to prevent a catastrophic failure of the dams. The Addicks and Barker Reservoirs mark the northern and western boundary of the Energy Corridor. Both reservoirs discharge into Buffalo Bayou, which runs through the southern portion of the Energy Corridor. After the release, on August 30, a flood gage along Buffalo Bayou at the Dairy Ashford Road Bridge located approximately 2 miles downstream from the Energy Corridor indicated a HWM of 76.90 feet, which exceeds the 0.2-percent-annual-chance flood elevation of 74.70 feet by 2.2 feet.

Floodgates. Prior to the release of water from Addicks Reservoir and Barker Reservoir, the passive floodgates deployed at least one time on August 26, but when floodwater receded, the gates lowered. On August 29, floodwater caused the passive floodgate to rise again; it reached its fully deployed position in approximately 30 minutes (see Figure 3-75). Floodwater did not recede in the area around the building until September 5, 2017.



[A] Aerial image of Energy Corridor Office Building #2, showing floodwater around the building and the passive floodgate (red oval) taken on August 30, 2017.

[B] Passive floodgate before it deployed (August 29, 2017 at 3:20 PM CDT).

[C] Passive floodgate after it deployed (3:36 PM CDT).

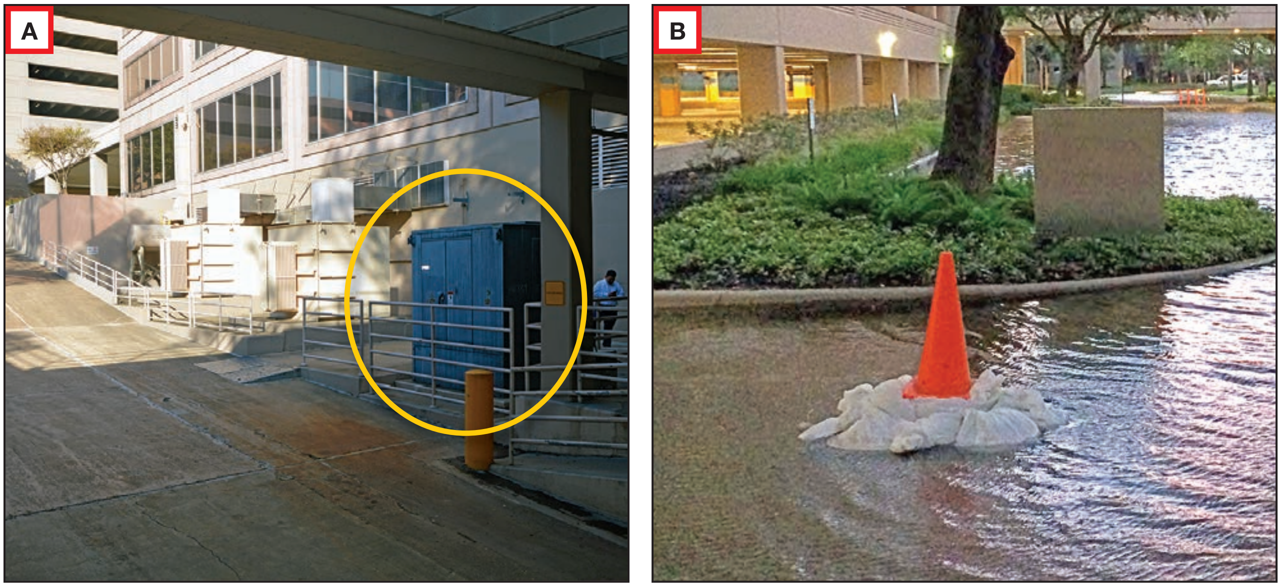
Figure 3-75: Flooding around Energy Corridor Office Building #2 August 29 to August 30

RIGHT SIDE PHOTOGRAPHS COURTESY OF ANDREW HOYNS, HICKS VENTURES

At its maximum elevation, the floodwater rose to within about 7 inches of the top of the floodgate. As a precaution, sandbags were placed on the top of the passive floodgate and adjoining concrete walls when the on-site maintenance personnel received information that the floodgates at neighboring office buildings were being overtopped. Floodwater did not overtop the gate, nor was excessive leakage past the gate reported, even though the rubber gasket at the base of the passive gate was cracked.

Switchgear conduit. Shortly after the passive floodgates were fully deployed, water flowed into the area of the loading dock ramp behind the floodgate. Water appeared to be flowing within the underground duct bank/conduit that runs between the utility switchgear in the loading dock area (see Figure 3-76, left) and the underground electrical manhole located in the street to the west of the building (see Figure 3-76, right). Maintenance personnel who were on site during Hurricane Harvey placed plastic lining and sandbags on the electrical manhole cover to reduce the rate of floodwater flowing into the loading dock to a rate at which the sump pumps in the loading dock were able to keep up.

Basement. Floodwater reportedly seeped over and down into the basement at the construction joint between the exterior pre-cast concrete panels and the first floor slab. This construction joint likely did not have a waterstop, or if the waterstop was installed, it had been compromised. Reportedly, no other portions of the basement experienced noticeable seepage. The water seeping



[A] Floodwater was able to enter the protected loading dock area by flowing within conduits that terminated at the utility switchgear (yellow circle). The electrical manhole in the street has conduit that connects to the utility switchgear in the loading dock.

[B] Electrical manhole is covered with plastic lining and sandbags to minimize floodwater infiltration into the duct bank/conduits to switchgear.

Figure 3-76: Floodwater entering protected area flowing within utility switchgear conduit
RIGHT PHOTOGRAPH COURTESY OF ANDREW HOYNS, HICKS VENTURES

into the basement was located near a sump pit that removes roof stormwater drainage; the sump was able to accept and remove the seepage. The stormwater sump pit was previously connected to a perimeter drain system, but it was disconnected a few years ago because it caused the sump pumps to continually run. Disconnecting the perimeter drain system prevented a considerable source of water from entering the building, one that could have overwhelmed the sump pump system during Hurricane Harvey.

Effect on operations. Due to the performance of the dry floodproofing systems and the ability of on-site maintenance personnel to identify a source of floodwater, this building was one of the few buildings in the area that was able to resume normal operations after floodwater receded. Minimal damage was reported during the MAT visit.

Summary of MAT Observations

- The Energy Corridor Office Building #2 is located in Unshaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- The flood damage to this office building should be considered a near miss. The passive floodgate performed as designed, but water entered the dry floodproofed area from the

electrical manhole through a duct bank/conduit to the utility switchgear and through horizontal piping passing through the basement foundation wall. If on-site maintenance personnel were not present to observe the inflow of water from beneath the utility switchgear and through piping, identify its source, and mitigate the source of water, this water flow could have overwhelmed the sump pump and flooded the basement.

- The passive floodgate was not designed to protect against a DFE flood level, and there was no flood vulnerability assessment for the building that identified possible sources of water infiltration. The gate was installed to protect against stormwater sheet flow flooding and was not designed for an event as severe as Hurricane Harvey. The passive floodgate performed as designed and was not overtopped.
- Seepage was directed towards a stormwater sump pit located in the basement that successfully removed the seepage with minor impact to the building's operating capabilities.

3.2.7 Houston Galleria Office Tower

This 20-story office building was constructed in 1977 in the Houston Galleria District (see Figure 3-77). This building contains a basement with a loading dock, which is accessed via a vehicle ramp constructed on the south side of the building. A majority of the building systems (MEP components, potable water supply pumps, and fire suppression equipment) are located in the basement.

GALLERIA OFFICE TOWER

FIRM = Unshaded Zone X

The office building is located in an Unshaded Zone X, approximately 1.5 miles from the nearest regulated floodplain. Although not in close proximity to a regulated floodplain, this building was severely flooded by both Tropical Storm Allison and the 2015 Memorial Day Flood as a result of stormwater sheet flow flooding (see Figure 3-78).

Dry Floodproofing Mitigation Measures

After sustaining considerable damage in the 2015 Memorial Day Flood, the building owners promptly began the repairs to restore the building to its pre-flood condition. A flood vulnerability analysis was performed to quantify flood risks and identify areas and the elevation where floodwater could enter. With the information obtained during the flood vulnerability analysis, a comprehensive approach was taken to mitigate the identified source for water intrusion. Where critical building systems could not be relocated, redundant dry floodproofing systems with alarms were installed to provide the desired level of protection. When a repair was made, the repair was independently verified to ensure the repair was properly constructed and to ensure proper performance for protection against future flooding events.

Flood mitigation included a multi-pronged approach and redundant systems. Independent testing of the dry floodproofing mitigation measures ensured that the components would properly function when tested by a flooding event. Numerous measures were undertaken by the building managers, as follows:

- **DFE.** Establishing a DFE to be used for the entire site.
- **Flood barrier.** Installing a passive floodgate at the top of the ramp to the below-grade loading dock (see Figure 3-79). The passive floodgate was connected to the floodwall constructed

Figure 3-77:
Houston Galleria Office Tower

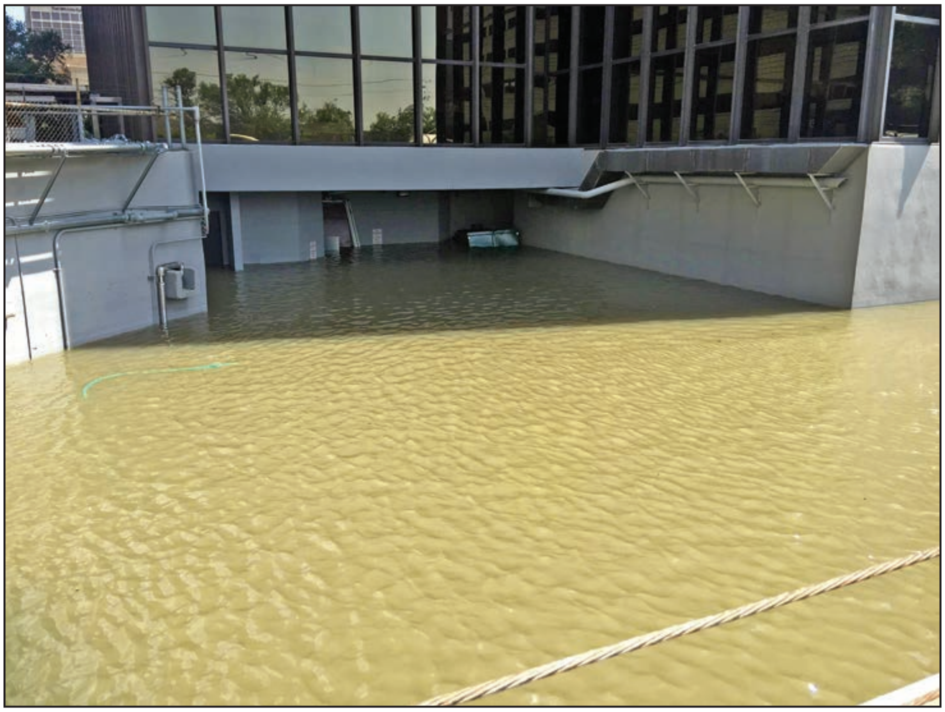


Figure 3-78:
Loading dock flood during the 2015 Memorial Day Flood

PHOTOGRAPH COURTESY OF GALLERIA OFFICE TOWER BUILDING MANAGEMENT around the loading dock in response to Tropical Storm Allison in 2001. The floodwall is also connected to the structure of the building.

- **Redundancy.** Constructing a redundant flood barrier system to protect the MEP components in the basement. The redundant flood barrier consists of a reinforced concrete wall with flood doors at the two pedestrian doors that provide access to the basement from the loading dock (see Figure 3-80). The reinforced concrete wall is tied into the existing structure with waterstops at the top and bottom of the wall. The concrete wall was designed to resist the hydrostatic load associated with a fully inundated loading dock and the loads transferred to the wall by the flood doors.

Figure 3-79: Passive floodgate located at the top of the loading dock ramp

- **Pony walls.** Constructing pony walls west of the building to prevent water from entering the basement via the fresh air intake louvers and prevent water from flowing into the parking garage and entering elevator pit. The area within the floodwalls is sloped to drain stormwater to the east to a scupper that allows stormwater to drain into the loading dock where it is emptied via a sump pump (see Figure 3-81, left image). The equipment is elevated on concrete pads to keep it above any stormwater that may collect in this area.
- **Larger sump pumps.** Increasing the size of the sump pumps in the loading dock. The sump pumps are designed to remove stormwater from the loading dock, including the stormwater that drains into the loading dock from the elevated equipment area. The sump pit is protected by a screen system to prevent debris from fouling any of the pumps (see Figure 3-81, left image). A high water level detection and alarm system was installed in the loading dock to notify building security that water is starting to collect in the loading dock (see Figure 3-81, right image).

Figure 3-80: Loading dock flood doors (the red line is a reflective strip and not an indicator of HWM); inset shows one of the flood doors installed to protect MEP

Figure 3-81: Loading dock sump pump screen protection (left) and high water level alarm (right)

- **Sealing.** Sealing around all pipe penetrations through the foundation wall.
  - Pipe penetrations into the mechanical room (see Figure 3-82) were sealed and the insides of electrical conduits were also sealed to prevent water from flowing inside the conduit and entering the mechanical room. Additionally, a wet alarm was installed in the mechanical room to notify security, building engineers, and building managers that water is leaking into the building in this area.
  - Other pipe penetrations and cracks through the foundation wall were sealed by pressure injecting a hydrophilic polyurethane foam to prevent water seepage. Areas with pipe penetrations or foundation cracks were not covered by building finishes or paint until it could be independently verified that the crack injection or pipe penetration sealing could prevent water seepage into the building.

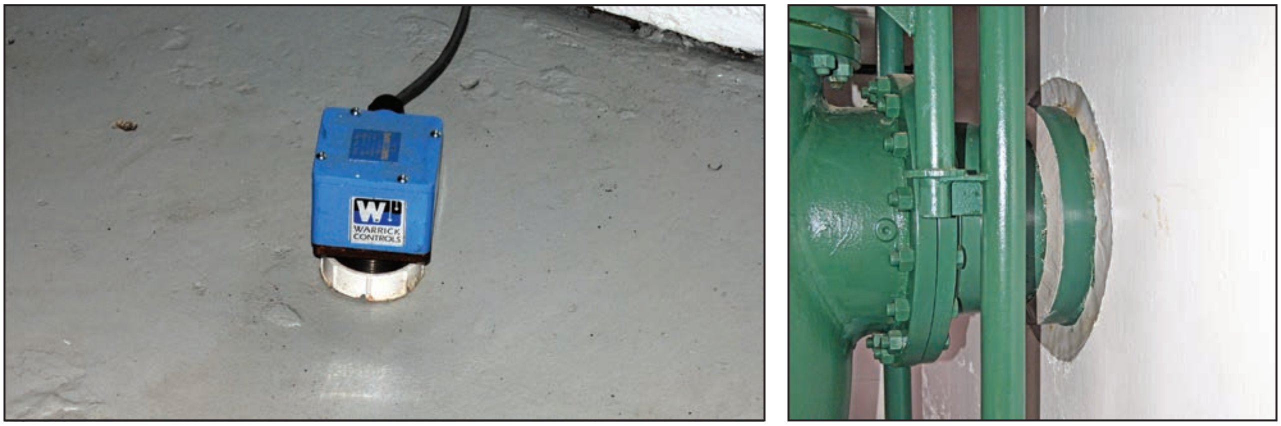


Figure 3-82: Wet alarm (left) and sealed pipe penetration (right)

The mitigation and dry floodproofing measures undertaken by the building were tested during the 2016 Tax Day Flood. The office tower did not sustain any damage from flooding of streets in the area. The installation of the passive floodgate at the loading dock was completed 5 days before that flood. The passive floodgate at the top of the loading dock properly deployed, and the sump pumps in the loading dock were able to keep up with the rainfall, preventing a repeat of the damage that occurred in 2015. The parking garage for the office tower was flooded by stormwater sheet flow, which damaged the elevator equipment in the parking garage and cars parked on the first level. In response to the flood, five additional passive floodgates, a 3-foot floodwall on the north perimeter of the garage, and check valves on all first- and second-level floor drains were installed around the parking garage (see Figure 3-83).

CONTINUED SUCCESSFUL PERFORMANCE

On July 4, 2018, when a severe thunderstorm dropped approximately 8 inches of rainfall in 3 to 5 hours across portions of western Houston that resulted in street flooding, the passive floodgates successfully deployed and protected the loading dock and basement from flood damage.

Figure 3-83: Parking garage for the Houston Galleria Office Tower

Performance during Harvey

Basement. During Hurricane Harvey, two leaks occurred in the basement of the building. The first leak was through a pipe penetration in the mechanical room that allowed the intrusion of approximately 10 to 15 gallons of water per day. The second leak was around a conduit penetration in the storage room that allowed the intrusion of approximately 5 to 10 gallons of water per day. The water from these two leaks was directed toward the existing sanitary sewer sump pit and removed from the basement.

Passive floodgates. The passive floodgates at the loading dock and at the parking garage entrances successfully deployed and prevented floodwater entering the protected areas.

Effect on operations. Minimal damage was reported during the MAT visit, mainly to ceiling tiles and drywall from the two leaks in the basement.

Summary of MAT Observations

- The Houston Galleria Office Tower is located in Unshaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.

- Damage from the 2015 Memorial Day Flood at the building resulted in the performance of a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures. The dry floodproofing mitigation measures undertaken were extensive, addressing both MEP components and the structure.
- Independent testing of the dry floodproofing mitigation measures ensured they would properly function when tested by a flooding event.
- The dry floodproofing components and mitigation activities performed at the Houston Galleria Office Tower provided a comprehensive flood barrier that performed as designed during the 2016 Tax Day Flood and Hurricane Harvey. The building experienced only two minor leaks in the dry floodproofing barrier during Hurricane Harvey that did not result in significant damage or loss of function down time.

3.2.8 Four Leaf Towers

The Four Leaf Towers are twin 396-unit, 42-story condominium towers that were constructed in 1982. The condominium towers are situated above the parking garage, with the first floor of the towers and access to the parking garage located approximately 8 feet above the grade of the surrounding streets (see Figure 3-84).

FOUR LEAF TOWERS

FIRM = Unshaded Zone X

(see Figure 3-86)

Figure 3-84:
Four Leaf Towers Condominium Complex, where yellow double arrows indicate street-level access locations to the complex and blue dashed arrows indicate access to parking garage

The condominium complex grounds contain several at-grade amenities, including a gym, tennis courts, a pool, restrooms, and a lounge. Additionally, on the northeast corner of the complex, an access ramp descends from street level to the loading dock. Within the loading dock is an access way to the parking garage, the waste pickup area, and the building central plant that generates steam and chilled water. Rooms that contain the remaining critical building systems, such as the electric room, potable water supply pumps, and fire suppression pumps, are located below grade in the garage. The condominium complex is located in Unshaded Zone X, approximately 0.4 mile from the nearest regulated floodplain (see Figure 3-85).

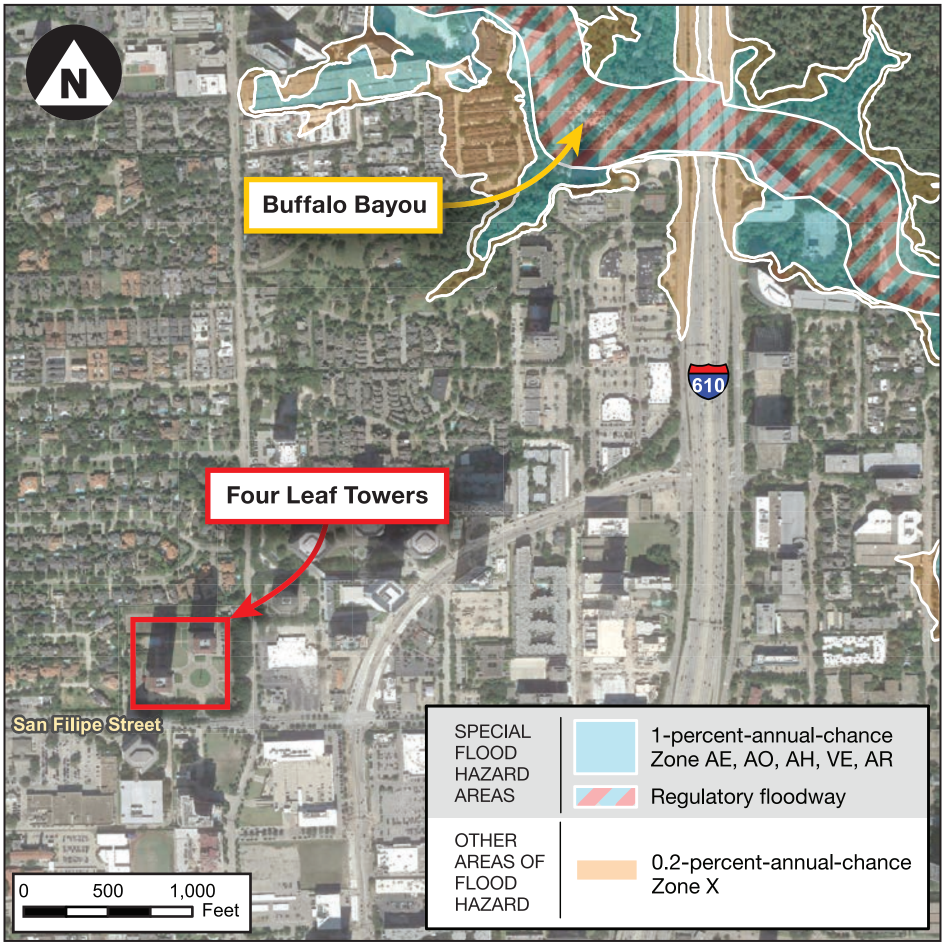
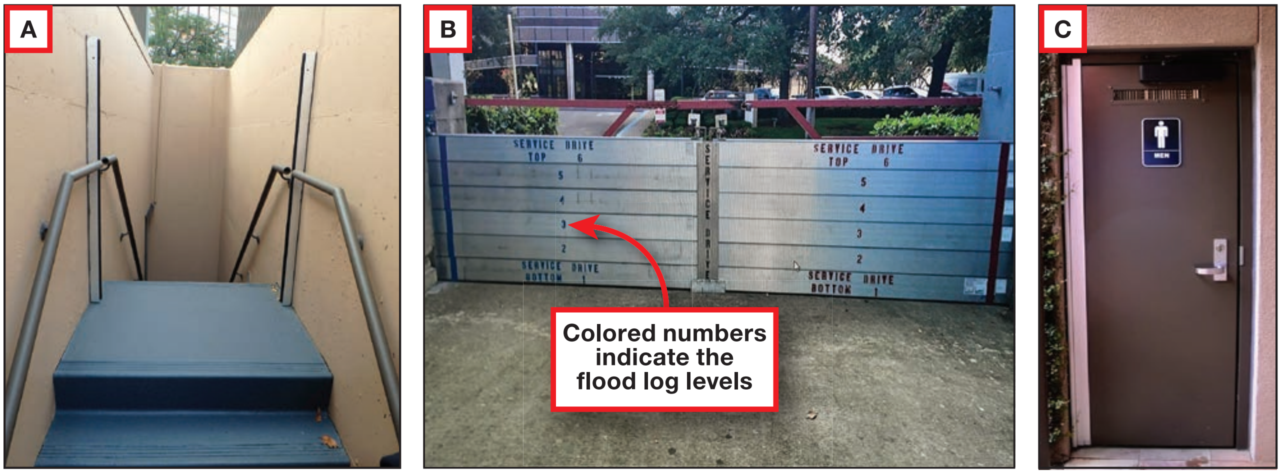


Figure 3-85:
FIRM for Four Leaf Towers Condominium Complex

Dry Floodproofing Mitigation Measures

At-grade portions of the Four Leaf Towers complex flooded from stormwater sheet flow during the Memorial Day and Tax Day Floods in 2015 and 2016, resulting in significant damage to the facility. After these two events, the property managers studied their grounds to identify areas susceptible to flooding or where water could enter the complex. Flood mitigation included a multi-pronged approach with independent testing of the dry floodproofing mitigation measures to ensure that the components would properly function when tested by a flooding event. Several measures were undertaken by the building managers, as follows:

- **Flood-resistant doors.** Installing seven flood-resistant personnel doors to replace doors for the gym, restrooms near the complex's at-grade level swimming pool and other amenities at the complex, and at pedestrian access points to the parking area.
- **Flood barrier.** Installing a flood log system at the top of the loading dock ramp and in a stairwell that provides access to the parking garage (see Figure 3-86).
- **Training.** Initiating a program of annual practice exercises. The building manager holds an annual exercise to implement the emergency operations plan with all building staff, including maintenance personnel and gardeners, to practice installing all of the dry floodproofing measures, recording the time it takes to install each component as well as the overall system. The training exercise is held in April because of its proximity to hurricane season, which allows any issues identified during the training, such as worn gaskets or missing components, to be fixed before any severe weather is likely to occur. Because flooding can occur with little warning, having multiple groups of people that know how to install the dry floodproofing measures and understand the installation time of each component is imperative.



Colored numbers indicate the flood log levels

[A] Stairwell that provides access to the parking garage with flood log system and pedestrian flood door, the bottom of which forms a redundant system.

[B] Flood log system installed at the top of the loading dock access ramp.

[C] Flood door at one of the at-grade bathrooms.

Figure 3-86: Examples of active and passive flood barriers at Four Leaf Towers

Performance during Harvey

At-grade areas. During Hurricane Harvey, stormwater sheet flow backed up in the at-grade swimming pool and amenities area, resulting in a flood depth of approximately 3.5 feet. Figure 3-87 shows the HWM that resulted from the flooding. The flood doors in those areas protected the restrooms and gym, which sustained only minor water seepage.

Parking garage. Within the stairwell providing access to the parking garage, the flood logs were loaded with approximately 6 inches of water; no water was reported inside the parking garage.

Loading dock. The location of the flood log at the top of the loading dock access ramp was not exposed to the stormwater sheet flow and was not tested as a result.

Effect on operations. The condominium complex escaped Hurricane Harvey with only minor damage to exterior finishes in the at-grade areas.

Figure 3-87: HWM near the swimming pool at the Four Leaf Towers condominium complex

Summary of MAT Observations

- The Four Leaf Tower condominium complex is located in Unshaded Zone X, outside of the SFHA, and is thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- Building damage from the 2015 Tax Day and 2016 Memorial Day Floods resulted in the performance of a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures.
- Independent testing of the dry floodproofing mitigation measures ensured they would properly function when tested by a flooding event.
- After previous flooding events, the building manager developed an extensive emergency operations plan and instilled a culture of preparedness that resulted in the complex being well prepared for Hurricane Harvey.

- The dry floodproofing components and mitigation activities performed at Four Leaf Tower condominium complex provided a comprehensive flood barrier, performing as designed during Hurricane Harvey. The building experienced only minor damage to exterior finishes in the at-grade areas.

3.2.9 Starbucks at 4660 N. Braeswood

STARBUCKS

FIRM = Zone AE

BFE = 53.2 feet

(see Figure 3-89)

The drive-through Starbucks coffee shop, constructed in 2016, is located along North Braeswood Boulevard. The building is located in Zone AE (see Figure 3-88), with a BFE of 53.2 feet and a 0.2-percent-annual-chance flood elevation of 54.5 feet. The design of the coffee shop used both elevation on fill and dry floodproofing to achieve the desired level of protection at elevation 54.8 feet, which is 2.67 feet above the finished floor (See Figure 3-89). The 2.67 feet dry floodproofed height resulted in 6 inches of additional freeboard beyond the 1-foot minimum required by ASCE 24. Elevation was achieved by adding approximately 3 feet of soil fill to the building pad, which was the maximum possible increase while maintaining vehicle access to the drive-through from the grade of the adjacent streets.

Sanitary sewer lines discharge by gravity to a municipal main that is reported to be “several feet” below grade (due to the proximity of the local wastewater treatment plant).

Figure 3-88: FIRM for the Starbucks building at 4660 N. Braeswood Boulevard

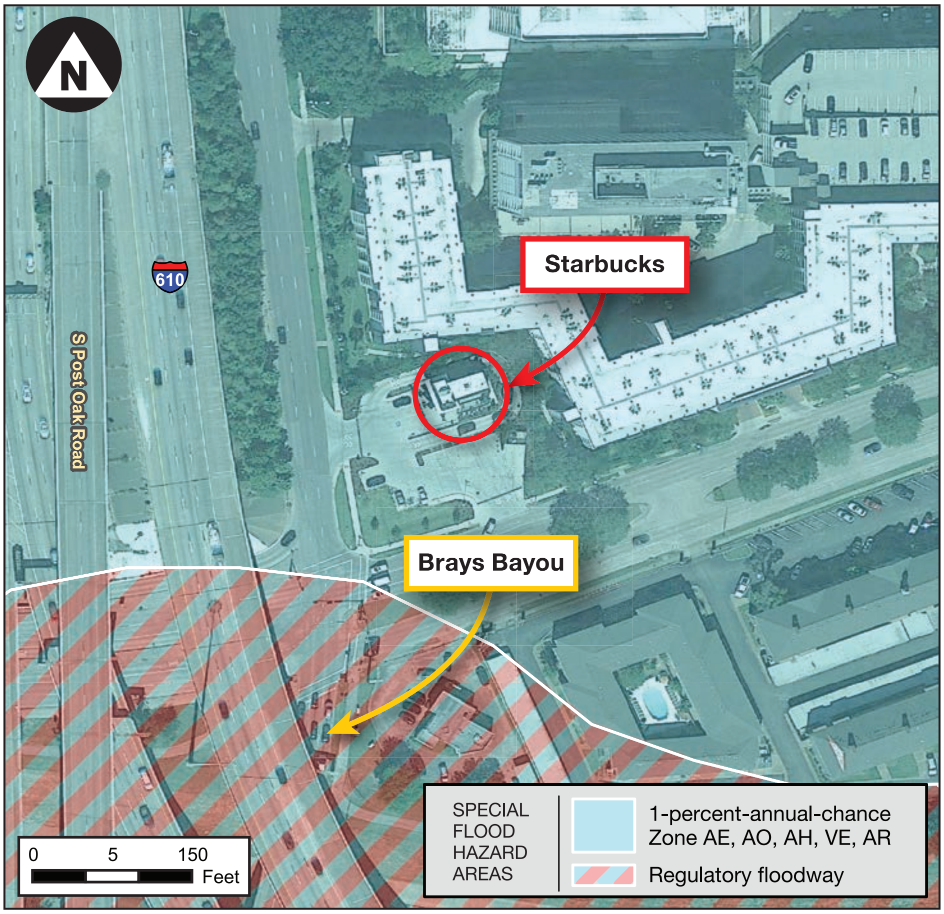


Figure 3-89:
Shows the Starbucks building elevated on fill with dry floodproofing

Dry Floodproofing Mitigation Measures

Several dry floodproofing measures were included in the design and construction of the Starbucks building, as follows:

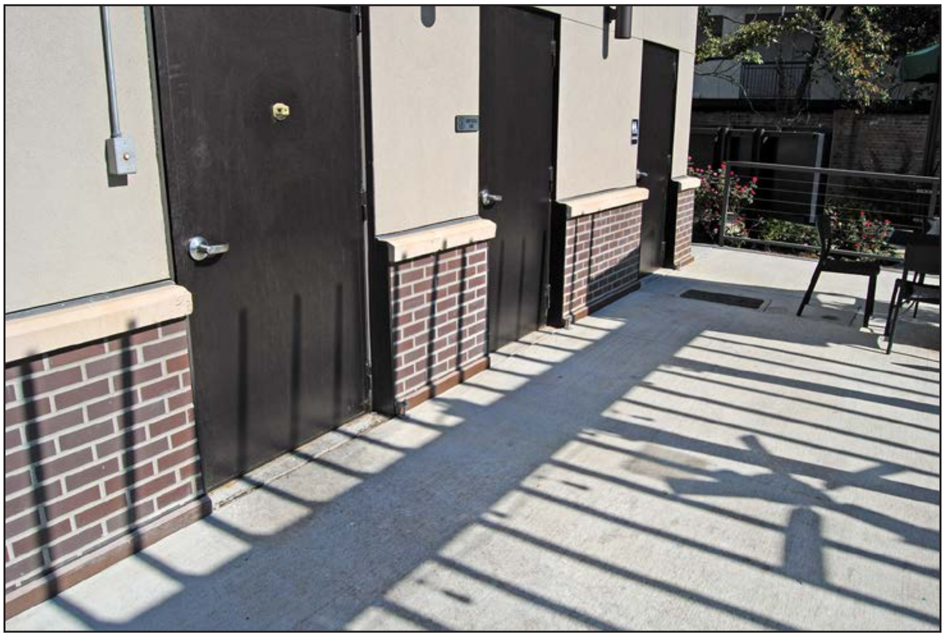
- **Flood barrier.** A flood barrier was created by constructing the lower portions of the exterior walls with fully grouted, reinforced CMUs, with an exterior brick veneer. A membrane was installed in the cavity between the CMU and the veneer (see Figure 3-90). The remaining portions of the building, built on top of the CMU walls, are composed of light-gauge, steel-framed walls that are not designed to prevent floodwater entry.

Figure 3-90:
Membrane installed on the fully grouted and reinforced CMU wall

PHOTOGRAPH COURTESY KEVIN MYERS OF MC MANAGEMENT AND DEVELOPMENT; TAKEN DURING CONSTRUCTION AT THE STARBUCKS FACILITY

- **Flood doors.** Three pedestrian flood doors were installed: one at the employee entrance, one at the store room entrance, and one at the restroom entrance (see Figure 3-91).
- **Sealing.** All of the penetrations through the flood barrier below the DFE were protected.

Figure 3-91: Pedestrian flood doors installed to access restrooms, storage room, and employee entrance



Performance during Harvey

During Hurricane Harvey, floodwater rose to an elevation of 54.2 feet, just below the 0.2-percent-annual-chance flood elevation of 54.5 feet and approximately 2 feet above the finished floor. The floodwater remained at that level for approximately 2 days (see Figure 3-92).

Figure 3-92: Starbucks during Hurricane Harvey flooding

PHOTOGRAPH COURTESY OF KATI SOUTHERN

First floor. Water reportedly entered through floor drains that discharged into the sanitary sewer lines (see Figure 3-93). Water levels within the building reached about 2 inches at the southwest corner of the building, where the floor elevation is lowest (see Figure 3-94).

Effect on operations. Minimal damage was reported for the coffee shop after having been exposed to floodwater for 2 days. Once floodwater receded and the minor water inside the coffee shop was cleaned up, normal business operations resumed.

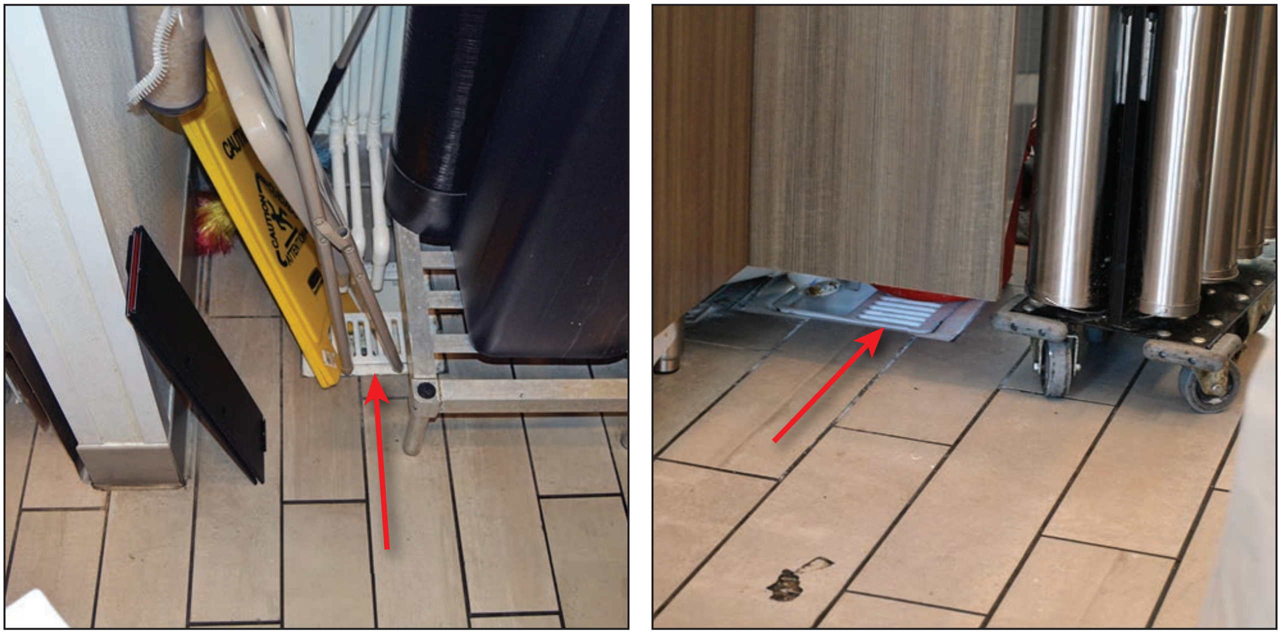


Figure 3-93: Floor drains (red arrows) where floodwater entered

Figure 3-94: Approximate flood levels during Hurricane Harvey on the outside of the building (left) and inside (right)

Summary of MAT Observations

- The Starbucks at 4660 N. Braeswood is located in Zone AE, in close proximity to the floodway, and has a BFE of 53.2 feet. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24.
- Numerous flood risk reduction measures were included in the design and construction of this building in 2016 because of the known flood risk.
- The building was exposed to floodwater for approximately 2 days, but experienced only minor water seepage into the building and minor backflow from the sanitary sewer into the building.
- The additional 6 inches of freeboard incorporated into the design beyond the code minimum of 1 foot of freeboard prevented the dry floodproofing measures from being overtopped and thereby prevented inundation of the building.
- The design of the coffee shop did not incorporate sump pumps or pits to collect and dispose of any seepage into the building. The omission of a sump pump and pit to collect and remove seepage is a violation of the ASCE 24 requirements for a dry floodproofed building.

3.2.10 Texas Medical Center

TEXAS MEDICAL CENTER

FIRM = Zone X and AE

BFE = 43.7 to 40.7 feet

(see Figure 3-96)

The TMC is primarily situated in southwest Houston along the north bank of Brays Bayou, with some facilities expanding to the other side; buildings on the TMC are located in either the Shaded Zone X or Zone AE (buildings located closer to the bayou) (see Figure 3-95).

The MAT selected the TMC as an example of essential hospital/medical and support facilities that had integrated dry floodproofing measures into their facilities. The MAT visited six of the TMC member institutions. The specific TMC facilities visited were selected based on several factors, including size, whether the specific facility was known to have implemented dry floodproofing mitigation measures, whether the installed mitigation measures were tested during Hurricane Harvey, whether FEMA funds were used for the installed mitigation measure, and whether the MAT was able to arrange access. Figure 3-96 shows the locations of the facilities visited by the MAT.

The dry floodproofing measures at TMC were mostly implemented after Tropical Storm Allison in 2001. Much, but not all, of the flood mitigation implemented at TMC facilities was funded through either FEMA Public Assistance (406 Mitigation) or the FEMA Hazard Mitigation Grant Program (404 Mitigation).

TEXAS MEDICAL CENTER

The TMC was established in the 1940s with funds from the MD Anderson Foundation and has grown to be the largest medical, patient care, research, and educational complex in the world. Currently, the TMC is made up of 59 member institutions, including world-renowned hospitals, academic institutions, and support service institutions. Although the overarching TMC umbrella organization provides a variety of services to its member institutions, including a police force, property management, and parking, the member institutions operate largely autonomously from one another.

The largest member institutions are:

- Baylor College of Medicine
- CenterPoint Energy Grant Substation
- CHI St. Luke's Health
- Harris Health System Ben Taub Hospital
- Houston Methodist
- Memorial Hermann
- Michael E. Debakey Veterans Affairs Medical Center
- Rice University
- Texas A&M University Health Science Center
- Texas Children's Hospital
- Texas Heart Institute
- The University of Texas Health Science Center at Houston
- The University of Texas MD Anderson Cancer Center
- The University of Texas Medical Branch at Galveston
- Thermal Energy Corporation (TECO) Paul G. Bell, Jr. Energy Plant
- University of Houston

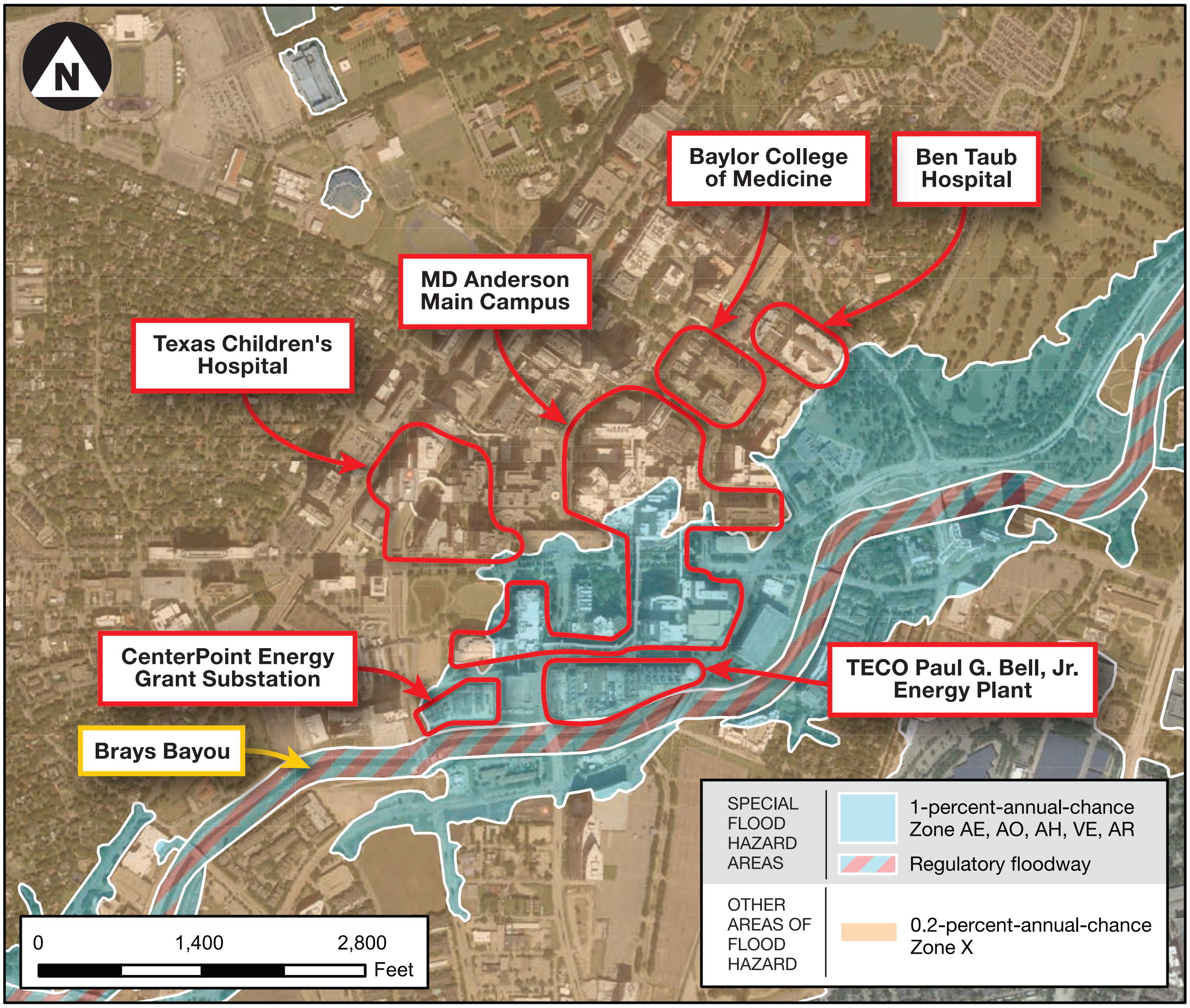


Figure 3-95: FIRM for TMC

Historic Flood Levels at TMC

A stream gage is located at the outlet of the Harris Gully box culvert where it feeds into Brays Bayou at the east side of TMC. The Harris Gully box culvert is a system of underground stormwater collection pipes and culverts that collects surface stormwater from throughout the TMC and Rice University area. The stormwater collection system was improved after Tropical Storm Allison in 2001 to lower flood levels on the TMC campus. Data for the stream gage at the Harris Gully box culvert are available from the Harris County Flood Warning System website and are summarized in Table 3-9, which shows various probability of exceedance with the associated MRI and flood elevations for the Harris Gully gage location. Probabilities are given as the annual chance of the site experiencing a flood event that meets or exceeds a given flood elevation.

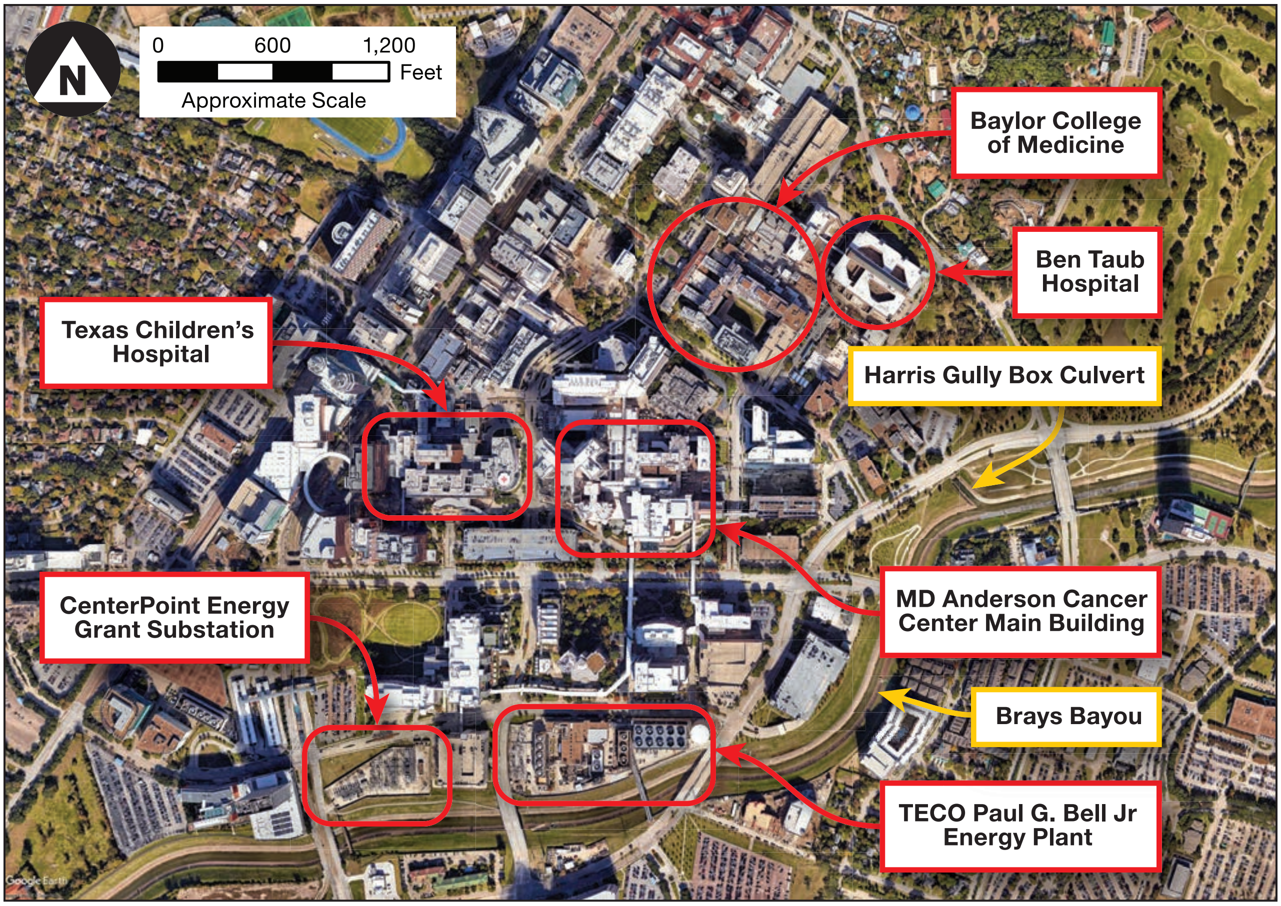


Figure 3-96: Locations of facilities observed by the Harvey MAT at TMC

Table 3-9: General Flood Information Measured at Harris Gully Box Culvert

Harris Gully Box Culvert				
Annual chance of exceedance	10%	2%	1%	0.2%
MRI	10 years	50 years	100 years	500 years
Flood elevation	34.9 feet	38.2 feet	39.9 feet	43.0 feet

MRI = mean recurrence interval

SOURCE: HCFCD, 2018A

The MAT compared historic flood levels at the Harris Gully box culvert to published flood elevations to determine the approximate MRIs for those events recorded at the Harris Gully box culvert stream gage. Table 3-10 lists the six most severe flood events in the last 20 years, including Hurricane Harvey, and their approximate MRIs at the Harris Gully box culvert. Data are not available for Tropical Storm Allison at this stream gage.

Based on the available data for the Harris Gully box culvert, the rainfall from Hurricane Harvey was a record setting event with a HWM of 41.5 feet and was a 0.42-percent-annual-chance-of-exceedance event. In comparison, a Harris County stream gauge along Brays Bayou just upstream of the TMC at South Main Street indicates a HWM of 45.70 feet, matching the 1-perecnt-annual-chance-of-exceedance event for that section of Brays Bayou and exceeding the Tropical Storm Allison HWM of 42.91 feet.

Table 3-10: Past Flood Events and Their Approximate Mean Recurrence Intervals

Event Name	Date	Harris Gully Box Culvert		
		Maximum Flood Elevation	Approximate MRI[(a)]	Annual Chance of Exceedance
Hurricane Harvey	08/27/2017	41.5 feet	235 years	0.42%
[No name]	01/18/2017	35.3 feet	12 years	8.3%
Tax Day	04/18/2016	37.4 feet	33 years	3.0%
Memorial Day	05/26/2015	38.0 feet	44 years	2.3%
[No name]	01/19/2012	36.1 feet	18 years	5.5%
Hurricane Ike	09/13/2008	34.0 feet	6 years	16.7%

(a) The MRIs (mean recurrence intervals) were determined using regression analysis whereby a best-fit curve was selected to model the data and compared to the published flood elevations. A logarithmic curve was selected, which produced a coefficient of determination (R2 value) of 99.9 percent.

SOURCE: BASED ON DATA FROM HCFCD, 2018A

TMC Operational Impact and Response

In general, the majority of facilities at TMC suffered only a minimal amount of floodwater intrusion and damage during Hurricane Harvey. This was a result of the facilities owners' proactive approaches to flood hazard mitigation over the past 15 to 20 years, rigorous emergency preparedness policies and procedures, and the significant amount of channel capacity improvements to the Harris Gully box culvert and Brays Bayou.

At several of the TMC facilities visited, the MAT discussed emergency planning activities and operational impacts before, during, and after Hurricane Harvey with key management contacts. As previously noted, the majority of the TMC facilities were damaged by Tropical Storm Allison, and facility emergency preparedness and response activities typically incorporated the lessons learned from that event. Given all the mitigations measures that had recently been implemented and/or improved upon at the respective TMC facilities, in combination with the lack of alternative options for critical patient care, most of the TMC facilities "defended in place." Typical preparatory activities included:

ELECTRICAL UTILITY RELOCATION MANDATE

After Tropical Storm Allison, TMC and CenterPoint Energy mandated that all buildings at the TMC had to elevate their electrical equipment to above the BFE if they wanted to remain connected to the electrical grid during a flood event to minimize the chance that an electrical failure at one building would cause electrical issues at another building.

- Canceling surgeries and other procedures 2 to 3 days before Hurricane Harvey's landfall
- Modestly reducing patient load (10 to 20 percent per hospital)
- Activating "ride-out" procedures and staff

3.2.10.1 Texas Children's Hospital (TCH)

Texas Children's Hospital (TCH), located at 6621 Fannin Street, consists of six buildings at the southwest corner of the TMC campus (see Figure 3-97). All of the buildings that make up the TCH campus are situated in a Shaded Zone X (see Figure 3-98). The concrete buildings, with construction dates between 1987 and 2017, consist of the following:

- The Pavilion for Women (16 stories + 4 basement parking stories)
- Legacy Tower (26 stories + 4 basement parking stories)
- Wallace Tower (17 stories + 4 basement parking stories)
- West Tower (21 stories + 2 basement stories)
- Abercrombie Building (8 stories + 2 basement stories)
- Feigin Tower (20 stories)

TEXAS CHILDREN'S HOSPITAL

FIRM = Shaded Zone X

(see Figure 3-99)

Figure 3-97: Texas Children's Hospital aerial view looking north

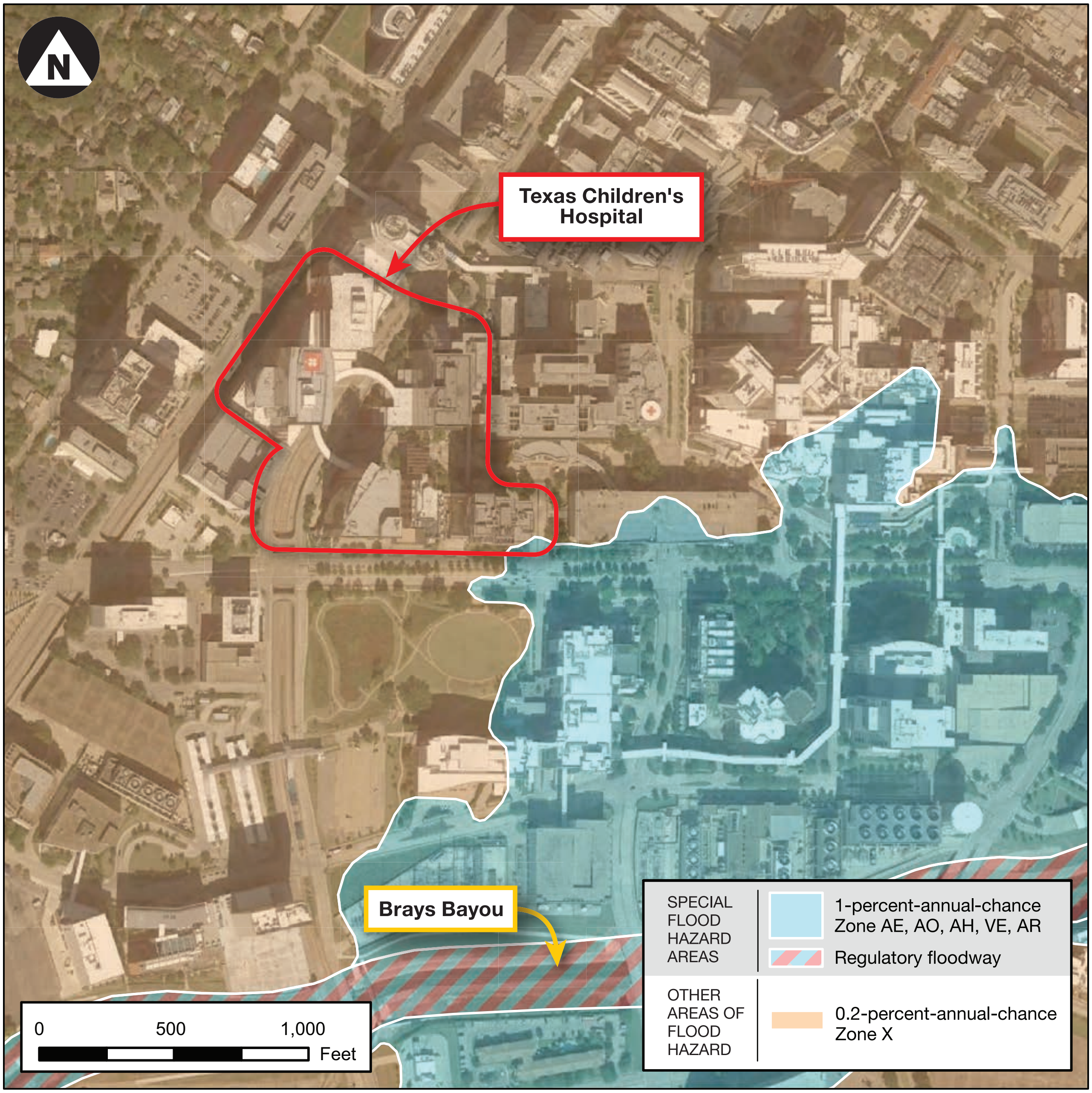


Figure 3-98: FIRM for Texas Children's Hospital

TCH is the largest specialty pediatric hospital in the United States with 851 licensed beds and 16,000 employees. It is affiliated with the Baylor College of Medicine and has three hospitals and eight urgent care centers. TCH is the only tertiary pediatric hospital in the region, so it had to remain open during Hurricane Harvey and was not able to transfer its specialty and critical patients because there were few other facilities in the region that could care for them.

Pre-event activities included slightly reducing the number of patients, cancelling elective procedures 36 hours before landfall, arranging for full staffing with staff support services, and focusing on care for vulnerable populations.

Dry Floodproofing Mitigation Measures

In the late 1990s to early 2000s, TCH installed a series of dry floodproofing submarine doors in its basement to address their flood vulnerability. The installation of these submarine doors was certified 3 weeks before Tropical Storm Allison struck the area. These submarine doors in the basement were closed in advance of the storm and successfully isolated the flooding during Tropical Storm Allison to the second basement level, which filled with 8 feet of water. As a result of the flooding, TCH lost primary power, but was able to remain operational using back-up power systems. During Tropical Storm Allison, TCH accepted patients evacuated from neighboring hospitals. Flooding in the basement of TCH resulted in approximately $30 million in damages, whereas neighboring hospitals sustained damages in excess of $100 million.

After Tropical Storm Allison, another flood vulnerability assessment was performed to identify areas to be protected resulting in the implementation of a variety of flood mitigation measures, described as follows:

Formation of the Tunnel Management Group. Although TCH suffered damage during Tropical Storm Allison due to loss of power, the flooding that occurred in the basement of TCH during Tropical Storm Allison entered through the Houston Methodist Neurosensory building tunnel, whose gate was not completely installed prior to the event. The basement levels of TCH are connected to its neighbors, Houston Methodist and CHI St. Luke's Health, via a series of tunnels.

As a result of the flooding that occurred during Tropical Storm Allison, these three facilities formed a Tunnel Management Group to facilitate working together to protect the tunnel system from floodwater intrusion. The Tunnel Management Group has taken planning and mitigation steps to improve coordinated efforts, such as developing an agreement that allows any one of the organizations to close any of the flood doors or floodgates that protect the tunnel system.

Flood doors, floodgates, and sump pumps. Flood doors and floodgates were installed to prevent flooding of the tunnel system. The tunnel is designed to direct any water that enters the tunnel to drain to a low point where sump pumps remove the water. Additionally, the tunnel is composed of flood damage-resistant materials to minimize any damage that may occur (see Figure 3-99).

Figure 3-99: Flood doors in basement tunnel (left) and below-grade parking garage (right)

Figure 3-100: Flood log gate (left) and swing floodgate (right) at parking garage entrances

Additionally, surface level floodgates were installed to protect the access points to below-grade areas. Examples of surface level floodgates are shown in Figure 3-100.

Elevation. Utilities, MEP components, and back-up generators that were located in the basement were elevated. The electrical components were elevated to comply with the TMC and CenterPoint Energy mandate.

Monitoring. Continuous flood monitoring systems through a 24-hour central operations facility are used to monitor and forecast incoming storms. Elements of TCH's emergency plan are triggered at different benchmarks, but important preparations, such as ensuring the availability of sufficient supplies and staffing, are typically reviewed 72 to 96 hours prior to the anticipated arrival of a storm. TCH staff reportedly began tracking Hurricane Harvey 12 days in advance of landfall when the storm was first forecast as a tropical wave.

Planning. Prior to an event, TCH undertakes advanced placement of materials and staffing. TCH rented additional potable water tanker trucks to supplement on-site storage tank supplies. In addition, construction crews and water remediation crews were placed under contract and housed on site during the storm. TCH also stockpiled drywall in advance of the storm so that crews could begin repairs immediately when the storm passed.

Preparedness. TCH management instills a culture of preparedness, including regularly scheduled preparedness exercises. This culture of preparedness, supporting by buy-in from executive-level management, contributed greatly to the successful performance of this facility and its operations during Hurricane Harvey.

Performance during Harvey

Staff implemented emergency preparedness procedures well in advance of the storm and were prepared to ride out the storm. TCH did not evacuate any patients and did not turn away any patients, although there appears to have been some miscommunications with emergency medical service providers about the hospital's status.

Water depth in the streets around the TCH was reported as 3 feet, but water never rose high enough to get close to any of the buildings or any of the flood barriers. Various leaks at the facility due to wind-driven rain were reported, and some floor drains in the basement and stairwells became overwhelmed by rainfall, but these water intrusions were effectively managed.

Effect on operations. The TCH facility was only minimally impacted by Hurricane Harvey. It never lost services or the ability to provide patient care during the event. TCH put numerous mitigation measures in place to deal with an event such as Hurricane Harvey. The mitigation measures, which were not fully tested by Harvey, performed well.

Summary of MAT Observations

- The buildings that make up the TCH are located in Shaded Zone X outside of the SFHA, and are thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- Building damage from Tropical Storm Allison resulted in the performance of a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures.
- Based on previous flooding events and goals of providing healthcare in all conditions, hospital management has instilled a culture of preparedness that is reinforced by annual training exercises.
- TCH developed an extensive emergency operations plan for hurricanes that had the hospital well prepared for the event.
- TCH installed numerous mitigation measures in place to deal with an event such as Hurricane Harvey. The mitigation measures, which were not fully tested by Hurricane Harvey, performed well.

3.2.10.2 The University of Texas MD Anderson Cancer Center

The MD Anderson Cancer Center consists of three campuses: the north, mid, and south. The north campus is located north of Brays Bayou, within the encompassing TMC, while the mid-campus and south campus are both located south of Brays Bayou. The combined MD Anderson Cancer Center facilities at TMC consist of over 16 million square feet of space. The MD Anderson Cancer Center is a specialty hospital for cancer care with more than 600 beds and 20,000 employees.

MD ANDERSON CANCER CENTER

FIRM = Zone AE
and Shaded Zone X

(see Figure 3-103)

The north campus facilities, centered around the Main Building, are located at 1515 Holcombe Boulevard and consist of numerous independent buildings, including outpatient clinics, research facilities, and a radiation outpatient center. The buildings of the MD Anderson north campus are connected to one another by above-ground pedestrian walkways, but are not connected to any other TMC institutions (see Figure 3-101 and Figure 3-102).

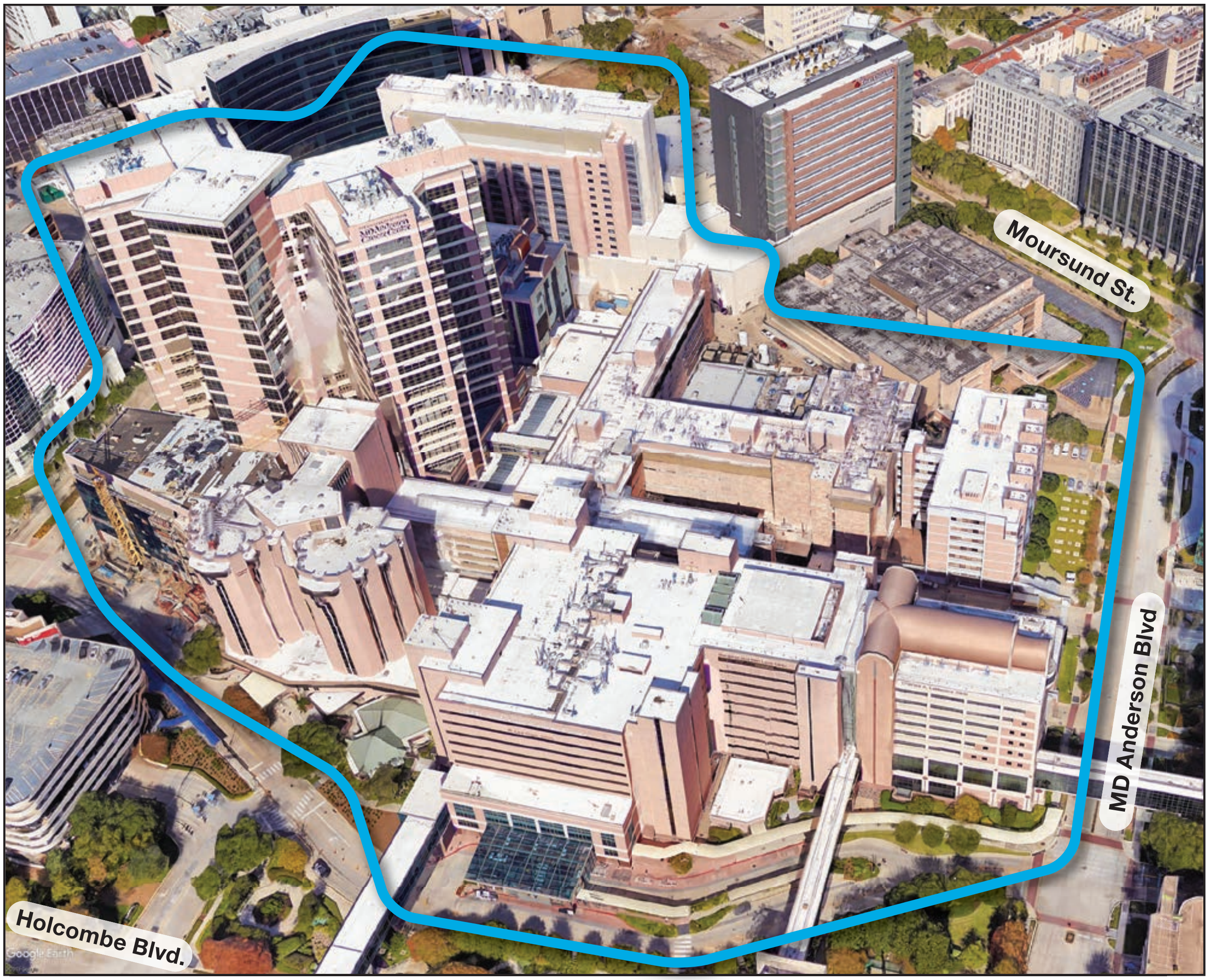


Figure 3-101: Aerial view of the MD Anderson Cancer Center north campus looking north

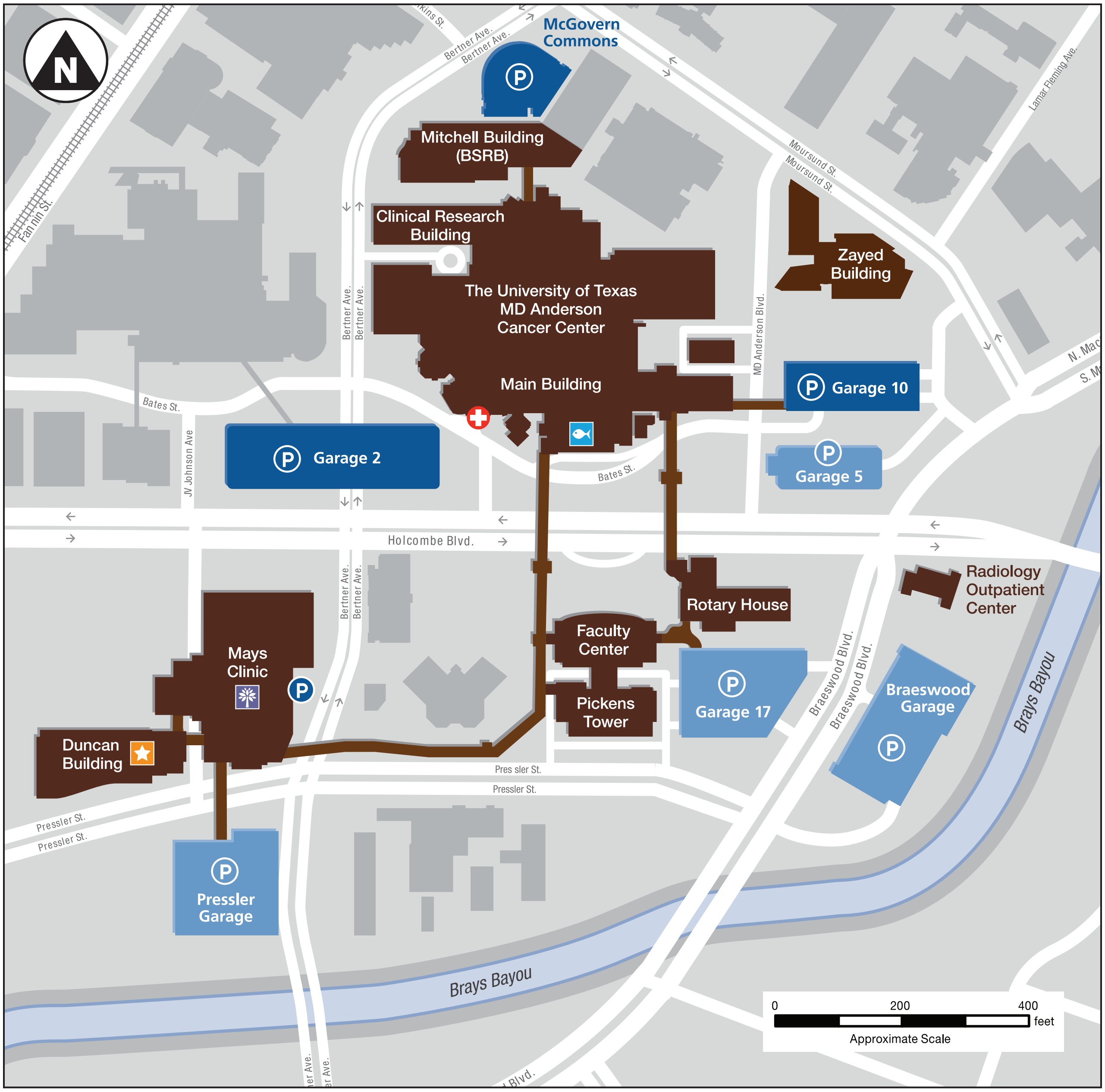


Figure 3-102: Map of the MD Anderson Cancer Center north campus

MAP SOURCE: OBTAINED FROM MD ANDERSON CENTER, USED WITH PERMISSION

Most of the north campus facilities are situated in Zone AE, including the Main Building, and the rest are in Shaded Zone X. The facilities on the north campus have different BFEs, depending on location. The mid-campus administrative building and a number of research buildings at the south campus facility are located in Shaded Zone X and Unshaded Zone X south of Brays Bayou. The north and mid-campus areas are shown on Figure 3-103.

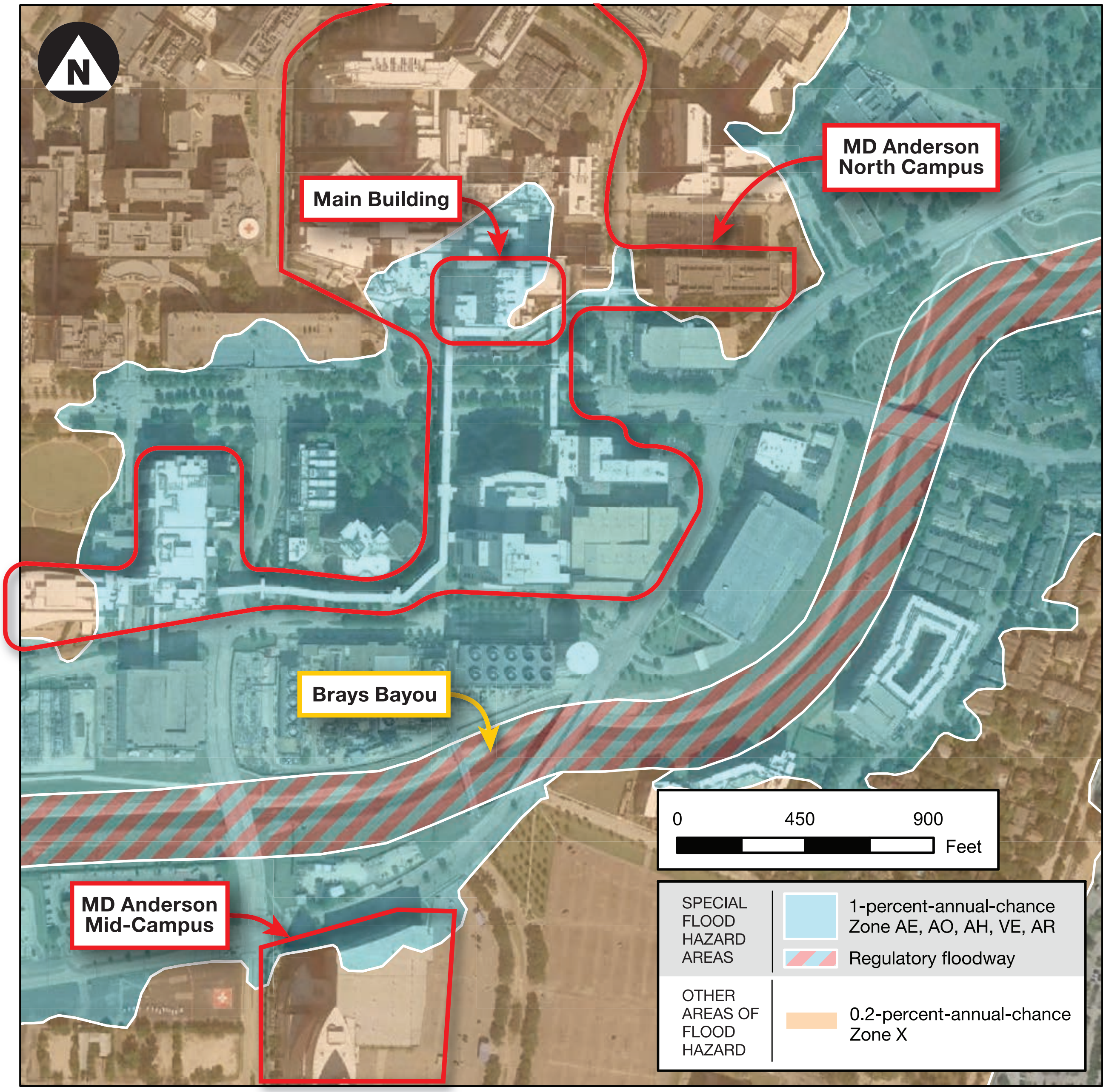


Figure 3-103: FIRM for MD Anderson Cancer Center north campus and mid-campus buildings along Brays Bayou

Dry Floodproofing Mitigation Measures

During Tropical Storm Allison in 2001, the MD Anderson Cancer Center lost power and experienced minor flooding and damage. After 2001, a flood vulnerability assessment was conducted to identify locations where water can infiltrate the Main Building. Subsequently, many flood mitigation measures have been implemented on the MD Anderson Cancer Center campus, primarily at the Main Building. Additionally, several of the MD Anderson Cancer Center buildings were constructed after Tropical Storm Allison and as a result, were designed with finish floor elevations and utilities elevated above the 0.2-percent-annual-chance flood elevation. These newer buildings include a few on the north campus (Mays Clinic, Duncan Building, and Pickens Tower), all the mid-campus buildings, and most of the south campus buildings. A description of implemented flood mitigation measures follows:

Perimeter floodwall, floodgates, and sump pumps. A complete perimeter floodwall (see Figure 3-104) with more than 75 active and passive floodgates (see Figure 3-105) was installed to provide protection against a 0.2-percent-annual-chance-of-exceedance event. After installation of the perimeter floodwalls, sections with aquarium glass and passive floodgates were independently tested to ensure adequate performance. Sump ejector pumps were installed throughout the campus behind the flood barrier.

Figure 3-104: Marble-faced floodwall (left) and aquarium glass windows in floodwall (right) at the Main Building

Figure 3-105: Passive floodgates (red arrows) at entrances through floodwall at the Main Building

Flood doors. Basement-level flood doors (see Figure 3-106) were installed to compartmentalize different areas if the basement were to become subject to flooding.

Figure 3-106: Flood doors in basement that subdivide basement areas within the Main Building

Elevation. All utilities and backup generators were elevated to upper floors. The electrical components were elevated to comply with the TMC and CenterPoint Energy mandate.

Monitoring. Continuous flood monitoring systems through a central operations facility, located in the Main Building, are used to monitor and forecast incoming storms (see Figure 3-107). Elements of MD Anderson Cancer Center's emergency plan are triggered at different benchmarks, but important preparations, such as ensuring sufficient supplies and staffing, are typically reviewed a few days in advance of a predicted storm.

Figure 3-107: Central operations 24-hour facility that provides continuous flood monitoring

Preparedness. The MD Anderson Cancer Center management instills a culture of emergency preparedness, including regularly scheduled preparedness exercise. These drills are unannounced and timed; due to the number of gates in the dry floodproofing system, only 10 gates are closed during the any individual drill. These drills are conducted until each gate in the dry floodproofing system has been closed. Maintenance on the gates is performed twice a year, before and after hurricane season, and sump pump maintenance is performed quarterly. This culture of preparedness, supported by buy-in from executive-level management, contributed greatly to the successful performance of this facility and its operations.

Performance during Harvey

Four days before the storm arrived in Houston, the MD Anderson Cancer Center's Incident Command team started making organizational decisions about the institution. Incident Command processes were in place during the storm and into recovery. Rotations were in place to allow the Incident Command team and others to rest during the event and through the post-storm recovery process. The north campus buildings are connected to one another by above-ground pedestrian walkways. During events such as Harvey, the outer buildings such as the Mays Clinic, Duncan Building, and Pickens Tower are staffed only to the extent required to maintain critical services; the other staff and support personnel relocate to the Main Building, which is where the in-patient functions are housed and is therefore critical to providing continued services.

Two days prior to Hurricane Harvey's landfall, MD Anderson Cancer Center personnel removed trash and hazardous waste from its campus; inspected the roofs of all buildings for possible debris sources and removed any items found; verified that rooftop equipment was properly secured; and began the process of installing active floodgates and manually raising the passive floodgates.

During Hurricane Harvey, the north campus of MD Anderson Cancer Center was entirely cut off by floodwater for just over 2 days, with no access to additional food, supplies, or municipal water.

Utility service and patient care. None of the buildings on any of the campuses of the MD Anderson Cancer Center lost utility service or the ability to provide patient care during Hurricane Harvey. Staff implemented their emergency preparedness procedures well in advance of the storm and were prepared to ride out the storm. As part of these procedures, elective procedures and admissions were cancelled and patients were discharged as rapidly as possible, enabling a reduction of their in-patient census to 540 patients and allowing staff to be reduced to a designated "ride-out" team of 1,000. MD Anderson Cancer Center personnel brought patients who were being treated with daily chemotherapy into the main facility so that they would not miss any of their treatments as a result of storm-related travel impacts. They did not evacuate any patients and did not turn away any patients.

At-grade areas. Portions of the Main Building were surrounded by approximately 3 feet of water in the streets (see Figure 3-108), but water never rose high enough to threaten the building or any of the flood barriers. Approximately 6 inches of water was reportedly up against the flood barriers in certain locations.

Figure 3-108:
Water level on Bates Street outside of MD Anderson Cancer Center north campus at the Main Building during Hurricane Harvey

A manhole located on the dry side of the floodwall at the southwest corner pavilion drop-off area whose cover blew off because of overpressure from the stormwater sump pump system was a point of failure. This resulted in minor flooding in the building lobby. Other sources of water infiltration in the Main Building included:

- Water flow through a conduit that connected to utility vault in the street on the other side of the floodwall.
- Wind-driven rain that entered the buildings in the north campus.

Effect on operations. The MD Anderson Cancer Center was only minimally impacted by Hurricane Harvey. At the time of the MAT visit, all damage had been repaired and all areas were functioning normally.

Thirty-five percent of the staff was directly affected by the floods and much of the staff was working long hours, the hospital brought in additional clinical staff (after flooding receded) from other hospitals, such as:

- University of Texas (UT) Southwestern – a fellow UT system institution in Dallas
- Banner MD Anderson Cancer Center – an MD Anderson Cancer Network® partner in Phoenix, AZ
- OhioHealth – an MD Anderson Cancer Network–certified member in Columbus, OH
- Northwell Health – a network of health care facilities based in New York

Summary of MAT Observations

- The buildings that make up the MD Anderson Cancer Center are located in Shaded Zone X or Zone AE; their BFEs vary, depending on their location along Brays Bayou. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- Building damage from Tropical Storm Allison resulted in the performance of a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures.
- Independent testing of the dry floodproofing mitigation measures ensured they would properly function when tested by a flooding event.
- Based on previous flooding events and goals of providing healthcare in all conditions, hospital management has instilled a culture of preparedness that is reinforced by annual training exercises. The annual exercises are unannounced and the time to install each component and the entire dry floodproofing system is timed.
- MD Anderson developed an extensive emergency operations plan for hurricanes that had the hospital well prepared for the event.
- MD Anderson installed numerous mitigation measures to deal with an event such as Hurricane Harvey. The mitigation measures performed as designed. MD Anderson escaped Hurricane Harvey with only minor damage to interior finishes in the main building.

3.2.10.3 Harris Health System Ben Taub Hospital

The Ben Taub Hospital, located at 1504 Taub Loop, is located at the east side of the TMC campus just west of the Houston Zoo and Hermann Park (see Figure 3-109). The site is situated in a Shaded Zone X (see Figure 3-110). The hospital has one basement story and six above-ground stories. The building was originally built in 1963, with an addition in 1990 and major remodel in 2014.

BEN TAUB HOSPITAL

FIRM = Shaded Zone X

(see Figure 3-111)

The Ben Taub Hospital is a 586-licensed-bed facility (450 staffed) with an elite Level 1 trauma center that is part of the Harris County Hospital District Ben Taub is staffed by the faculty, residents, and students from Baylor COM and is one of the most active hospitals in southeast Texas, with over 100,000 emergency department visits annually. Ben Taub is also an important psychiatric facility for the region.

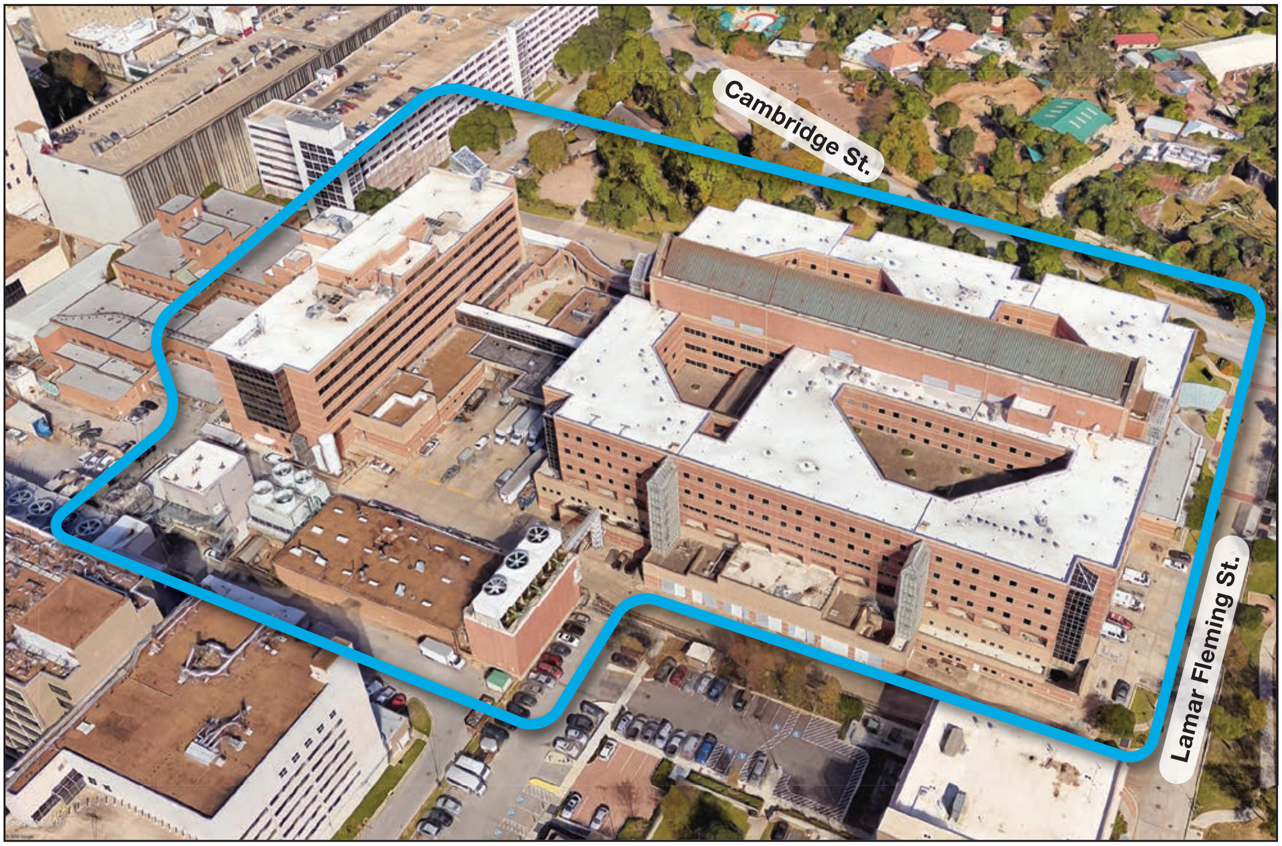


Figure 3-109: Harris Health System Ben Taub Hospital aerial view looking north

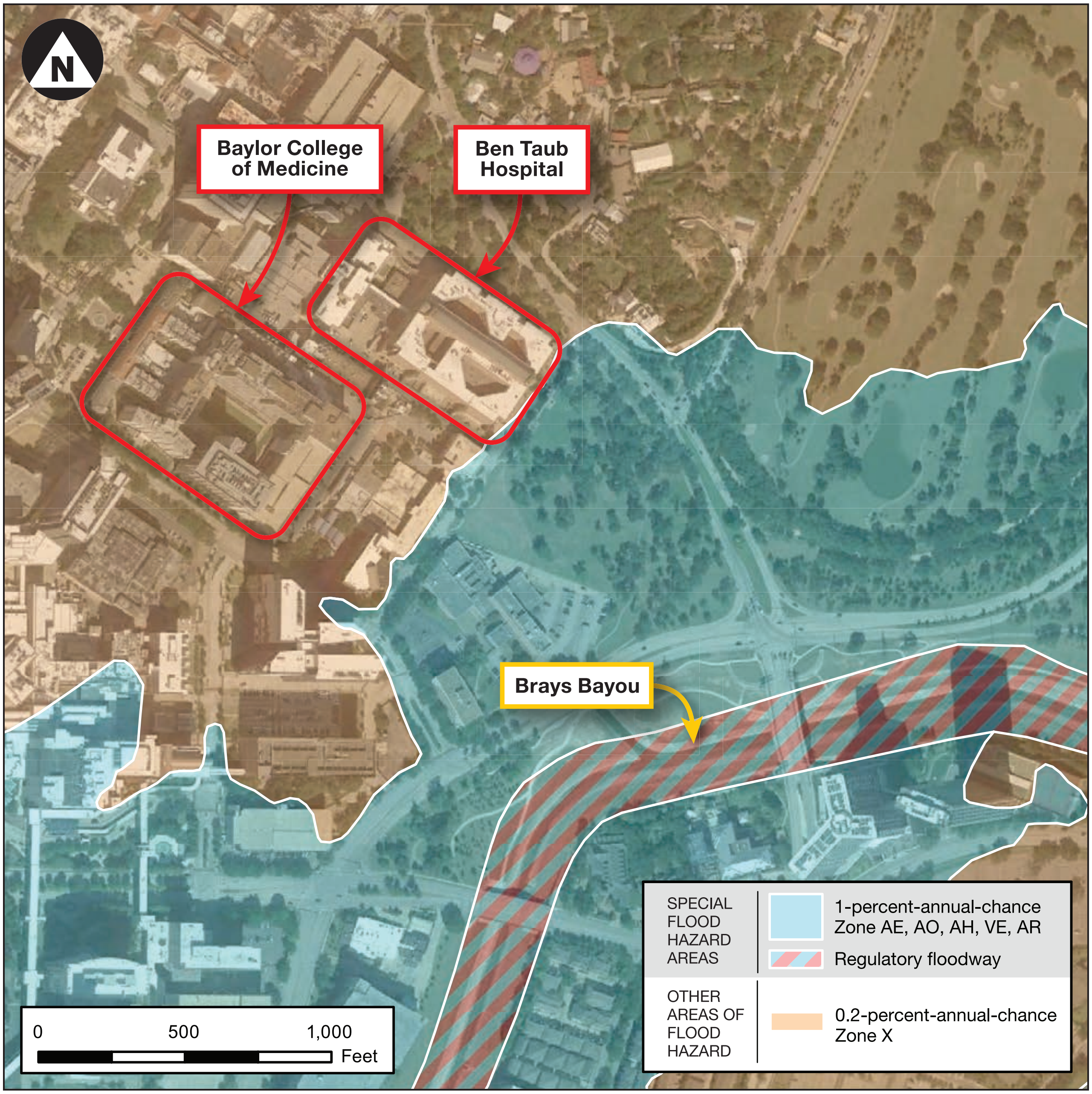


Figure 3-110: FIRM for Ben Taub Hospital and Baylor College of Medicine

Dry Floodproofing Mitigation Measures

During Tropical Strom Allison, Ben Taub Hospital temporality lost power but did not sustain any flood damage. The hospital does not have any surface floodgates or surface dry floodproofing measures; it is located on the highest grade elevation in the TMC. The Harris County Emergency Management Office provides much of the hazard mitigation planning and flood control at the site. The hospital is connected with the Baylor COM building through a single basement tunnel. This tunnel is equipped with a submarine door designed to protect Baylor's basement from flooding with water from the Ben Taub tunnel (see Figure 3-111) or vice versa.

Figure 3-111: Basement tunnel submarine door between Ben Taub Hospital and the Baylor College of Medicine (viewed from Ben Taub)

Performance during Harvey

During Hurricane Harvey, floodwater came within approximately 6 inches of the first floor elevation of Ben Taub Hospital but did not breach the perimeter.

Basement. Portions of the basement flooded as a result of two pipe breaks caused by backflow overpressures. Stormwater from the Ben Taub and other at-grade storm drains discharge to a stormwater tank operated by Harris County. When water levels in Brays Bayou prevent gravity drainage, stormwater collects in a tank and is then pumped into Brays Bayou. During Hurricane Harvey, the pumps to remove the stormwater from the tank malfunctioned, causing the tank to completely fill with water, pressurizing all of the connecting stormwater lines and causing the two stormwater pipes inside Ben Taub Hospital to break. After the pipe break, maintenance personnel from Harris County were contacted and dispatched to manually start the stormwater pumps. Once back pressure in the system was reduced, hospital facility engineers were able to repair the broken pipes and stop the flow of water.

Food service. Floodwater in the basements from the broken pipes destroyed approximately 30 percent of the hospital's food stores and other service-related items. As a result of the losses to the food stores and other supplies, hospital staff attempted to transfer five patients in the Intensive Care Unit. However, the intense flooding throughout the Harris County region forced them to bring three of the transfers back to the hospital within 2 hours of their original departure. The hospital was unable to admit new patients or conduct procedures for 7 days following the event.

Utility service. Water from the broken pipes damaged an electrical panel that controls the production of chill water. Chill water production halted, forcing the air conditioning in the hospital to turn off. In the days after Hurricane Harvey, indoor temperatures reached 88 degrees Fahrenheit (°F).

Effect on operations. Water also came close to other electrical equipment, which could have cut off all electricity to portions of the hospital and would have resulted in an extended shutdown of the hospital. Fortunately, hospital facility engineers were able to channel the floodwater into an auditorium and subbasement areas to protect this electrical equipment and other areas of the basement from floodwater (see Figure 3-112). During the MAT visit, repairs in the basement were still underway, but the hospital was operational.

Figure 3-112: Basement auditorium used as water retention area (left) and reported water level in subbasement indicated by staff member (right)

Summary of MAT Observations

- The buildings that make up the Ben Taub Hospital are located in Shaded Zone X. All of the buildings are located outside of the SFHA and thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.
- The failure of stormwater piping resulted in damage to 30 percent of the food supply in the hospital and shorted out an electrical panel that controlled chill water production.
- Hospital facility engineers were able to fix the broken pipes and prevented the floodwater from damaging electrical equipment that would have caused a significant power failure in the hospital.

3.2.10.4 Baylor College of Medicine (COM)

The Baylor College of Medicine (COM) is located at 1 Baylor Plaza (see Figure 3-113). The site is situated in Shaded Zone X (see Figure 3-110). The Baylor COM Cullen Building was completed in

BAYLOR COLLEGE OF MEDICINE

FIRM = Shaded Zone X

(see Figure 3-111)

1947 and is one of the oldest buildings at the TMC. The campus now contains numerous other buildings providing educational and research facilities for approximately 800 medical students, 1,000 graduate students, 1,000 residents, and 300 allied health students. All of the Baylor COM buildings are immediately adjacent to one another and interconnected by basement tunnels. Baylor COM is connected to the adjacent Ben Taub Hospital (Section 3.2.9.3) via a single underground tunnel.

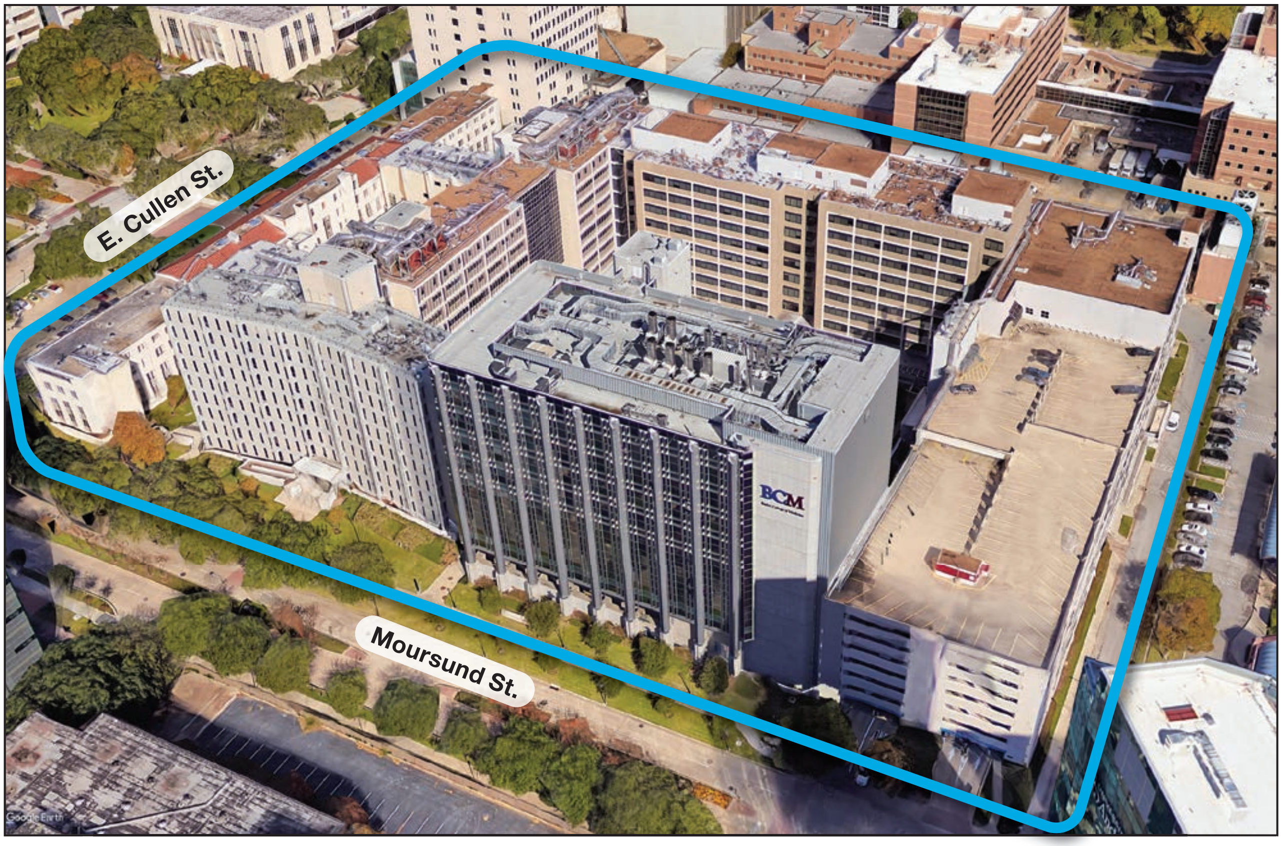


Figure 3-113: Baylor COM aerial view looking north

Dry Floodproofing Mitigation Measures

Baylor COM was significantly impacted by Tropical Storm Allison in 2001. The entire basement flooded because the flood log gates were not installed at the time. Primary and backup power failed, and critical storage freezers stopped, resulting in the loss of 60,000 tumor samples and other critical research specimens that were housed in the basement. Damages from Tropical Storm Allison were estimated at nearly $500 million. With assistance from FEMA's Public Assistance Program (e.g., 406 Hazard Mitigation), approximately $9.1 million was provided to fund dry floodproofing mitigation. Since Tropical Storm Allison, Baylor COM conducted a flood vulnerability assessment and has implemented several flood hazard mitigation projects, as follows:

Floodwall, floodgates, and flood doors. Floodwalls, floodgates, and flood doors were installed to block the intrusion of floodwater (see Figure 3-114). The floodwall surrounding the entire campus was designed and constructed to meet the 0.2-percent-annual-chance probability flood elevation plus 2 feet of additional freeboard. The floodgates in many locations are well designed into the architecture of the site and are not readily apparent.

Figure 3-114: Swing flood door (left) and guillotine floodgate (right)

Sump pumps. The basement has eight different sump pits that are sized to handle water intrusion into the basement (see Figure 3-115). Each sump pit is sized and fitted with a redundant pump. The basement is constructed from flood damage-resistant materials in the areas where water is directed to the sump pits.

Figure 3-115: Typical sump pit in basement (left) and ejection pipes over floodwall (right)

Elevation. Mechanical and electrical utilities were elevated to protect against floodwater (see Figure 3-116 and most research facilities were elevated. The electrical components were elevated to comply with the TMC and CenterPoint Energy mandate.

Figure 3-116: Elevated central plant structure (in red outline)

Performance during Harvey

Baylor COM facilities were only minimally impacted by Hurricane Harvey. All classes were cancelled during the storm to allow students and staff to stay away from campus during the event. The facilities management personnel were stationed on campus to ride out the storm and help set up and maintain the flood mitigation devices to protect the campus. Although management personnel had been monitoring Hurricane Harvey's development several days prior to the arrival of the storm and implementing initial preparedness measures, they did not begin final preparations until the morning of August 26, when it appeared that the impact of Hurricane Harvey was going to be greater than originally forecast.

At-grade. During Hurricane Harvey, the water around the campus was approximately 1 foot above grade at the floodwalls and gates. The seal at one gate failed; however, the water seepage flowed to a sump pit located near the gate.

Basement. A 1940s-era cleanout inside the basement failed due to backflow pressures; the failure was adjacent to one of the new sump pits installed in response to Tropical Storm Allison and it prevented the water from spreading throughout the basement. A mechanical room sump pit failed because a conduit penetration through the floodwall was not properly sealed and leaked water onto the control panel. Water from this area was removed by the redundant pump. The penetration has since been sealed and the control panel has been moved away from the wall. Baylor COM is in the process of relocating all control panels to the interiors of rooms. There was also a small amount of water intrusion into the research area, but staff used a squeegee to move the water to one of the sump pits.

Effect on operations. The facilities never lost any services on site.

Summary of MAT Observations

- The buildings that make up the Baylor COM are located in Shaded Zone X. All of the buildings are located outside of the SFHA and thereby exempt from the flood provisions of model codes and standards such as the IBC and ASCE 24. Although not required, flood-resistant features are recommended as a best practice even for buildings located outside the SFHA, especially those with a history of flooding.

- Building damage from Tropical Storm Allison resulted in the performance of a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures.
- The dry floodproofing components and mitigation activities performed at the Baylor COM provided a comprehensive flood barrier that performed as designed during Hurricane Harvey. Though the building experienced minor areas of water intrusion and pipe breaks there was no significant damage or downtime due to loss of function.
- Providing redundant sump pumps in each sump pit prevented damage from occurring when pumps failed.

3.2.10.5 CenterPoint Energy Grant Substation

The CenterPoint Energy Grant Substation is located along the southern edge of the TMC adjacent to Brays Bayou (see Figure 3-117). The site is situated in Zone AE, with a BFE of 43.0 feet, on the north bank of Brays Bayou adjacent to the floodway (see Figure 3-118). This substation supplies electric service to all TMC facilities. It contains three transformers, but on-site personnel reported that a single transformer can carry the full TMC load, if needed.

GRANT SUBSTATION

FIRM = Zone AE

BFE = 43.0 feet

(see Figure 3-119)

Figure 3-117: CenterPoint Energy Grant Substation and TECO Paul G. Bell, Jr. Energy Plant; aerial view looking northeast

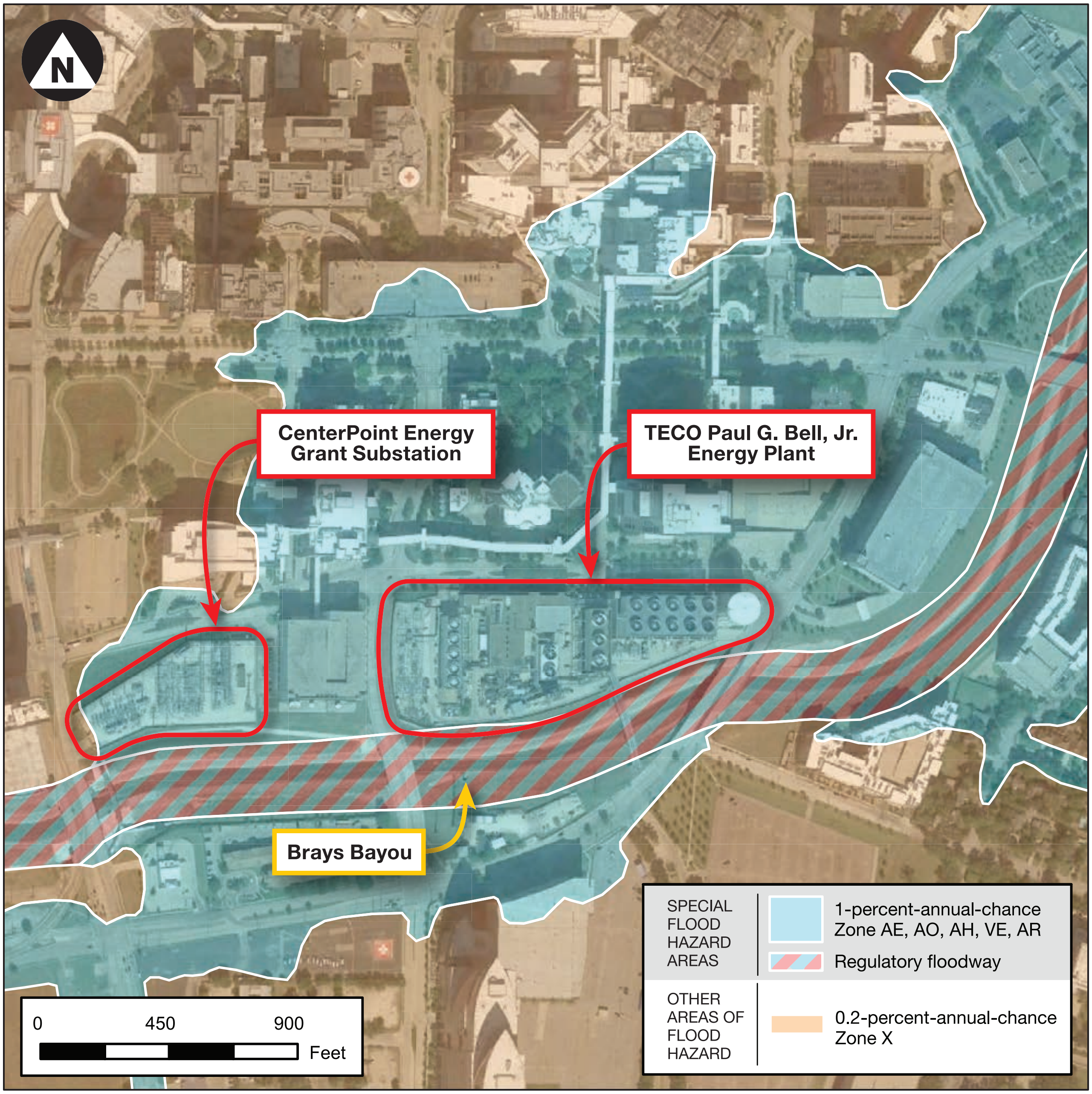


Figure 3-118: FIRM for CenterPoint Energy Grant Substation TECO Paul G. Bell, Jr. Energy Plant

Dry Floodproofing Mitigation Measures

Although the substation was not damaged during Tropical Storm Allison in 2001, most of the TMC facilities lost electrical power because their basements flooded and critical electrical equipment was damaged. Because of the significant damage from Tropical Storm Allison and the critical nature of the TMC facilities, CenterPoint Energy worked with TMC management to mandate raising electrical equipment above the 0.2-percent-annual-chance probability BFE in all TMC buildings and installing disconnect switches that allow CenterPoint Energy a means to disconnect any single TMC institution from the electrical grid, thereby preventing a system-wide failure.

As part of the system upgrades after Tropical Storm Allison, a flood vulnerability assessment was performed and the following flood mitigation measures were implemented:

Floodwall. A floodwall surrounding the CenterPoint site was constructed in 2003 (see Figure 3-119) with a 30-foot-wide floodgate installed at the southwest corner and northeast corner of the site (see Figure 3-120). The floodgates were designed to retain 6 feet of water against the gate with 2 feet of additional height for site security. The top of the floodwall is at an elevation of 51 feet and is at least 8 feet above the surrounding grade for security reasons. The 0.2-pecent-annual-chance-event flood elevation is 46.7 feet and therefore, the wall provides 4.3 feet of freeboard for the 0.2-pecent-annual-chance event.

Figure 3-119: Exterior substation floodwall with water height shown (left) and interior wall surface (right)

Figure 3-120: Substation floodgate

Sump pit and pump. The site also has a sump pit at the southwest corner to evacuate rainwater inside the facility and water that gets through the floodwall (see Figure 3-121). The sump pump system was designed to remove 3 inches of rainfall an hour from the substation. The sump pump is connected to a supervisory control and data acquisition (SCADA) system that indicates its operating status.

Figure 3-121: Substation sump pit and pumps

Performance during Harvey

The substation was only minimally impacted by Hurricane Harvey. Electrical service was never disrupted even though water surrounded the facility up to approximately 2 to 3 feet above grade on the outside of the floodwall. The sump pumps for removing stormwater reportedly stopped working causing water to accumulate to a depth of 6 inches at the southwest corner of the site. The SCADA system indicated the pumps had stopped running and a maintenance crew was dispatched to manually reactivate the pumps.

Summary of MAT Observations

- The CenterPoint Energy Grant Substation is located in Zone AE, adjacent to the floodway, with a BFE of 43.0 feet. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24.
- Damage to the TMC from Tropical Storm Allison resulted in the need for a flood vulnerability assessment and subsequent installation of dry floodproofing mitigation measures at the substation.
- The dry floodproofing components and mitigation activities performed at the substation provided a comprehensive flood barrier, with minimal openings or penetrations, that performed as designed during Hurricane Harvey. The substation did not lose its ability to distribute power during Hurricane Harvey.

3.2.10.6 Thermal Energy Corporation (TECO) Paul G. Bell, Jr. Energy Plant

The TECO Paul G. Bell, Jr. Energy Plant is located at 1615 Braeswood Boulevard on the north bank of Brays Bayou adjacent to the floodway. The facility is in Zone AE, with a BFE of 43.0 feet (see Figure 3-118).

TECO BELL ENERGY PLANT

FIRM = Zone AE

BFE = 43.0 feet

(see Figure 3-119)

The TECO Paul G. Bell, Jr. Energy Plant is the largest combined heat and power chilled water district energy plant in North America. TECO produces steam, chilled water, and electricity. TECO has the ability to produce 100 percent of its electricity requirements on the energy plant site. The plant delivers its products through underground pipes to most of TMC's member institution buildings. The institutions use the energy for air conditioning, space heating, dehumidification, sterilization, kitchen and laundry processes, and domestic hot water use.

The MAT noted that most institutions have backup electric power generators and fuel supplies in case they lose externally supplied power, but the majority of the TMC institutions do not have any way to produce steam and chilled water themselves, making the services that TECO provides critical for continued operations.

Dry Floodproofing Mitigation Measures

TECO reported that there was approximately 3 inches of water across the site during Tropical Storm Allison in 2001. Although the plant was not damaged during Tropical Storm Allison, most of TMC's facilities lost services because their basements flooded and critical electrical and mechanical equipment was damaged.

Because of the significant damage resulting from Tropical Storm Allison and the critical nature of the TMC facilities, TECO undertook the following flood mitigation measures to fortify their supply of the necessary steam, chilled water, and electricity.

Floodwall and floodgates. TECO constructed a floodwall surrounding its site (see Figure 3-122). The top of the floodwall is designed to be at the 0.2-percent-annual-chance probability flood elevation plus 2 feet of freeboard. TECO also installed floodgates at openings in the floodwall to compartmentalize the plant site (see Figure 3-123). After construction of the floodwall and installation of the floodgates, joints in the floodwall and the floodgates were independently tested to verify that water would not seep through them.

Figure 3-122: TECO floodwall adjacent to Brays Bayou (left image) and along Pressler Street (behind ivy in right image)

Figure 3-123: Floodgates in floodwall at TECO Energy Plant

Sump pit and pump. TECO constructed sump pits and sump pumps, including the addition of a redundant pump (see Figure 3-124).

Figure 3-124: Sump pits and pumps inside TECO floodwall

Preparedness and redundancies. TECO management also implemented very robust emergency preparedness policies and procedures with multiple redundancies built into the systems. For example, redundant electric supplies were installed. To further strengthen its floodproofing, TECO installed restraining devices to secure manholes and underground vault covers (see Figure 3-125).

Figure 3-125: Vault flood cover restraining device (left) and barrels used as manhole cover restraining devices (right)

Performance during Harvey

TECO was minimally impacted by Hurricane Harvey. The plant did not lose any services or its ability to provide steam, chilled water, or electricity to TMC customers. TECO personnel implemented emergency preparedness procedures well in advance of the storm and were prepared to ride out the storm. TECO had 40 staff on site for 5½ days to manage the operations during the event. The facility was surrounded by approximately 1 to 4 feet of water in the adjacent streets, with higher water depths along the floodwall adjacent to the Bayou. The water did not rise high enough to threaten the top of the floodwall surrounding the site. The floodwall and floodgates have approximately 5 feet of freeboard along Brays Bayou (see Figure 3-126) and there were no reported problems with water intrusion into the site through the floodwall or floodgates.

Figure 3-126: Brays Bayou adjacent to TECO Energy Plant floodwall during Hurricane Harvey

PHOTO COURTESY TECO; USED WITH PERMISSION

Summary of MAT Observations

- The TECO Paul G. Bell, Jr. Energy Plant is located in Zone AE, adjacent to the floodway, with a BFE of 43.0 feet. Buildings located in Zone AE should follow the flood provisions of model codes and standards such as the IBC and ASCE 24.
- TECO's numerous physical and operational mitigation measures performed well during and immediately after Hurricane Harvey.
- The dry floodproofing components and mitigation activities performed at the Paul G. Bell, Jr. Energy Plant provided a comprehensive flood barrier, with minimal openings or penetrations, that performed as designed during Hurricane Harvey. The energy plant did not lose its ability to distribute steam and chilled water and to generate electricity during Hurricane Harvey.

MITIGATION ASSESSMENT TEAM REPORT

HURRICANE
HARVEY
IN TEXAS

4

Wind-Related Observations

The MAT evaluated building systems to determine the effectiveness of the various design and construction practices and ascertain the effect of code adoption and enforcement on reducing wind damage.

Although most of the damage from Hurricane Harvey was caused by flooding, Hurricane Harvey generated near design wind speeds that produced pressures that approximated design pressures derived from various editions of ASCE 7 (depending on a building's proximity to the track of the storm and building and site characteristics) near where it first made landfall. The MAT was deployed to Aransas, Nueces, Refugio, and San Patricio Counties to assess wind performance issues of residential and non-residential buildings.

The MAT primarily examined the wind pressure performance of the MWFRSs and building envelopes. The MAT documented the effects of wind-borne debris on building envelopes and rain infiltration at building envelope breaches. The MAT also examined the performance of ground- and rooftop-mounted solar panel arrays.

Within the greater Rockport, TX, area, winds from Hurricane Harvey caused extensive damage to roof coverings and rooftop equipment, which resulted in rain damage of interior finishes, furnishings, and equipment. Wind-related building damage was primarily attributable to using improper materials in hurricane-prone regions; design deficiencies; poor installation of wall coverings, windows, and doors and failure to follow guidelines for installations in high-wind zones; and inadequate attachment of roof coverings and roof-mounted equipment. MWFRS damage was observed mainly at older buildings; the observed building envelope damage for more recently constructed residential and non-residential buildings was less severe, but was significant. The MAT observed one ground-mounted solar array and two rooftop-mounted solar arrays, each with varying degrees of damage.

MAT observations. Evaluating buildings to observe performance of residential and non-residential buildings, as well as solar panel arrays, was one of the MAT's main goals. In Aransas, Nueces, Refugio, and San Patricio Counties, the MAT primarily examined the wind pressure performance of MWFRS and building envelopes, and the effects of wind-borne debris on building envelopes, and rain infiltration at building envelopes.

Chapter organization. The MAT observations of wind-impacted buildings are divided into three main sections: Residential Buildings (Section 4.1), Non-Residential Buildings (Section 4.2), and Wind Performance of Solar Panel Systems (Section 4.3).

4.1 Residential Buildings

The Hurricane Harvey MAT visited numerous residential buildings (single family homes and apartment buildings) in Aransas, Nueces, Refugio, and San Patricio Counties. The MAT assessed the performance of the MWFRSs as well as building envelope components of buildings with varying ages and governing building codes.

Texas does not have an adopted building code at the State level but rather allows and encourages counties and municipalities to adopt the latest version of the IRC and ASCE 7. At the time of Hurricane Harvey, the latest versions were IRC 2015 and ASCE 7-16. Many cities in the areas affected by Hurricane Harvey had adopted the 2009, 2012, and 2015 IRC and ASCE 7-05. Prior to these adoptions, most of the coastal cities had adopted IRC 2000 and ASCE 7-98. The Texas Department of Insurance (TDI), which is the administrator of coastal windstorm insurance, adopted IRC 2006 in July 2007.

General Observations

The MAT observed that roof systems of residential buildings were particularly vulnerable to the high winds of Hurricane Harvey. Positive wind pressures under roof eaves, large overhangs, and roof surfaces caused significant damage to many homes. The MAT also observed broken windows and garage doors.

TDI has required tie-downs and wind clips since the first printing of the requirements to obtain insurance from the Texas Windstorm Insurance Association, described in the *Texas Windstorm Insurance Association Building Code for Windstorm Resistant Construction*, developed by the TDI. Such connections include top plate-to-foundation connections with bolts or stud-to-bottom plate clips with stud-to-top plate clips at every other stud. Wind clips from top plates to trusses or ceiling joists are also required, with the associated rafter allowed to be shear-nailed to the joist. On many of the older homes, the MAT observed that either poor installation or intermittent spacing of these devices intended to prevent wind uplift, which led to significant failures. Section 4.1 includes a discussion of wind-related observations for residential buildings. Specifically, the section discusses structural systems, non-load-bearing walls, wall coverings, roof coverings, roof ventilation, soffits, fascia, doors, windows, shutters, garage doors, and damage produced by wind-borne debris impacts.

4.1.1 Structural Systems / Main Wind Force Resisting Systems

The primary determinant for retaining the structural integrity of a building is the proper design and installation of the Main Wind Force Resisting System (MWFRS). The MAT observed successes and failures of the MWFRS in the residential buildings that were visited. This section explains the MWFRS, with examples from the rebuilding that was occurring in the area affected by Hurricane Harvey, and discusses the importance of connectors and sheathing in transferring loads. A discussion of MAT observations, both successes and failures, of these structural systems follows.

CONNECTORS

Additional information on connectors can be found in Technical Fact Sheet 4.3, "Use of Connectors and Brackets," in FEMA P-499 (2010b).

According to the design load standard referenced in 2009 IRC and ASCE 7-05, the MWFRS is an assemblage of structural elements that provides structural support and stability. The MWFRS can be thought of as the portion of a building's structural frame that collects dead loads, wind loads, and other live loads from the building envelope and transfers these loads to the ground via the building's foundation, whether a slab-on-grade or elevated pier system. Technical Fact Sheet 4.1, "Load Paths," in FEMA P-499 (2010b) illustrates the concept of load paths and highlights important connections in a wind uplift load path. Elements of the building envelope that do not qualify as part of the MWFRS are identified as C&C, which includes siding, windows, doors, and roof-covering materials.

Although some of the residential structures the MAT surveyed after Hurricane Harvey were not in municipal jurisdictions and had no building code inspection requirement, many were in jurisdictions that had adopted the 2009, 2012, and 2015 IRC. Wind-related building failures ranged from roof and wall structure failure to loss of siding and damage to openings. Wall and roof failures are considered structural failures of the MWFRS.

Connectors and sheathing are critical elements of the MWFRS and are discussed below.

Connectors. Structures in coastal high wind zones should have robust MWFRS connections to adequately transfer loads from the roof structure to the wall structure and into the foundation's system.

Figures 4-1 and 4-2 show a two-story apartment building under construction that is well connected by wall and roof connectors and structural sheathing.

The MAT also observed MWFRS connections using all-threaded tie rods extending from the foundation or elevated support structure with continuous connections to the top floor top plate. The system in Figure 4-3 uses floor-to-floor couplings, heavy nuts, and square washers. This system was observed in existing and new construction.

Figure 4-1:
Apartment building under construction (Rockport)

Structural sheathing is shown with the red arrow and an uplift connector is shown with the blue dashed arrow.

Figure 4-2:
Clips connecting stud to bottom plate and anchor-bolted bottom plate to slab (red arrow) (Rockport)

Same building as Figure 4-1.

Sheathing. In addition to robust connectors, another vital part of the MWFRS is the sheathing—both roof and wall sheathing. Roof sheathing transfers roof loads to the rafters and trusses. Wall sheathing in a shear wall transfers all of the lateral loads to the wall system, which transfers the loads to the foundation or pier and beam system. To perform as intended, sheathing must be rated for its purpose and installed properly with fasteners that are installed according to the building code and manufacturer's recommendations.

The bottom plate and coupling are shown with green arrows. Same building as Figure 4-1.

Figure 4-3:
An example of all-threaded MWFRS connection system (Rockport)

The green wall in Figure 4-1 is an example of rated structural sheathing that is properly installed and incorporates a water-resistive barrier. Figure 4-4 is an example of sheathing material that was attached improperly, making it potentially vulnerable to failure. Nails that miss their intended target are often referred to as “shiners.”

Same building as Figure 4-1.

Figure 4-4:
Sheathing nails that missed the bottom plate (shiners) are shown with red arrows (Rockport)

MAT Observations

Figure 4-5 shows an older home in Rockport that appears to have been built in accordance with the 1997 TDI *Texas Windstorm Insurance Association Building Code for Windstorm Resistant Construction*. It has wood panel siding, let-in corner wall bracing, straps between the floors, and clips at every other stud to the top plate. Figure 4-6 (same house in Figure 4-5) shows wind clips attached from the top plates to the ceiling joists. The rafters are missing and may have been toe-nailed to the top plate or nailed to the sides of the ceiling joists.

Figure 4-5:
Older home with roof failure due to poor connection of the rafters to the joists (120 mph, Exposure B) (Rockport)

Figure 4-6:
Another view of the older home with roof failure in Figure 4-5 (Rockport)

Ceiling joists clipped to top wall plate (red arrows). Missing roof rafters appeared to be either toe-nailed or nailed to the ends of the ceiling joists (red circles).

The Rockport home shown in Figure 4-7 is a post-2009 construction on the Intracoastal Waterway that experienced design-level winds. Most of the MWFRS remained intact during Hurricane Harvey as a result of good connections, but the structure was significantly damaged when a large, open, covered front porch suffered major wind uplift. Figures 4-8 and 4-9 illustrate the type and quantity of structural wind-resistant connections that kept most of the MWFRS together.

Although the MWFRS did not fail, the connections and support for the large overhangs were not sufficiently robust to resist both internal and external wind pressures produced by the 130 mph winds at this location. Furthermore, debris impacts caused significant C&C failures. Damage included loss of window eyebrow roofs, wind-borne debris missile impacts (green dotted arrows in Figure 4-7), damage to the metal roofing, broken hurricane glazing, and extensive water inundation.

The building suffered significant wind uplift damage (red arrows) and debris impacts (green dotted arrows).

Figure 4-7:
Intracoastal Waterway home that experienced a design-level wind event (130 mph, Exposure C) (Rockport)

Figure 4-8:
Wind-resistant connections (red arrows) (same building as Figure 4-7) (Rockport)

Figure 4-9: Second floor wind-resistant connections (red arrows) (same building as Figure 4-7) (Rockport)

4.1.2 Exterior Wall Coverings

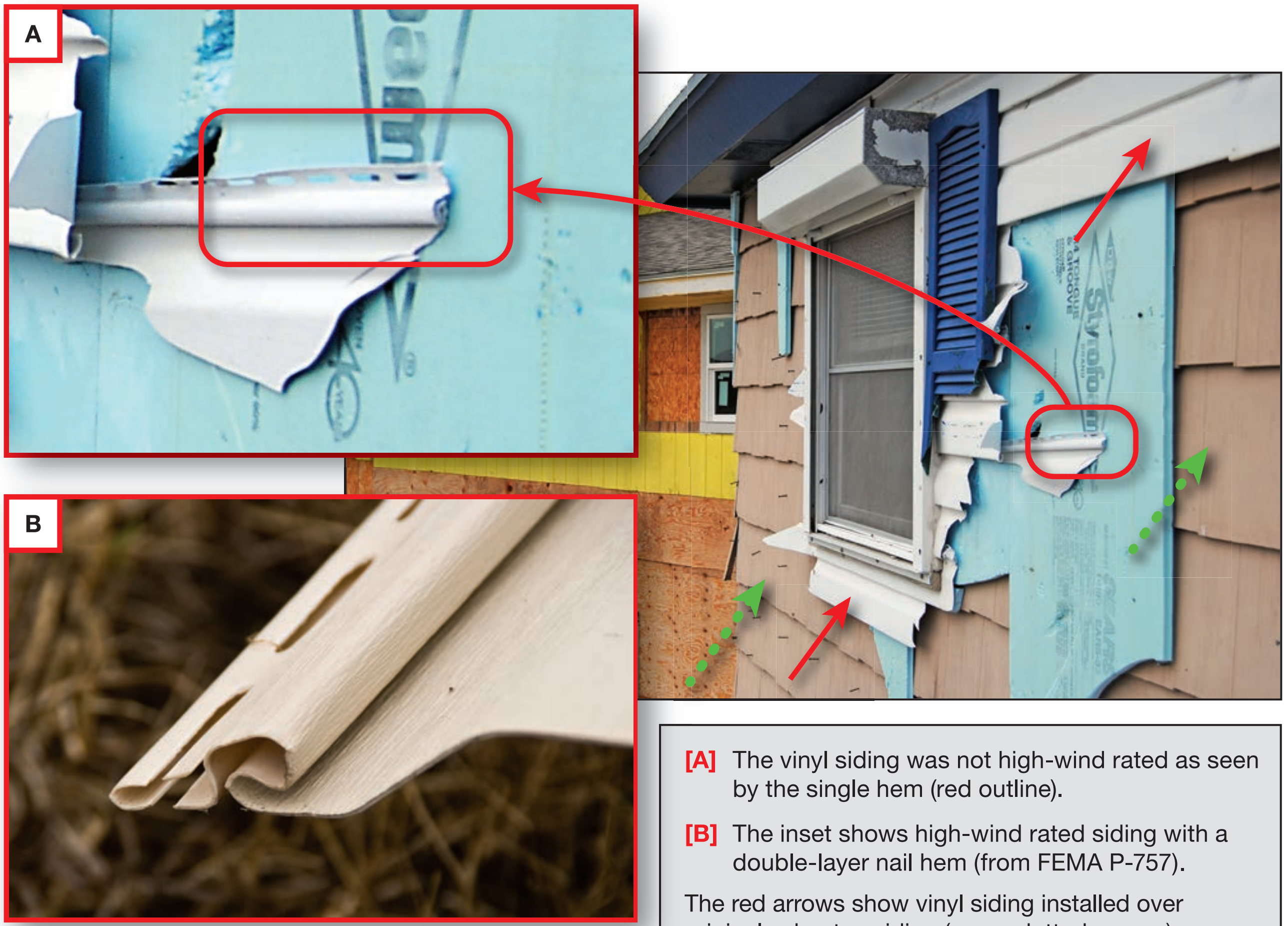
Section 4.1.2 covers exterior wall coverings (also known as cladding or siding), including vinyl siding (Section 4.1.2.1), fiber-cement lap siding (Section 4.1.2.2), brick veneer (Section 4.1.2.3), and other cladding types (panels of wood and hardboard) (Section 4.1.2.4).

4.1.2.1 Vinyl Siding

The most important factors for vinyl siding performance during a high-wind event are the selection of siding that is appropriate for the designated wind speed at that location and the use of proper application techniques and installation details. Proper application techniques and installation details include using the right accessories, such as starter strips, receivers, and utility trim; selecting and placing nails; and locking successive panel courses to each other. Siding intended for higher wind speeds (greater than 90 mph basic wind speed based on ASCE 7-05) usually has a double-layer nail hem that strengthens the vinyl at the point where the nail attaches, thus resisting tearing or pull-through of the nail head.

MAT Observations

Although vinyl siding was the predominant and most vulnerable siding observed by the 2008 Hurricane Ike MAT, the Hurricane Harvey MAT observed significantly fewer newer structures clad in vinyl siding. Many of the structures had re-claddings over foam board and original siding materials (see Figure 4-10). In a vinyl-sided home in Holiday Beach (Figure 4-11), all of the openings were properly protected, but the home lost virtually all of its vinyl cladding. The MAT determined that the vinyl siding was not rated for high-wind applications.



[A] The vinyl siding was not high-wind rated as seen by the single hem (red outline).

[B] The inset shows high-wind rated siding with a double-layer nail hem (from FEMA P-757).

The red arrows show vinyl siding installed over original asbestos siding (green dotted arrows).

Figure 4-10: Older home with vinyl siding (Rockport)

Figure 4-11: Home that lost vinyl siding (red arrows) and soffits (blue dashed arrow) (120 mph, Exposure C) (Holiday Beach)

4.1.2.2 Fiber-Cement Siding

Fiber-cement siding was introduced to the public in the 1950s. The original product was reinforced with asbestos. Because of safety concerns regarding asbestos, the industry changed the reinforcing product to cellulose in the mid-1980s, and the product was re-introduced in the 1990s.

According to area building officials and architects, the allowable method of installing fiber-cement siding is to nail the top edge of the siding, locating the nail ¾ inch to 1 inch from the top edge prior to installing the next piece of lap siding—a method referred to as “blind nailing.” The lower edge of the next piece of siding is required to be caulked to prevent wind and water from being blown between the lapped edges.

International Code Council Requirements

According to the 2009 IRC, Section R703.10.2, fiber-cement “lap siding shall be lapped a minimum of 1¼ inches … and courses may be installed with the fastener heads exposed or concealed …” Unless otherwise stated in the code, installation recommendations relate only to the basic wind speeds in the area. However, in high-wind zones, published ratings and International Code Council evaluation reports for the application of fiber-cement lap siding require that the siding be face-nailed through both layers of siding at the lap joint, as shown in Figure 4-12. The spacing of the nails (16 inches or 24 inches) and permitted material exposure depend on the thickness and width of the siding boards and wind zone.

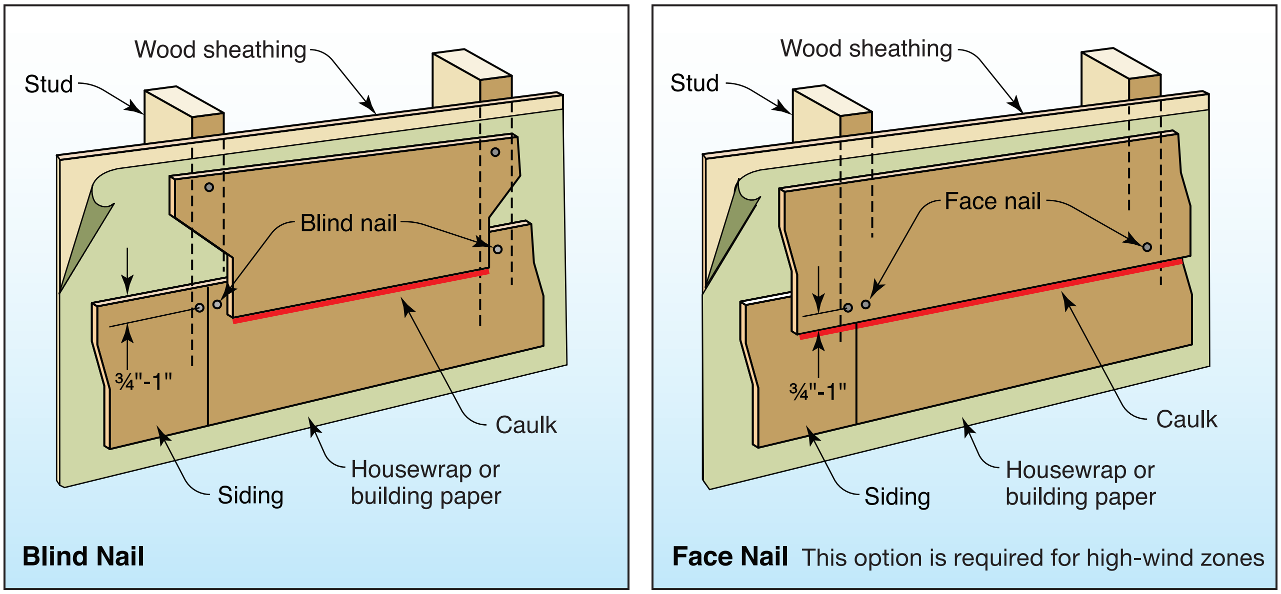


Figure 4-12: Installation guidance for fiber-cement siding

SOURCE: FEMA, 2010b (TECHNICAL FACT SHEET 5.3)

MAT Observations

Fiber-cement siding failure was common throughout the area that the MAT investigated. Examples are shown in Figures 4-13 and 4-14.

Red arrows show missing fiber-cement siding.

Figure 4-13:
Fiber-cement siding damage to a residence (130 mph, Exposure C) (Copano Village)

Figure 4-14:
Fiber-cement siding ripped from walls (red arrows) (130 mph, Exposure C) (Port Aransas)

The MAT observed improper installations and failed installations of fiber-cement siding. Figure 4-15 shows a nail that was placed too close to the edge. Figure 4-16 shows fiber-cement siding with no caulking, and Figure 4-17 shows failed caulking.

Figure 4-15:
Fastener installed in fiber-cement siding ½ inch from edge, which led to failure of the plank attachment (Port Aransas)

Figure 4-16:
Failed fiber-cement siding without caulking (red arrows) (130 mph, Exposure C) (Rockport)

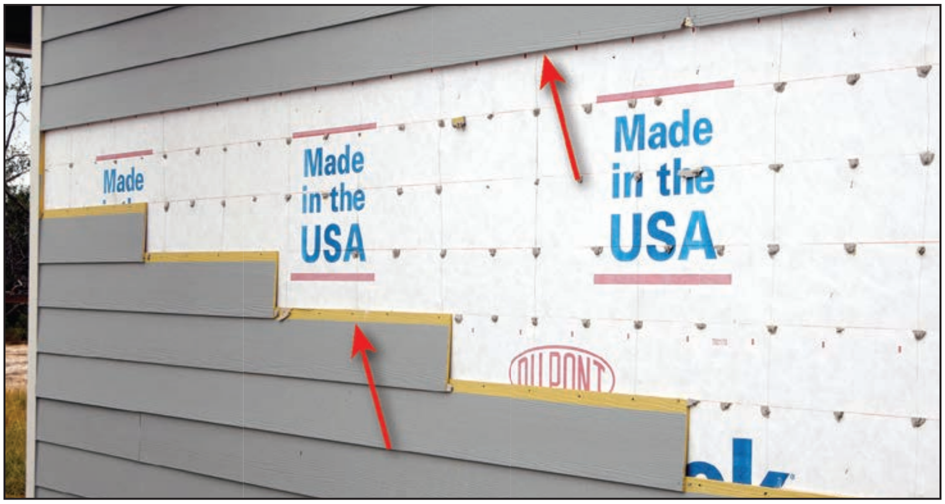
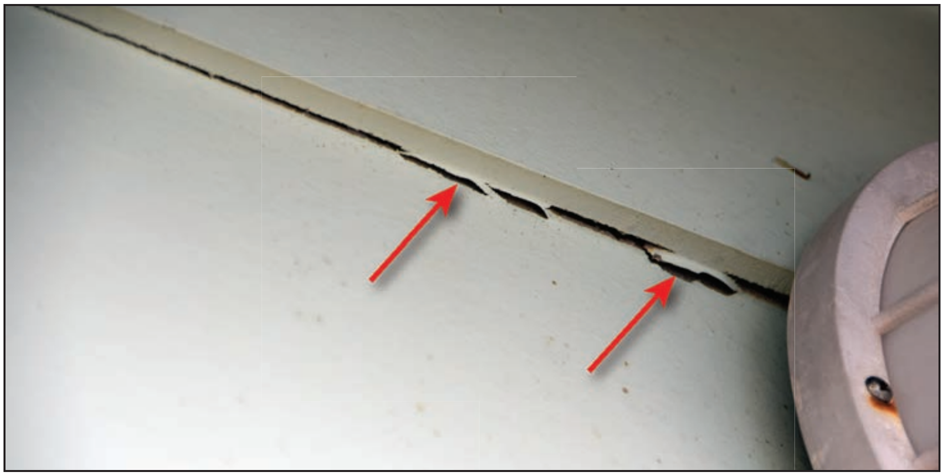


Figure 4-17:
Failed caulking (red arrows) (Port Aransas)



4.1.2.3 Brick Veneer

The Hurricane Harvey seaward and inland zones experienced at or near ASCE 7-05 and TDI hurricane design wind speeds. Numerous brick veneer failures throughout the Hurricane Harvey-damaged areas were observed. The observed performance was reflective of these higher wind speeds, but more importantly, showed the lack of adherence to good installation practices. Common failure modes include tie (anchor) fastener pull-out due to failure of masons to embed ties into the mortar, poor bonding between ties and mortar and mortar of poor quality, and tie corrosion.

Figure 4-18 shows a common problem with brick veneer installation. The misalignment of the tie reduces the embedment and promotes veneer failure by tie fastener pull-out. In contrast, Figure 4-19 provides an example of proper brick installation, which includes:

- Proper alignment with the mortar joint and bent at a 90-degree angle at the nail head; this 90-degree bend minimizes tie flexing when ties are loaded in tension or compression (left-hand illustration of Figure 4-19)
- Embedment in the joint such that mortar completely encapsulates the tie
- Ties embedded at a minimum of 1½ inches into the bed joint, with a minimum mortar cover of ⅝ inch to the outside face of the wall as shown

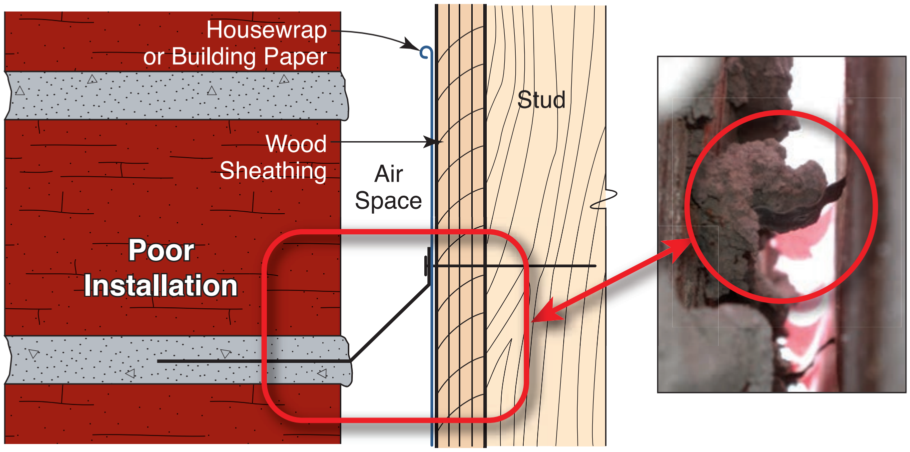


Figure 4-18: Common problem with brick veneer installation: sloped installation of corrugated brick ties offer no resistance to horizontal wall movement produced by wind pressures

SOURCE: FEMA, 2010b (TECHNICAL FACT SHEET 5.4)

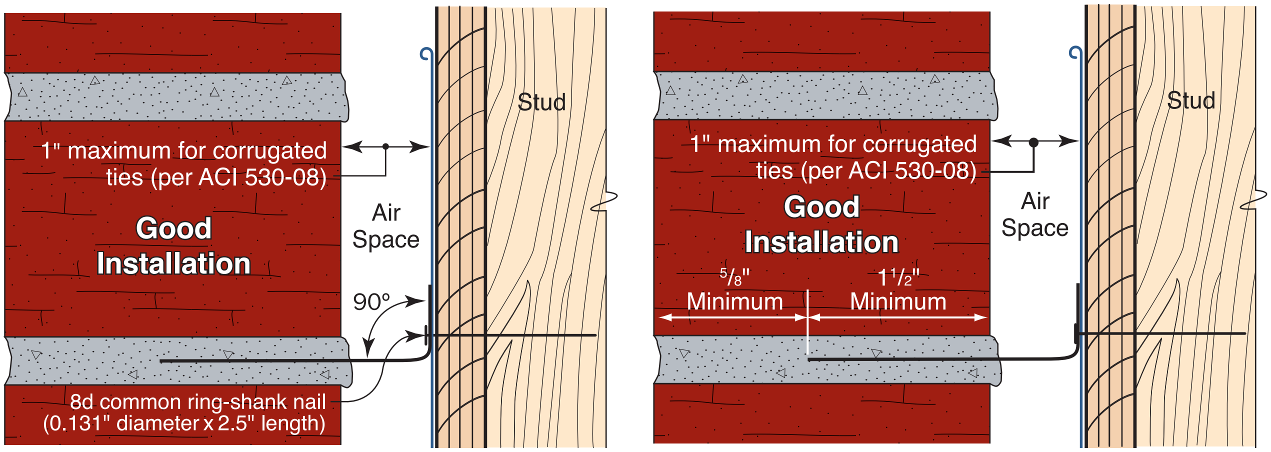


Figure 4-19: Example of proper brick installation

SOURCE: FEMA, 2010b (TECHNICAL FACT SHEET 5.4)

Figure 4-20 shows tie spacing for high-wind zones.

Wind Speed (mph) (3-Second Peak Gust)	Wind Pressure (psf)	Maximum Vertical Spacing for Ties (inches)	
		16-inch stud spacing	24-inch stud spacing
90	–19.5	24[a,b]	16[a]
100	-24.1	24[a,b]	16[a]
110	-29.1	20½[b]	13½
120	-34.7	17	NA[c]
130	-40.7	15	NA[c]
140	-47.2	13	NA[c]
150	-54.2	11	NA[c]

a. Maximum spacing allowed by ACI 530-08.

b. In locales that have adopted the 2006 IBC/IRC, the maximum vertical spacing allowed by ACI 530-05 is 18 inches.

c. 24-inch stud spacing exceeds the maximum horizontal tie spacing of ACI 530-08 prescribed for wind speeds over 110 mph.

Notes:

1. The tie spacing is based on wind loads derived from Method 1 of ASCE 7-05, for the corner area of buildings up to 30 feet high, located in Exposure B with an importance factor (I) of 1.0 and no topographic influence. For other heights, exposures, or importance factors, engineered designs are recommended.
2. Spacing is for 2½ inches long 8d common (0.131 inches diameter) ring-shank fasteners embedded 2 inches into framing. Fastener strength is for wall framing with a Specific Gravity G=0.055 with moisture content less than 19 percent and the following adjustment factors, C_t=0.8; and C_D, C_M, C_{eg}, and C_{tn}=1.0. Factored withdrawal strength W'=65.6#.
3. The brick veneer tie spacing table is based on fastener loads only and does not take into account the adequacy of wall framing, sheathing, and other building elements to resist wind pressures and control deflections from a high-wind event. Prior to repairing damaged brick veneer, the adequacy of wall framing, wall sheathing, and connections should be verified by an engineer.

ACI = American Concrete Institute
ASCE = American Society of Civil Engineers
IBC = International Building Code
IRC = International Residential Code
mph = miles per hour
psf = pounds per square foot

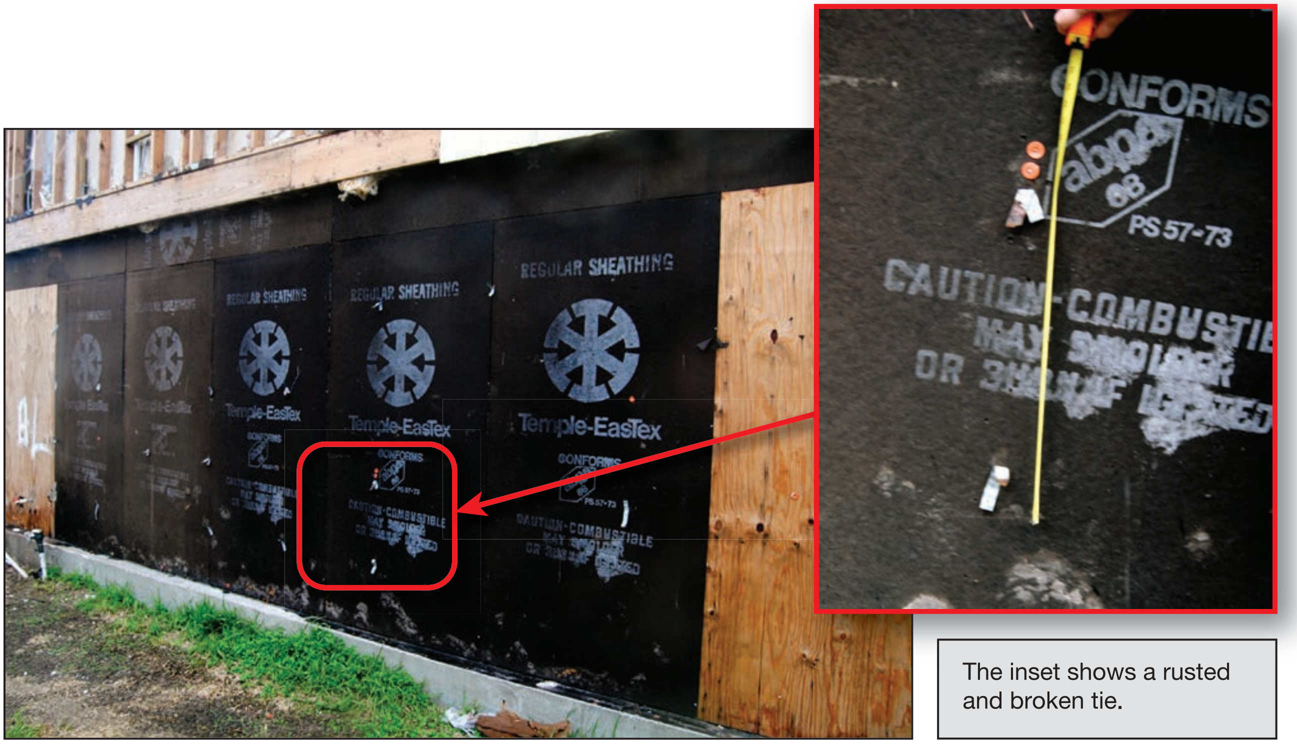
Figure 4-20: Brick veneer tie spacing

SOURCE (MODIFIED FROM): FEMA, 2010b (TECHNICAL FACT SHEET 5.4)

MAT Observations

Numerous brick veneer failures throughout the Hurricane Harvey-damaged areas were observed. Many of the brick veneer structures observed by the MAT to have suffered damage from Harvey were older residential structures and apartments, but some newer mid-rise condominiums also suffered significant masonry cladding failures. The common issues observed by the MAT included brick ties that were randomly spaced, with the horizontal spacing ranging from 32 inches to 16 inches on center and the vertical spacing ranging from 32 inches to 24 inches; see Figure 4-20 for proper spacing. Many of the corrugated ties that were observed were rusted and broken, were not embedded into the masonry, or had minimal embedment.

Figures 4-21 and 4-22 illustrate a residential brick veneer installation that failed. The damaged brick had been cleared prior to the MAT investigation. The installation shown had rusted and broken ties, as well as horizontal tie spacing of 32 inches; the vertical spacing of 24 inches is consistent with basic wind speed installations.



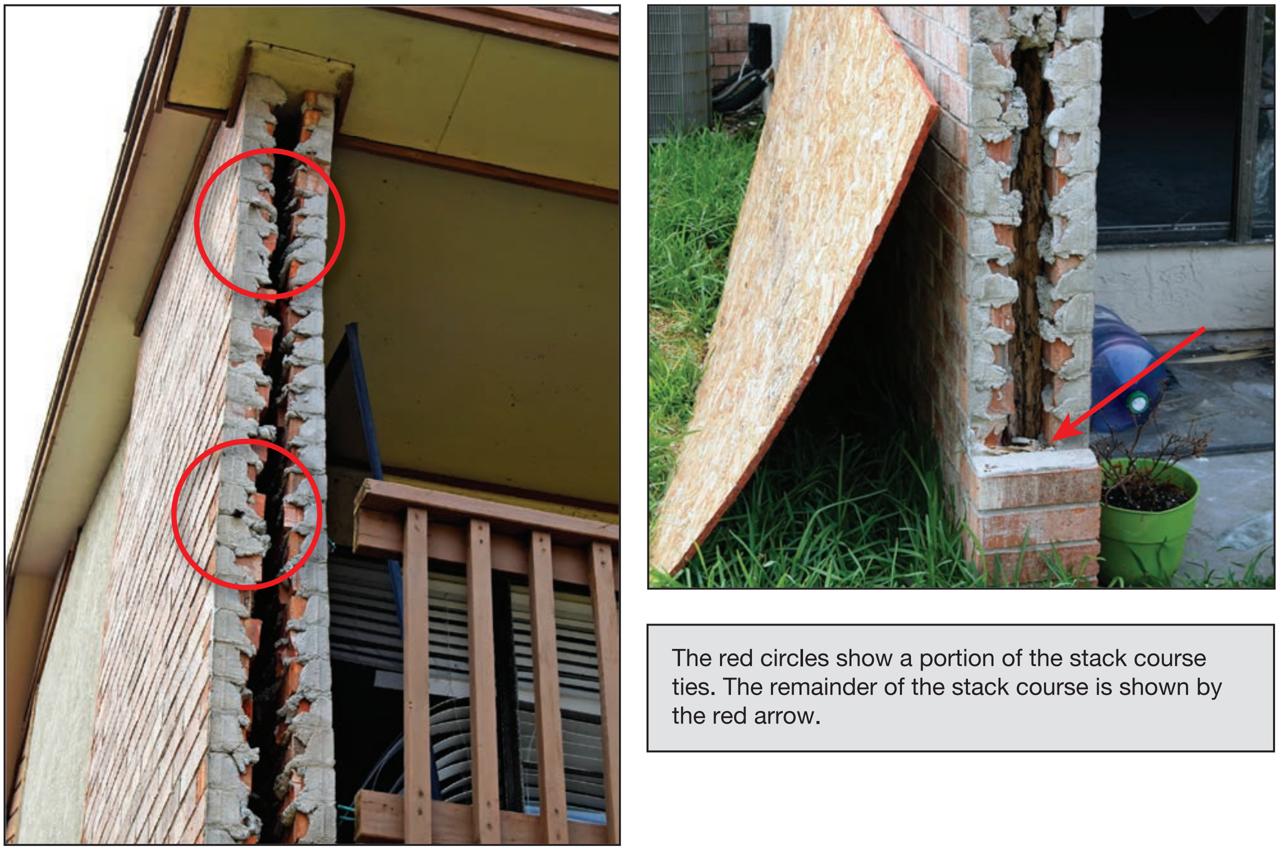
The inset shows a rusted and broken tie.

Figure 4-21: Residence brick veneer failure (120 mph, Exposure B) (Rockport)

Tie horizontal spacing was at 32 inches.

Figure 4-22: Residence with failed brick veneer installation (see also Figure 4-23) (Rockport)

Figure 4-23 shows a 10-inch double-wythe wing-wall of an apartment building in Port Aransas. Brick ties were randomly installed between each wythe, and the corrugated ties connecting each wythe to the end brick stack course were attached at 32 inches on center and the corrugated ties were only observed in one wythe.



The red circles show a portion of the stack course ties. The remainder of the stack course is shown by the red arrow.

Figure 4-23: Double-wythe brick wing-wall that lost its brick stacked course (130 mph, Exposure B) (Port Aransas)

The Sea Gull Condominiums, a 12-story brick veneered structure in Port Aransas, and the Princess Condominiums, a 9-story brick veneered structure south of Port Aransas, experienced brick veneer failures. Both structures are in the narrowing portion of Mustang Island between the Gulf and the Intracoastal Waterway. Given the height of both buildings and the narrowness of the land mass between both bodies of water, as well as Applied Research Associates data, the MAT believes that both buildings experienced 140 mph winds with an Exposure D.

The Sea Gull Condominiums are shown in Figures 4-24 and 4-25. The floor-to-floor distance in this building is 8 feet; steel brick shelves are located at every other floor, making the supported masonry wall height 16 feet. The original brick ties were adjustable "eye and pintle" anchors, but very few pintles remained when the MAT observed the building, as shown in Figure 4-25. Since a few of the pintles remained, the MAT assumed that all pintles were originally installed. These anchors were installed 24 inches on center horizontally and 16 inches on center vertically.

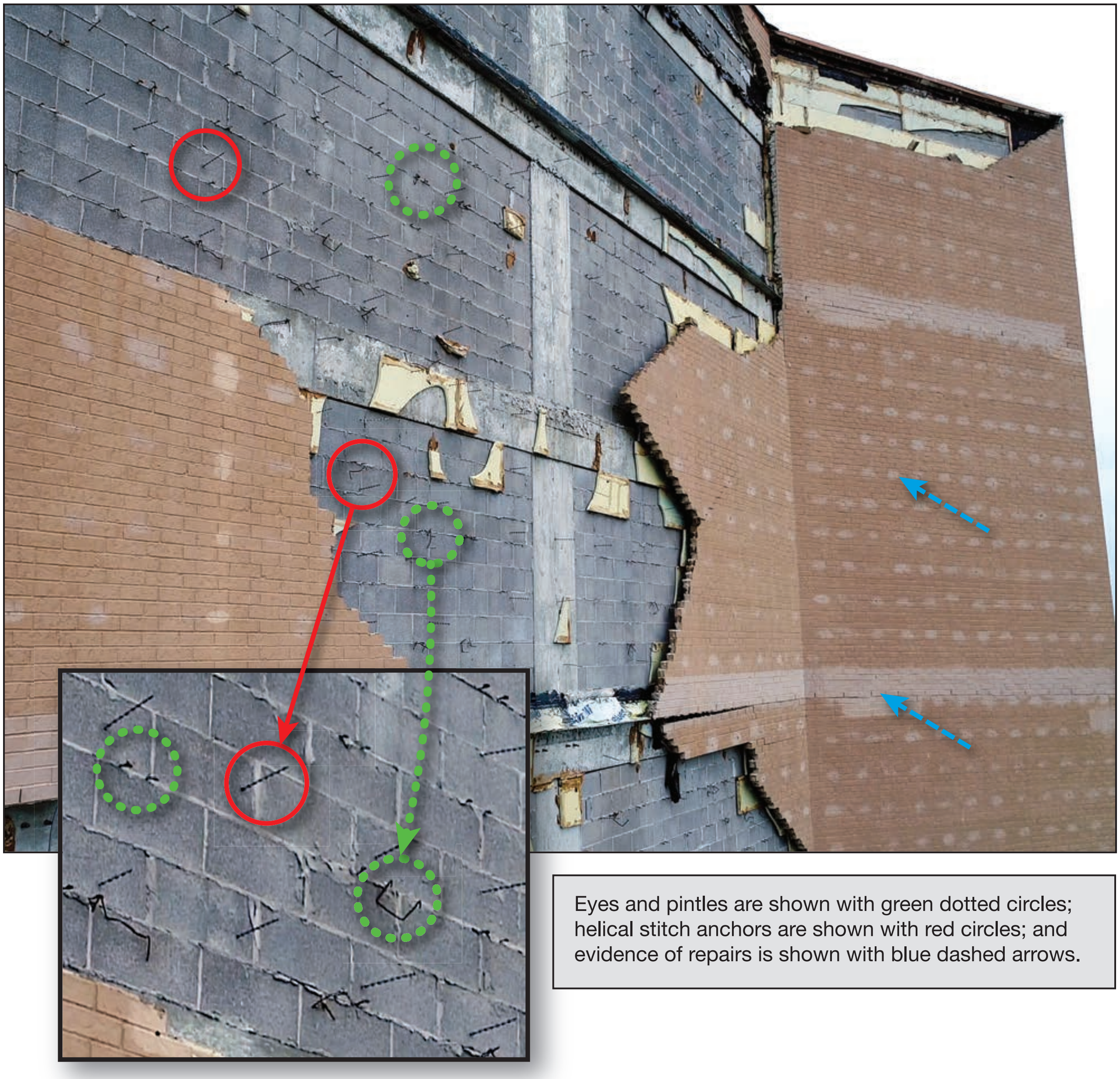
The light blotches on the brick walls shown in Figure 4-25 are indicative of a wall repair. As shown in this portion of the failed wall, the repair appears to have been performed using helical stitching anchors that were mechanically drilled through the veneer into the backup material, which was either CMU or concrete columns and beams. The stitching anchors were installed through brick joints into the backup material at approximately 24 inches on center horizontally and 16 inches on center vertically.

HELICAL TIES

Helical ties are normally constructed of Type 304 or Type 316 stainless steel. They are installed with a rotary hammer with a special installation head and countersunk up to ½ inch to allow repair to be patched with mortar or caulk.

The previously repaired wall was damaged by Hurricane Harvey (red arrow). The wall detail is shown in Figure 4-25.

Figure 4-24:
Sea Gull Condominiums (140 mph, Exposure D) (Port Aransas)
DRONE IMAGE

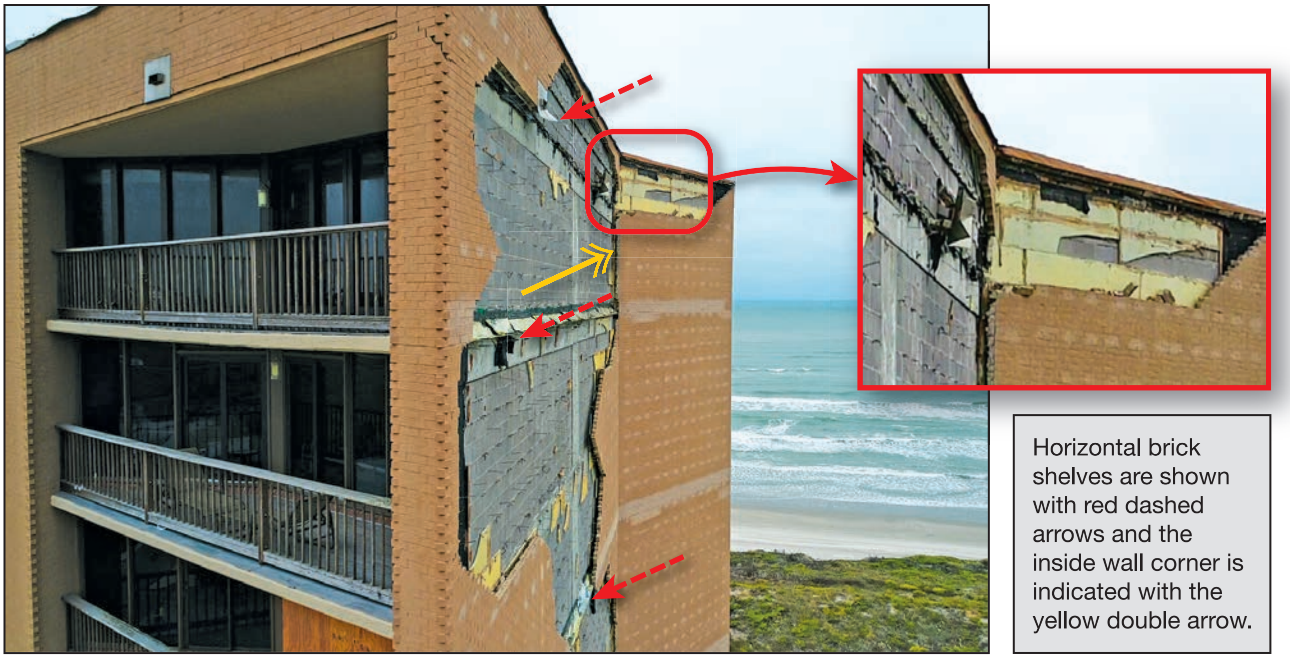


Eyes and pintles are shown with green dotted circles; helical stitch anchors are shown with red circles; and evidence of repairs is shown with blue dashed arrows.

Figure 4-25: Wall detail of Sea Gull Condominiums (Port Aransas)

DRONE IMAGE

The reasons for the failure of the original and retrofit anchors in the Sea Gull Condominiums structure can only be surmised as being the result of oscillations due to high wind pressures, thermal expansion, and/or a poor repair. The Brick Industry Association's Technical Note 28, *Brick Veneer/Wood Stud Walls* (2012), requires that brick veneer wall heights and anchorage in high wind zones be rationally designed for the wind pressures in the wind zone and thermal expansion. The repair was likely necessitated by poor spacing of the original eyes and pintles and may have been poorly installed. The MAT observed horizontal expansion joints between the top of the brick wall and the bottom of each shelf angle that were 16 feet apart (see red dashed arrows in Figure 4-26). No vertical expansion joint was observed besides the natural joint that occurs in the inside corner of the short wall (shown by a yellow double arrow in Figure 4-26).



Horizontal brick shelves are shown with red dashed arrows and the inside wall corner is indicated with the yellow double arrow.

Figure 4-26: Sea Gull Condominiums (140 mph, Exposure D) (Port Aransas)

DRONE IMAGE

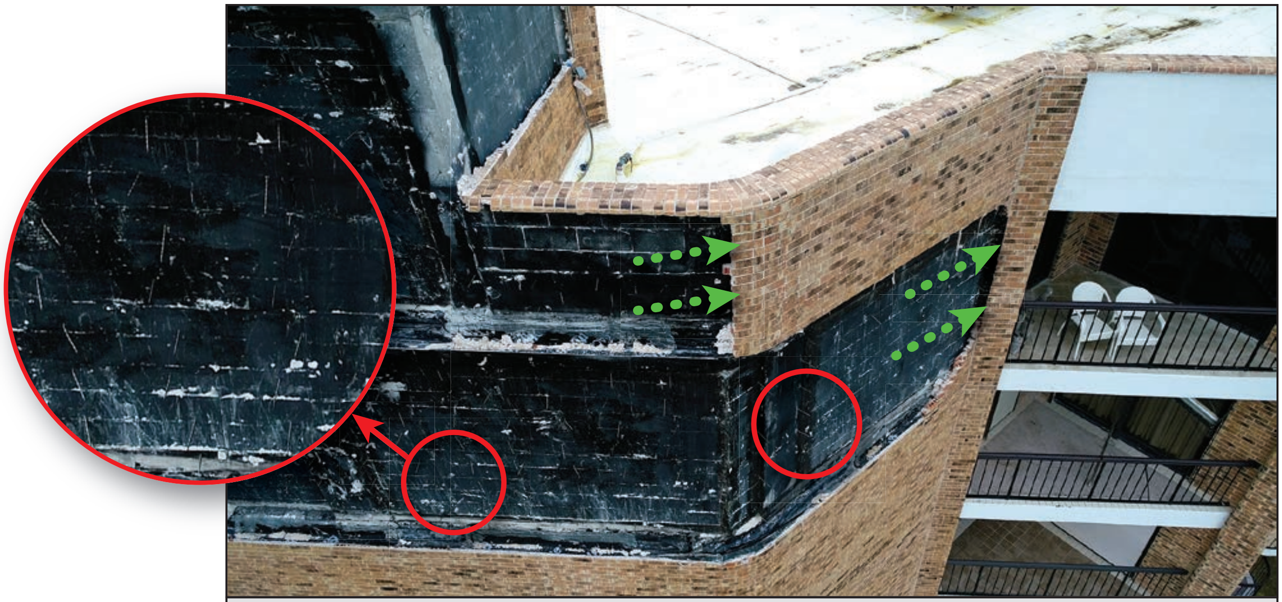
The Aransas Princess Condominiums are near the Sea Gull Condominiums and sustained similar damage, as shown in Figures 4-27 and 4-28. The stitches observed at Aransas Princess Condominiums appeared to be approximately 8 inches on vertical centers and approximately 16 inches on horizontal centers, so they may have been original to the installation. The MAT observed vertical expansion controls, illustrated by green dotted arrows in Figures 4-27 and 4-28.

The failures in both the Sea Gull Condominiums and the Aransas Princess Condominiums occurred at the top of the buildings, where wind pressures are highest, and on the southwest faces, where the building walls are the hottest.

Brick wall damage is shown in the red circle and thermal expansion control is shown with the green arrows.

Figure 4-27: Aransas Princess Condominiums (140 mph, Exposure D) (Port Aransas)

DRONE IMAGE



Brick veneer constructed or repaired with stitches, shown by the red circles. The green dotted arrows show thermal expansion control.

Figure 4-28: Aransas Princess Condominiums (140 mph, Exposure D) (Port Aransas)
DRONE IMAGE

4.1.2.4 Other Cladding Types

Most other types of cladding, which performed poorly due to rot and decay, are relegated to 1980s and 1990s vintage homes.

MAT Observations

Many of the older homes had been re-sided, such as the ones shown in Figures 4-29 and 4-30, or were destroyed by Hurricane Harvey and removed prior to the MAT investigation.

Figure 4-29:
Older residence with original hardboard lap siding (red arrow) that had been re-sided with blue foam insulation vinyl siding (130 mph, Exposure C) (Key Allegro)

Figure 4-30:
Older residence previously sided with hardboard vertical siding (red arrows) that had been re-sided with foam board and vinyl siding (yellow double arrows) (120 mph wind, Exposure B) (Rockport)

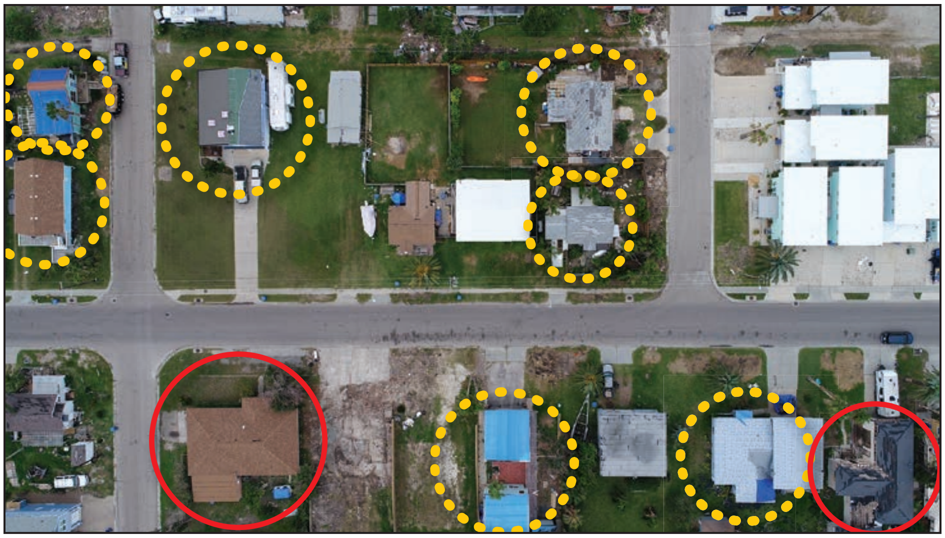
4.1.3 Roof Coverings

Damage to roof coverings is one of the leading causes of building performance problems during hurricanes. A damaged roof covering allows rainwater to enter the building, which can cause major damage to the interior finishes and contents. Such damage can be reduced if building owners address damaged roof coverings quickly. In the case of Hurricane Harvey, the historic rainfall—in terms of intensity and duration—made it difficult for contractors and homeowners to respond rapidly to limit the effects of rainwater infiltration.

The MAT observed a variety of roof coverings, including asphalt shingles, architectural standing seam metal panels, and various types of cementitious and clay tiles. The type of damage variability observed after Hurricane Harvey is consistent with damage observed by MATs after Hurricane Charley (FEMA 488), Hurricane Ivan (FEMA 489), Hurricane Katrina (FEMA 549), and Hurricane Ike (FEMA P-757). Although roof damage noted in these reports is variable, a commonality shared among them is that roofing on hip-roofed residences generally performs better than gabled roofs. Data collected by various research teams after Hurricane Harvey supports this finding: over 1,000 roofs were analyzed and the results showed that hip roofs overall had less severe damage than gable roofs (Fulcrum Community, 2018). An example of this is shown in Figure 4-31.

Figure 4-31: Neighborhood showing varying examples of gable roof (yellow dotted circles) and hip roof (red circles) performance (120 mph, Exposure B) (Rockport)

DRONE IMAGE



4.1.3.1 Asphalt Shingles

Asphalt shingles are available with Class D, G, H, and F labels (see text box). Class D is intended for the interior regions of the United States with normal ASCE 7 design wind speeds. Classes G, H, and F are intended for installation in high wind zones as designated by ASCE 7 for the United States and by TDI in Texas. Figure 4-32 shows the 15 coastal and near-coastal counties designated by TDI as Catastrophe Areas (refer to Section 2.2 for additional explanation). According to the TDI wind ratings, Class H shingles are required seaward of the Intracoastal Canal, and G and F would be approved in Inland I and Inland II areas.

ASPHALT SHINGLE CLASS RATINGS

Testing and labeling are prescribed in ASTM D 7158-05.* The following classes of shingles are specified in this standard:**

Class D: Suitable for use up to 90 (115) mph

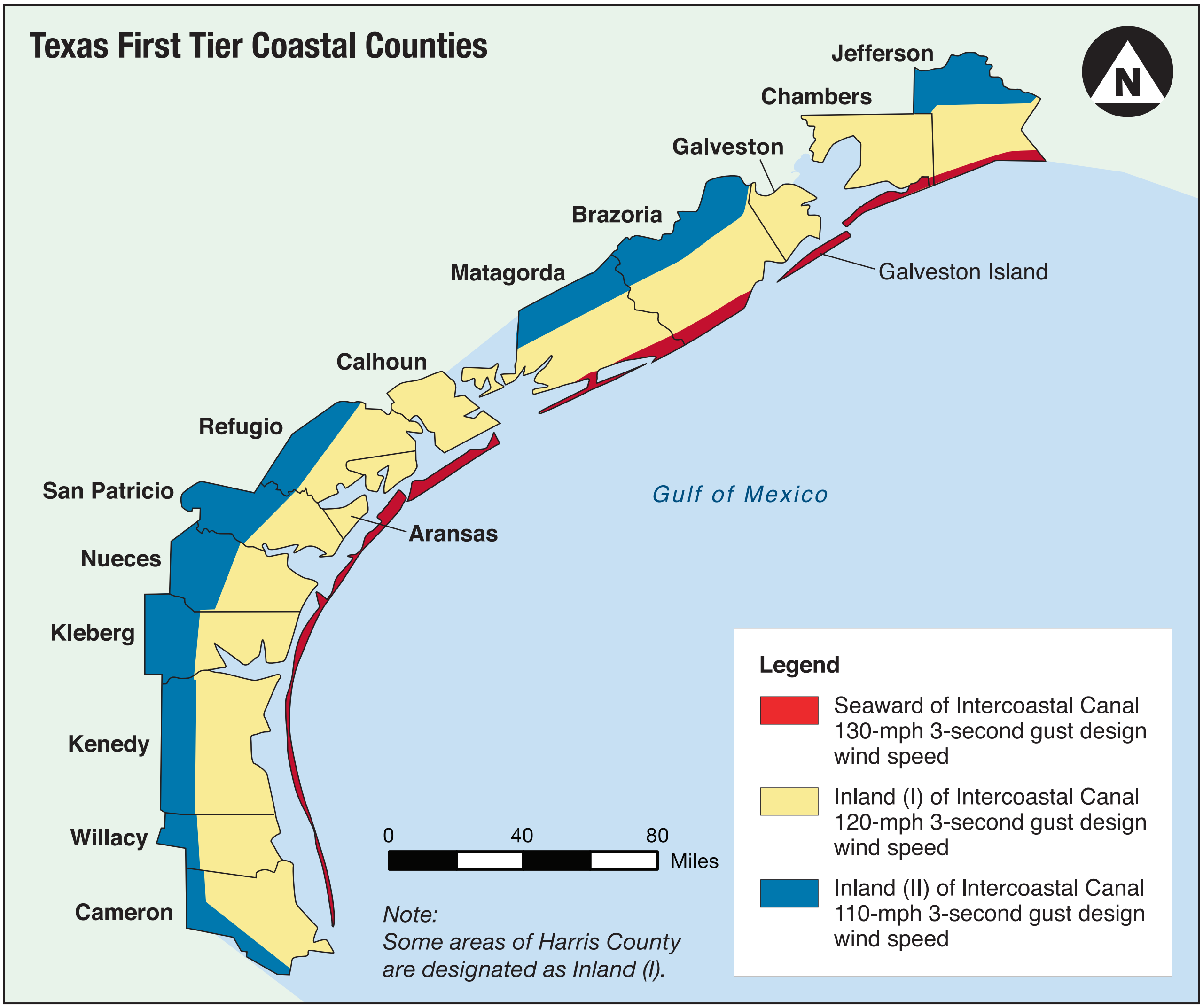
Class G: Suitable for use up to 120 (150) mph

Class H: Suitable up to 150 (190) mph with a six-nail installation

Class F: Shingles with this classification are tested in accordance with the old test method prescribed in ASTM D 3161.

* Wind speeds cited are design wind speeds in IBC/IRC/ASCE 7 (based on Exposure C and a maximum mean roof height of 60 feet).

** Wind speeds shown in parentheses are from ASTM D 7158-17.



Note:
Some areas of Harris County are designated as Inland (I).

Figure 4-32: TDI-designated Catastrophe Areas, 2006

ADAPTED FROM: TDI, 2018

MAT Observations

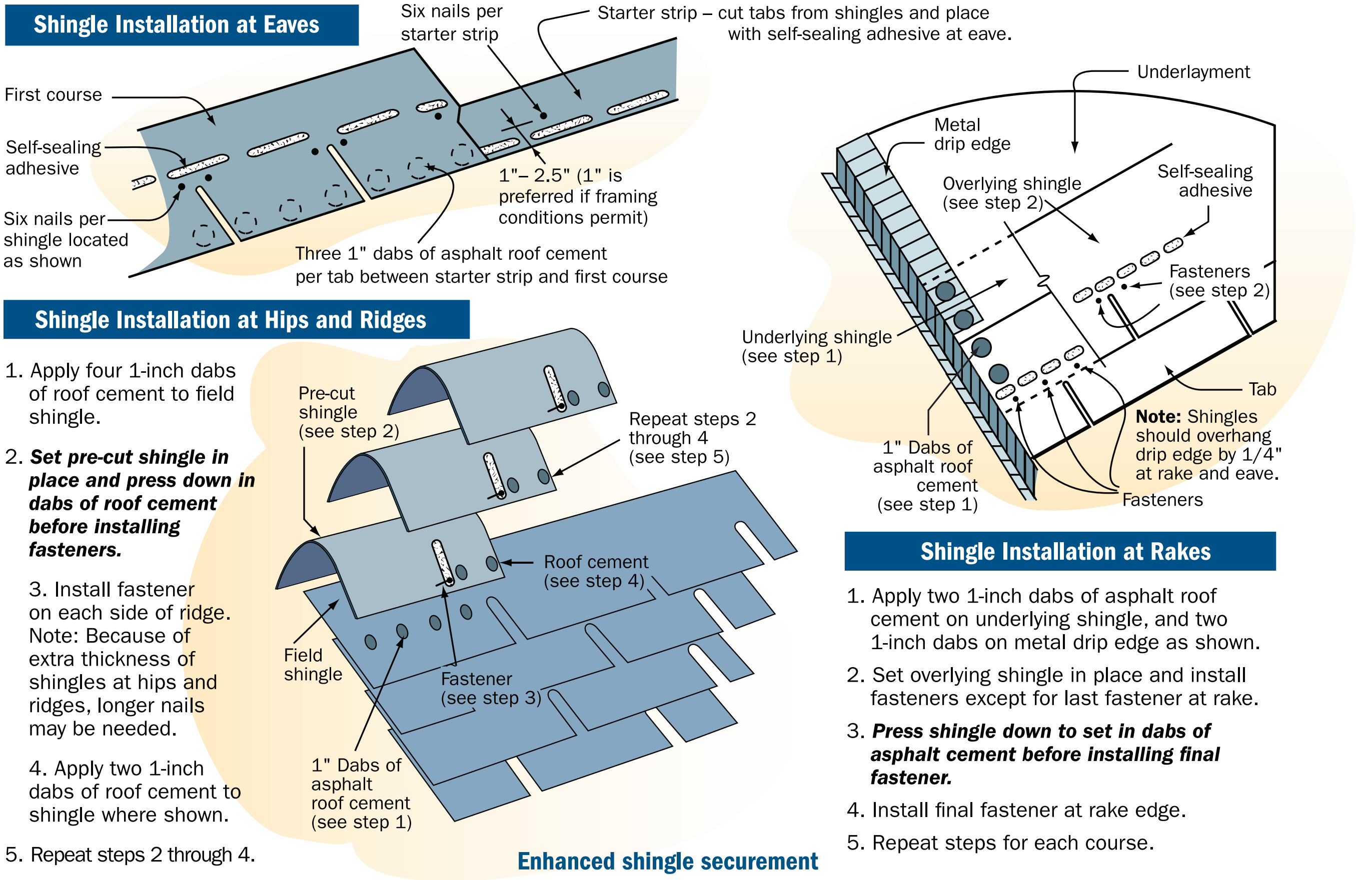
Most of the residences the MAT observed had asphalt shingle roof coverings. The home shown in Figure 4-33 is in the Port Aransas area, seaward of the Intracoastal Waterway, and was being re-roofed with Class F shingles when the MAT visited it. The 2006 IRC indicates that ASTM D-3161 Class F is appropriate for sites in all cases where special fastening is required. Section R905.2.6 indicates that asphalt shingles shall be installed per the manufacturer's installation instructions. A recommended best practice is to use six fasteners per shingle, rather than the typical four, where the basic wind speed is greater than 90 mph (ASCE 7-05 wind speed).

Figure 4-33:
Home being reroofed with Class F shingles (see red arrows) (Port Aransas)

The type of installation (4-nail or 6-nail) is unknown.

As previously mentioned, hip roofs tend to perform well when subjected to high winds. The home shown in Figure 4-34 is in Port Aransas and lost areas of shingles due to poor adhesion of the leading edge of the shingles. Failure along eaves commonly occurs because of incorrect application of the starter course and inadequate hand-dabbing of asphaltic roof cement, as recommended in Technical Fact Sheet 7.3, “Asphalt Shingle Roofing for High-Wind Regions,” in FEMA P-499 (2010b), as illustrated in Figure 4-35.

Figure 4-34:
Home that lost shingles due to poor adhesion of the leading edges of the shingles (red arrows) (Port Aransas)



Shingle Installation at Eaves

Shingle Installation at Hips and Ridges

1. Apply four 1-inch dabs of roof cement to field shingle.
2. ***Set pre-cut shingle in place and press down in dabs of roof cement before installing fasteners.***
3. Install fastener on each side of ridge. Note: Because of extra thickness of shingles at hips and ridges, longer nails may be needed.
4. Apply two 1-inch dabs of roof cement to shingle where shown.
5. Repeat steps 2 through 4.

Note: Shingles should overhang drip edge by 1/4" at rake and eave.

Shingle Installation at Rakes

1. Apply two 1-inch dabs of asphalt roof cement on underlying shingle, and two 1-inch dabs on metal drip edge as shown.
2. Set overlying shingle in place and install fasteners except for last fastener at rake.
3. ***Press shingle down to set in dabs of asphalt cement before installing final fastener.***
4. Install final fastener at rake edge.
5. Repeat steps for each course.

Figure 4-35: Asphalt shingle roofing for high-wind regions

SOURCE: FEMA, 2010b (TECHNICAL FACT SHEET 7.3)

Hip, gable, and hip rafter ridges are particularly vulnerable to blow-off because winds increase over and around corners and edges. Figure 4-36 shows a Fulton home with generally good shingle performance apart from damage to the ridge vent and the loss of some eave and hip-ridge shingles due to loss of adhesion along the sealing strip.

Figure 4-36:
Home with damaged ridge, hip-ridges, and eave shingles (red arrows) due to poor adhesion of the shingle tabs (Fulton)

4.1.3.2 Architectural Standing Seam Metal Roofing

The two basic types of metal roofing are (1) common corrugated roofing that is surface-screwed to the substrate and (2) architectural standing seam metal roofing that is installed with a hidden clip system that is screwed to the substrate and to which the roofing is latched. Numerous finish colors and types of metals are available in architectural metal roofing.

Most of the metal roofing the MAT observed was prefinished steel. Many manufacturers offer a 20 year warranty for weather tightness and finish. Performance of this type of roofing depends on the quality of the substrate and the installation.

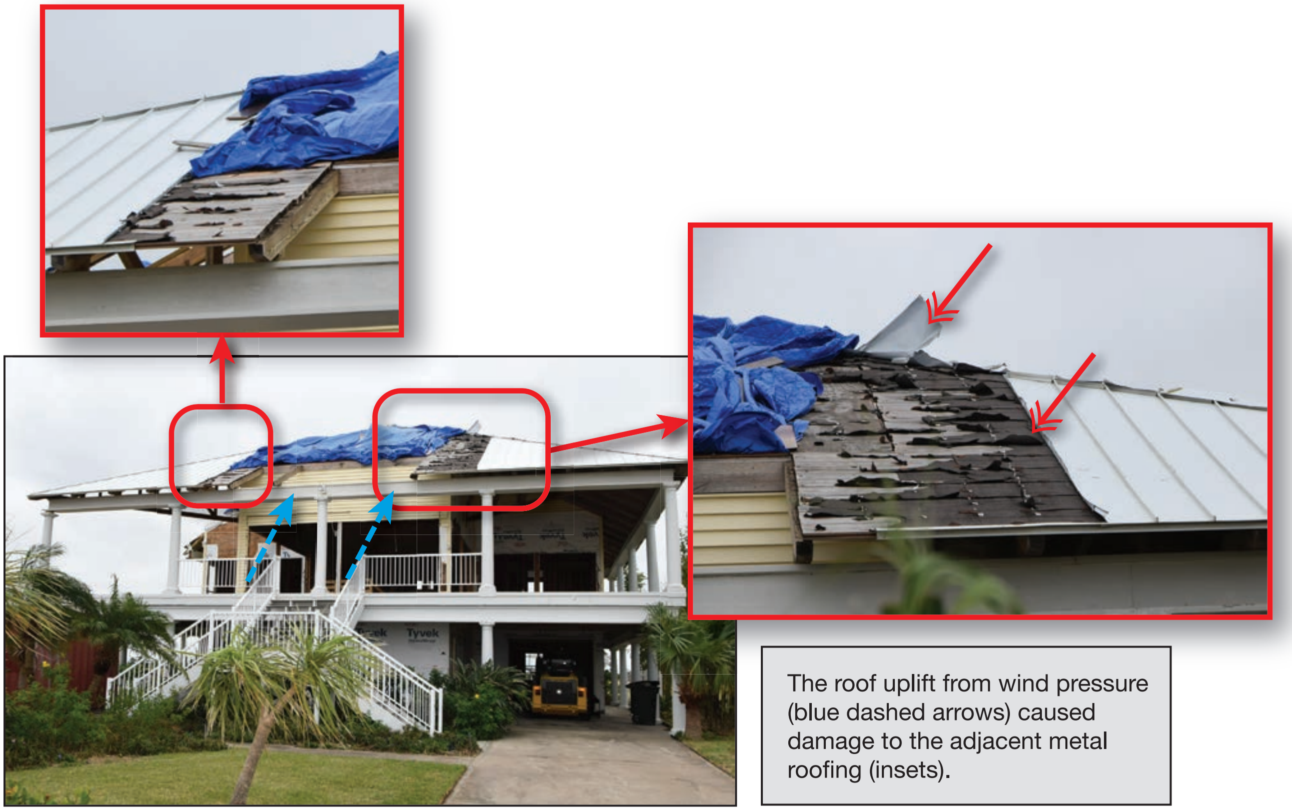
MAT Observations

The Copano Village home shown in Figure 4-37 shows a rake edge of the roof that appears to have been installed improperly because no edge nailing or edge trim was observed. Figure 4-38 shows another Copano Village home in which the substrate failed under the wind load, causing the metal roof to fail. The lack of membrane underlayment between the substrate and the roofing suggests that the installation may have been poor.

Figure 4-37: Residence with failed rake edge with loss of metal roofing edge trim (red arrows) (130 mph, Exposure B) (Copano Village)

Figure 4-38: Residence with failed substrate (green dotted arrows) and no membrane underlayment (red arrows) (Copano Village)

The home in Cape Valero shown in Figure 4-39 suffered severe standing seam roofing damage when the rake edge of the roof that was installed over asphalt shingles (red double arrows) and the rake edge became unlatched from the rake edge trim (blue dashed arrows).



The roof uplift from wind pressure (blue dashed arrows) caused damage to the adjacent metal roofing (insets).

Figure 4-39: Home damaged by wind pressure (130 mph, Exposure C) (Cape Valero)

4.1.3.3 Tile Roofing Systems

Tile roofing systems include clay tile, concrete tile, fiberglass tile, and metal tiles. Installation methods of these types of tiles vary. Some tiles are nailed to the substrate, while others require nailing strips, either vertical (up the slope) or horizontal (across the slope).

MAT Observations

The Key Allegro home shown in Figure 4-40 has clay tile with horizontal nailing strips. The mode of failure appears to have been wind uplift that "zippered" several sections of tile. Figure 4-41 shows a home in Copano Village with a concrete tile roof that failed when the roof structure failed.

4.1.4 Soffits, Fascia, and Roof Ventilation

Soffits, fascia, and roof ventilation are all vulnerable to high winds, and their failure can allow water into attics, damaging insulation and ceilings.

Figure 4-40: Home with clay tile roof failure (green arrows) (120 mph, Exposure C) (Key Allegro)

Figure 4-41: Home with concrete tile roof failure (red arrows) (120 mph, Exposure B) (Copano Village)

4.1.4.1 Soffits and Fascia

The opening created where the roof extends beyond the plane of the wall below (called eaves on the downslope side of a roof and a rake for the end of a gable roof) is normally closed off with a soffit. The fascia is the horizontal band at the roof edge. The soffit is the surface bounded by the fascia and below the rafters.

Soffit panels can be wood, hardboard, fiber cement, aluminum, or vinyl. They have aluminum or vinyl grilles or small openings, slots, or perforations to provide ventilation into the attic, which is particularly important in hot and humid coastal Texas. Soffit venting allows air to enter the attic space, circulate through the attic, and be exhausted through passive vents (ridge vents, off-ridge vents, or gable end vents) or mechanical vents. The loss of soffit vents can allow hurricane winds to drive large amounts of water through the openings and soak insulation, which can lead to mold growth and, in some cases, the collapse of ceilings.

Being the leading edge of the roof system, soffits and fascia are particularly vulnerable to high winds. Except for steeper sloped roofs, roof edges (eaves and rakes) sustain the highest uplift pressures on the roof system.

MAT Observations

The Copano Village home shown in Figure 4-42 is a classic representation of soffit and leading-edge sheathing failure due to wind pressurization from below and from within. Figure 4-43, which shows the same home, shows the roof overhang snapped off by the winds.

Figure 4-44 shows a soffit re-covered with vinyl soffit panels that were blown off, exposing the original attic vent opening. Figure 4-45 shows a soffit opening that was previously covered by a ventilating fiber-cement board.

Figure 4-42:
Home in which soffit and roof pressurization caused roof failure (red arrows) (120 mph, Exposure C) (Copano Village)

Green dotted arrow shows typical gable vent.

Figure 4-43:
Roof overhang that snapped off (red arrows); image is a different view of home shown in Figure 4-42 (120 mph, Exposure C) (Copano Village)

Figure 4-44:
Vinyl soffit product (green dotted arrow) removed by the storm, exposing the vent opening (red arrows) (120 mph, Exposure B) (Cape Valero)

Figure 4-45:
Ventilating fiber-cement board removed by the storm, exposing the attic (red arrows)
(120 mph, Exposure B)
(Holiday Beach)

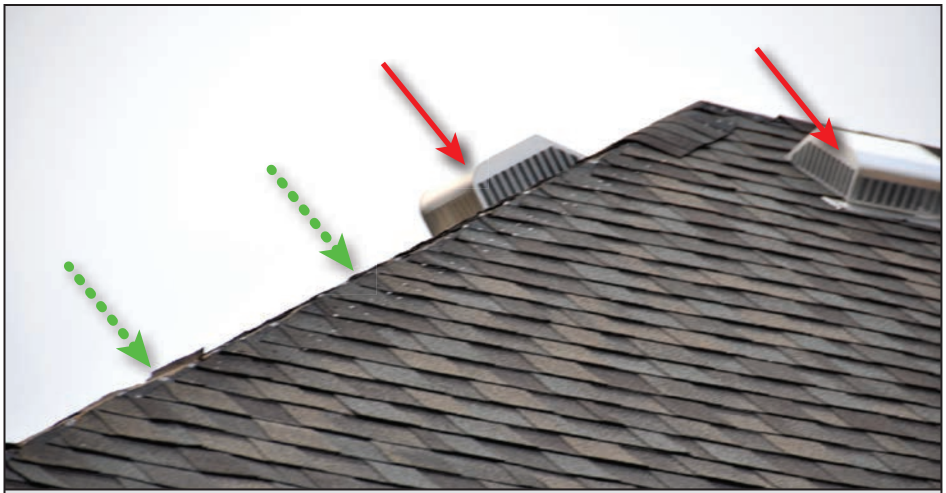
4.1.4.2 Roof Ventilation

Attic ventilation is a process of supplying fresh air through soffits or gable end vents, then exhausting the mixed attic air through ridge vents, off-ridge vents, or mechanical ventilators. Manufactured attic ridge vents are vulnerable to blow-off in high winds if not installed according to the manufacturer's recommendations. Guidelines require the contractor to cut the decking along both sides of the ridge line. Failure of the vent filter can allow blowing rain to enter the attic, and if a portion of the vent is lost, a 3-inch slot can open in the ridge and allow direct water intrusion into the attic.

MAT Observations

The Rockport home shown in Figure 4-46 lost a 4-foot section of its ridge vent. The Fulton home shown in Figure 4-47 shows a more conventional off-ridge attic vent that performed well, though the home lost most of its hip-ridge shingles.

Figure 4-46:
Home with a portion of ridge vent removed by Hurricane Harvey winds (red arrows)
(120 mph, Exposure B)
(Rockport)



The off-ridge attic ventilators performed well (red arrows) and hip-ridge shingles were blown off (green dotted arrows).

Figure 4-47: Home with off-ridge attic ventilators (120 mph, Exposure B) (Rockport)

4.1.5 Doors

Failure of an exterior door has two important consequences. First, the failure can cause a rapid increase in internal pressure, which may lead to exterior wall, roof, interior partition, ceiling, or structural failure. Second, wind can drive rainwater through the opening, causing damage to interior contents and finishes that can lead to the development of mold.

The essential elements of good high-wind door performance include product testing to ensure sufficient factored strength to resist design wind loads (both static and cyclic loading); suitable anchoring of the door frame to the building; proper flashing, sealants, tracks, and drainage to minimize water intrusion into wall cavities or into occupied space; and, for glazed openings, the use of laminated glass or shutters to protect against wind-borne debris damage.

MAT Observations

The wood-framed, light-metal-gauge double entry door in the Rockport canal residence, shown in Figure 4-48, failed as a result of Hurricane Harvey winds and debris that knocked the inactive door leaf off its hinges.

Figure 4-48:
The inactive leaf of the door to this residence failed when wind and debris tore the door from its hinges (red arrows)
(120 mph, Exposure C)
(Rockport)

4.1.6 Windows and Shutters

Many of the communities along the Texas coastline affected by Hurricane Harvey had adopted the 2009 IRC and ASCE 7-05 wind provisions, which require buildings in the most hazardous portion of the hurricane-prone region (wind-borne debris regions) to be equipped with impact-resistant glazing or shutters and the home to be designed as an enclosed structure.

TDI requires opening protection for both Seaward and Inland I Areas (see Figure 4-32 for TDI-designated Catastrophe Areas). As required by TDI, glazing or shutters must be impact-resistant as prescribed by the ASTM E1886 and ASTM E1996 test standards, which require resistance to impacts produced by a 9-pound, wooden, 2x4 board propelled at 34 mph (50 feet per second). Though not a TDI standard, many other States require the same resistance for wall and roof assemblies. The intent of the impact resistance standard is to minimize the number of breaches in the entire building envelope.

MAT Observations

At the time of the MAT visit, repairs to glazing and shutters on many homes had been started. The MAT observed compliant and non-compliant glazing on both new and pre-Harvey installations. The MAT was often unable to determine the rating of the existing double-paned windows it observed due to access, as well as damage to the outer pane that made the label illegible. The impact resistance of a window is best determined when investigating window replacements or windows in new construction that still have window labeling in place; see Figures 4-49 through 4-51. The inspector must locate the certification label affixed to the window frame to determine tested performance criteria for wind and impact tests. The label is issued by a certification agency such as the American Architectural Manufacturers Association (AAMA), Window and Door Manufacturers Association, or the National Accreditation and Management Institute, Inc, (NAMI).

Figure 4-49:
Outside layer of glazing sacrificed by the impact of wind-blown debris
(Key Allegro)

The red arrows indicate the sacrificed outer layer of glazing. Without labeling, the MAT was not able to determine whether the glazing was impact resistant.

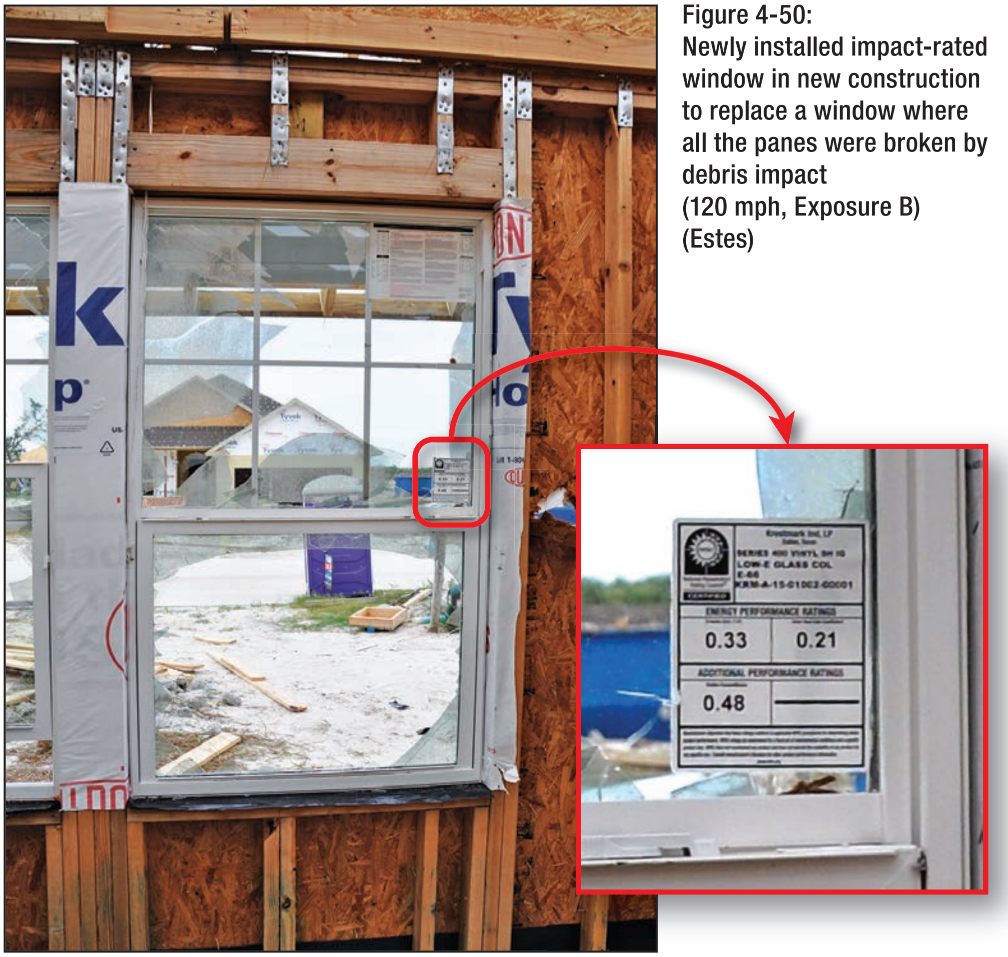


Figure 4-50:
Newly installed impact-rated window in new construction to replace a window where all the panes were broken by debris impact
(120 mph, Exposure B)
(Estes)

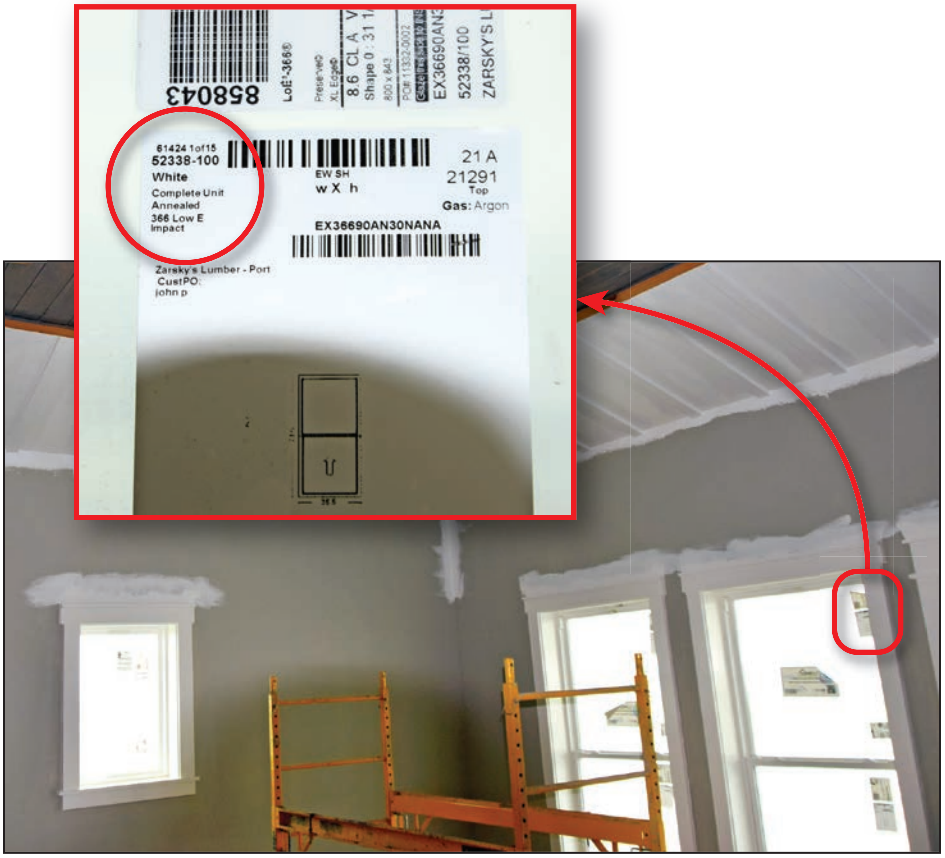
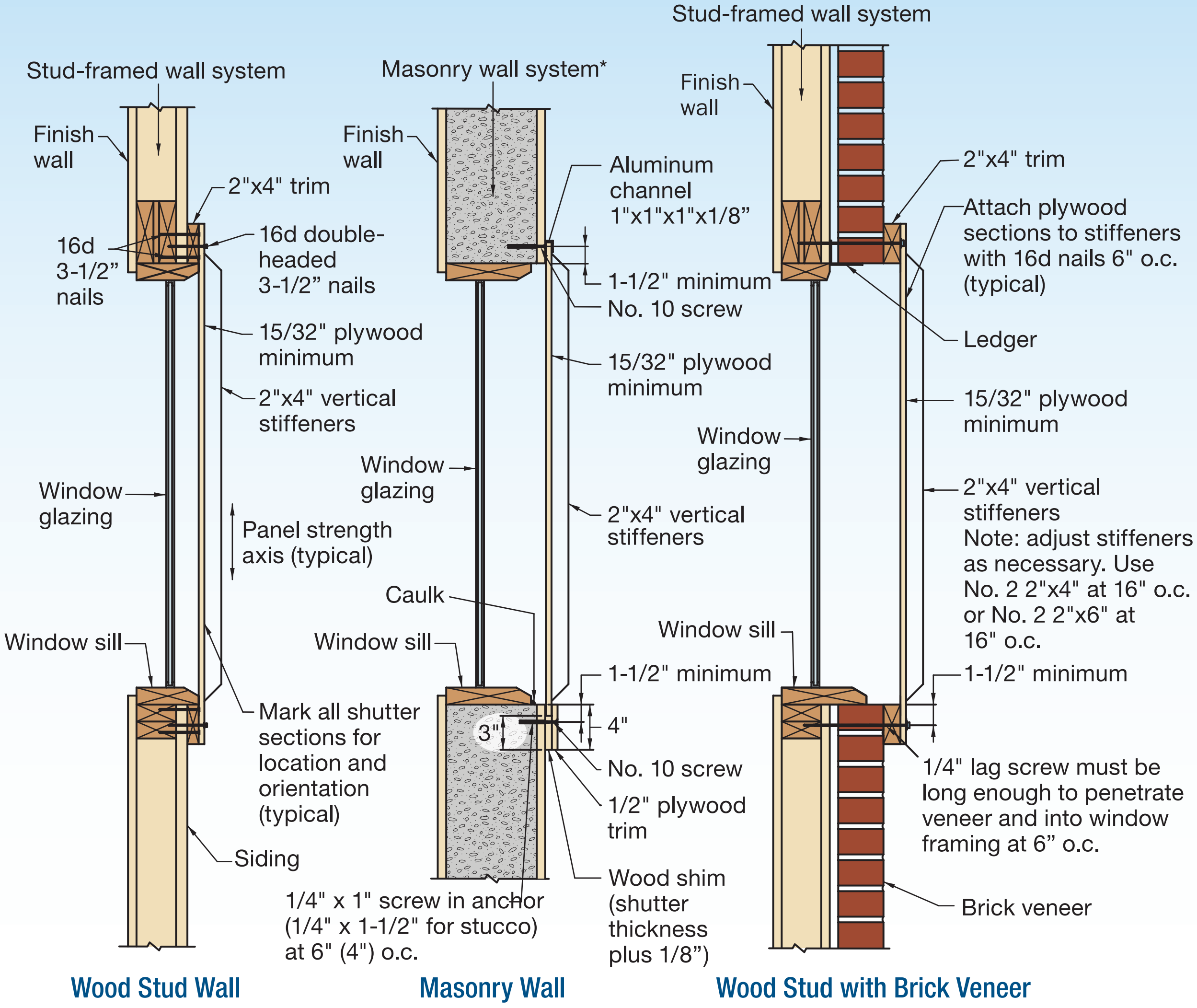


Figure 4-51: Impact-resistant glazing in new construction (red circle) (Cape Valero)

Many of the homes the MAT observed had windows that were protected by impact-resistant shutters in lieu of impact-resistant glazing. TDI minimally accepts 15/32-inch plywood shutters pre-cut to the size of each door and window. See Figure 4-52, from FEMA P-499, *Home Builder's Guide to Coastal Construction* (2010b), for recommended methods for plywood shutter attachment to wood-frame and masonry walls. The model International Code Council codes do not mandate the use of 2x4 stiffeners in conjunction with the wood structural panel, as shown in the illustration. Most structures in the affected area of Hurricane Harvey did not incorporate the 2x4 stiffener on the 15/32-inch plywood panel. Along with plywood shutter installations, the MAT observed many types of removable and operable shuttering systems, including classic fixed-in-place overhead coiling shutters that generally performed well; see Figures 4-53 through 4-60.



*For a latch bolt option of masonry walls, see the APA guidance

Common methods for plywood shutter attachment to wood-frame and masonry walls (only for use in residential structures with a mean roof height of 45 feet or less). For shutter design, details, and nail specifications, refer to APA guidelines for constructing plywood shutters (APA-The Engineering Wood Association, 2013).

Figure 4-52: Methods of plywood shutter attachment

SOURCE: FEMA, 2010b (TECHNICAL FACT SHEET 6.2)

Figure 4-53:
Typical plywood shutter installation on house (Rockport)

Figure 4-54:
Barn door sliding shutters on house shown by red arrow (Key Allegro)

Figure 4-55: Classic roll-down shutter with missile impact (red arrow) (Copano Village)

Figure 4-56: Operable Bahama shutters (red arrow) (Key Allegro)

Figure 4-57:
Bi-folding shutters (red arrows) on house (Rockport)

Figure 4-58:
Sliding slatted shutter system (red arrow) (Key Allegro)

Figure 4-59: Sliding plywood shutter frame system (red arrows) on house (Port Aransas)

Figure 4-60: Corrugated metal shutter system and storage system (Cape Valero)

4.1.7 Garage Doors

Because garage doors have a longer span and larger effective area than windows and access doors, garage door assemblies must resist higher forces even though they are exposed to the same basic wind speed. A breach increases internal pressures within the breached area of the building and commonly produces partial building failures in high-wind events, such as tornadoes and hurricanes.

According to the TDI's Designated Catastrophe Area map (see Figure 4-32), Mustang Island (Port Aransas) is classified as Seaward with a 130 mph design wind speed (3-second gust) per 2006 IBC/IRC as a Category C Exposure. For the 2012 IBC/IRC and later versions, the site would be classified as Category D Exposure (flat, unobstructed areas and water surfaces).The Ingleside, Rockport, Fulton, and Copano Bay communities are classified as Inland I with Exposure B and a 120 mph design wind speed. Unless a structure is elevated and required to have breakaway walls, the garage should be protected with doors meeting the required wind speed for the appropriate classification. However, TDI does not require garage doors to be impact rated for Inland I, unless the garage door includes glazing. TDI requires garage doors to be rated to meet or exceed the code required design pressure. Garage doors that are part of a breakaway storage area are not required to comply with minimum design pressure requirements specified by code. In the Seaward area, all openings must be impact resistant or protected by wind-borne debris panels.

MAT Observations

The MAT observed many garage doors that were not rated for high winds that failed during Hurricane Harvey (see examples in Figures 4-61 and 4-62) but very few hurricane-rated garage doors that failed. Figure 4-63 shows a partial failure that appears to have been caused by negative pressure. Figure 4-64 is a 150 mph-rated hurricane garage door in a new home in Cape Valero on Copano Bay (130 mph wind speed, Exposure C) with no damage. Figure 4-65 shows a hurricane-rated garage door in a Fulton home remained closed even though it suffered two bent roller wheels apparently from the impact of adjacent site construction material (130 mph wind speed, Exposure B).

Figure 4-61: Home with wind failure of an unreinforced garage door (red arrow) (Cape Valero)

Figure 4-62: Home with insulated unreinforced garage door with loss of the lower exterior panel (red arrows) (Estes)

Figure 4-63: Hurricane-rated garage door that was damaged (red arrow); cause of failure unknown (Cape Valero)

Figure 4-64: 20 feet x 9 feet hurricane-rated garage door that was not tested by debris impacts; red arrows show hurricane door stiffeners (Cape Valero)

Figure 4-65: Hurricane-rated (red arrow) garage door subjected to debris impact resulting in two bent rollers (green dotted arrows) (130 mph, Exposure B) (Fulton)

4.1.8 Debris Impacts

Flying debris is a common occurrence in all high-wind events. The size of debris that can become wind-borne increases as wind speeds increase. In wind speeds of 120 to 140 mph, such as those produced by Hurricane Harvey, significant amounts of lighter debris, such as shingles, metal and tile roofing, and building siding, along with heavier debris, such as roof sheathing and structural elements, are released as flying projectiles that impact buildings. The impacts of the debris break windows and puncture doors, walls, and roofs. The envelope openings produced by these impacts allow wind to enter the structure, thereby causing internal pressurization, which, when added to the external pressures, can cause the building structure to fail. Furthermore, punctured and broken elements allow hurricane rains to enter the structure, thus damaging building contents and soaking building elements, which fosters mold growth.

MAT Observations

The MAT observed debris impacts throughout the Hurricane Harvey damage area as shown in Figures 4-66 through 4-71.

The MAT could not determine whether the windows were impact resistant, but they were still broken (red arrow). The residence received multiple debris impacts (red arrows).

Figure 4-66: Post-2009 home that was well anchored and clipped and even had a garage door rated for high-wind zones (140 mph, Exposure C) (Key Allegro)

Figure 4-67:
Impact from 2x4 on fiber cement siding (red arrow) (120 mph, Exposure C) (Key Allegro)

Figure 4-68:
Plywood debris impact on hardboard siding (red arrow) (120 mph, Exposure C) (Port Aransas)

Figure 4-69: Small debris impacts on stucco walls (red arrows) (120 mph, Exposure C) (Key Allegro)

Figure 4-70: Multiple debris impacts on hardboard siding (red arrows) (120 mph, Exposure C) (Holiday Beach)

Figure 4-71:
Large impact on fiber cement wall on the backside of the same residence as shown in Figure 4-66 (red arrows) (140 mph, Exposure C) (Key Allegro)

4.2 Non-Residential Buildings

Non-residential buildings include commercial, critical, and government facilities that may or may not be deemed critical. Critical facilities include schools, fire and police stations, nursing homes, and hospitals. The MAT made wind performance observations of all of these building types.

Section 4.2 includes pertinent observations of the MWFRS (Section 4.2.1); roof systems and rooftop equipment (Section 4.2.2); non-load-bearing walls, wall coverings, and soffits (Section 4.2.3); doors, windows, and shutters (Section 4.2.4); and building operational issues (Section 4.2.5).

Unless otherwise noted, the estimated wind speed at the buildings discussed in this section was 130 mph (gust, Exposure C, at 33 feet above grade), based on Figure 1-11. Also, unless noted otherwise, the buildings are located in Exposure B.

General Observations

Roof covering and rooftop equipment damage was the most common type of damage observed for all building types. As expected, newer buildings typically performed better than older buildings. Critical facilities observed by the MAT generally did not perform significantly better than commercial buildings. The observed critical facilities typically did not incorporate the best practices provided in FEMA P-424 (schools), FEMA P-543 (critical facilities), and FEMA P-577 (hospitals).

FEMA P-1000, *SAFER, STRONGER, SMARTER:*
***A GUIDE TO IMPROVING SCHOOL NATURAL HAZARD SAFETY* (2017)**

This publication provides "up-to-date, authoritative information and guidance that schools can use to develop a comprehensive strategy for addressing natural hazards. It is intended to be used by administrators, facilities managers, emergency managers, emergency planning committees, and teachers and staff at K through 12 schools. It can also be valuable for state officials, district administrators, school boards, teacher union leaders, and others that play a role in providing safe and disaster-resistant schools for all. Parents, caregivers, and students can also use this guide to learn about ways to advocate for safe schools in their communities."

Available at www.fema.gov/media-library/assets/documents/132592.

4.2.1 Main Wind Force Resisting System

Although the MAT saw MWFRS failure at some older buildings, the MAT made detailed observations of MWFRS failure at only two locations because it believed there would be limited opportunity to learn from additional observations of older failed MWFRS.

4.2.1.1 Nursing Home in Rockport

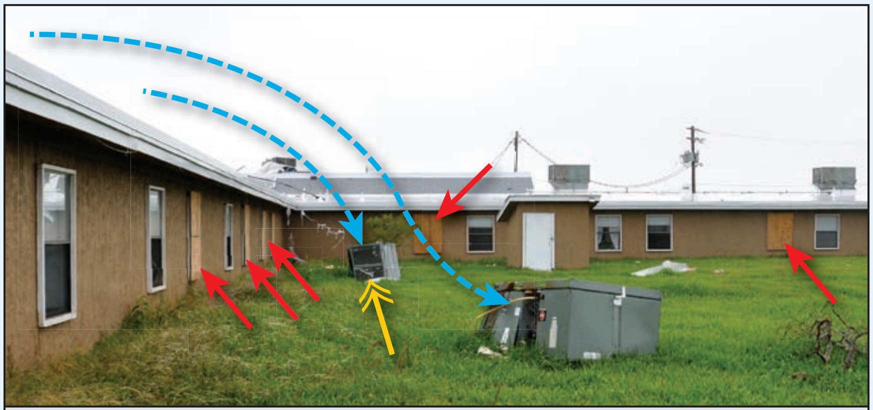
Figure 4-72 shows a collapsed wood-framed porte cochere at an 88-bed nursing home. Part of the roof deck also blew off, as shown in the aerial drone image of this building in the text box titled "Aerial Drone" in Chapter 1. The building was not occupied at the time of the MAT observations.

Figure 4-72: Collapsed porte cochere at a nursing home

ADDITIONAL DAMAGE OBSERVED AT NURSING HOME IN ROCKPORT

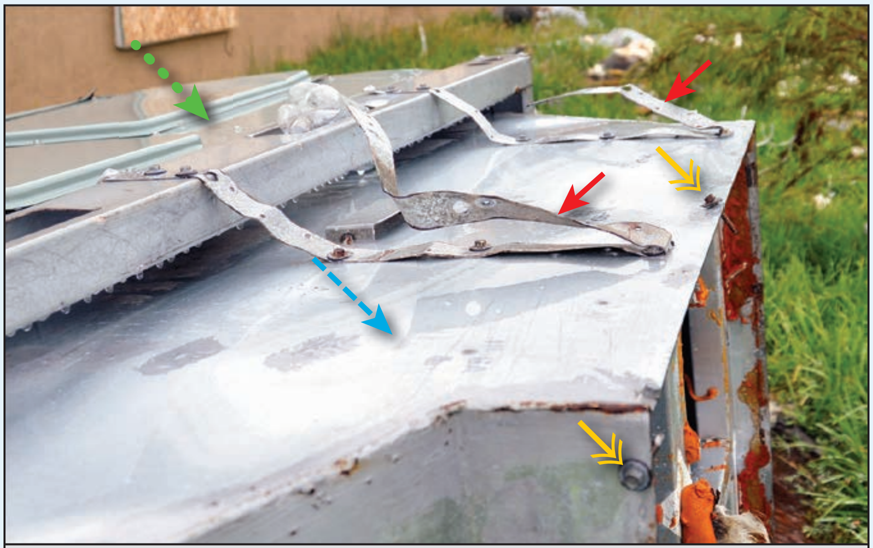
In addition to the MWFRS collapse observed at the nursing home, a few HVAC units (also known as rooftop units) were blown off the roof, and several windows were broken (Figure 4-73). All or most of the HVAC units sat on a sheet metal curb adaptor, which sat on a curb. The unit indicated by the yellow double arrow in Figure 4-73 is also shown in Figure 4-74. At this unit, straps connected the unit, curb adaptor, and curb. The curb adaptor was also screwed to the curb. Some attention was given to connecting the unit to the curb. However, although there was a complete load path, the load path had inadequate strength to resist the wind load. The curb was not examined to determine the type of attachment deficiency because access to the roof was not obtained.

Figure 4-73:
Blown-off HVAC units at a nursing home (see Figure 4-74 for the unit indicated by the yellow double arrow)



The blue dashed arrows show where two HVAC units were blown off of the nursing home. See Figure 4-74 for the unit indicated by the yellow double arrow. The red arrows indicate oriented strand board over windows that were believed to be broken.

Figure 4-74:
View of one of the HVAC units indicated by a yellow double arrow in Figure 4-73



The green dotted arrow indicates the unit. The blue dashed arrow indicates the curb adaptor. The red arrows indicate straps that were supposed to attach the unit, curb adaptor, and curb. The yellow double arrows indicate screws between the adaptor and the curb (which was still on the roof).

4.2.1.2 Texas Department of Transportation Maintenance Facility in Rockport

The other building with an MWFRS failure that the MAT observed was an older Texas Department of Transportation maintenance facility, in which much of the roof structure was blown off (Figures 4-75 and 4-76). The steel roof deck was welded to steel joists that were supported by unreinforced CMU-bearing walls between CMU pilasters.

Roof joists were blown off the wing indicated by the red line. The yellow outline indicates where the CMU wall between pilasters collapsed. Note the collapsed communications tower.

Figure 4-75:
General view of the leeward side of the Texas Department of Transportation maintenance facility

The yellow X's indicate where the roof structure was blown off. The yellow polygon and the yellow arrow indicate where large sections of the roof assembly landed (see Figure 4-77).
The collapsed communications tower is to the right of the red line. The blue dashed arrow indicates the location on another building where metal roof panels blew off.

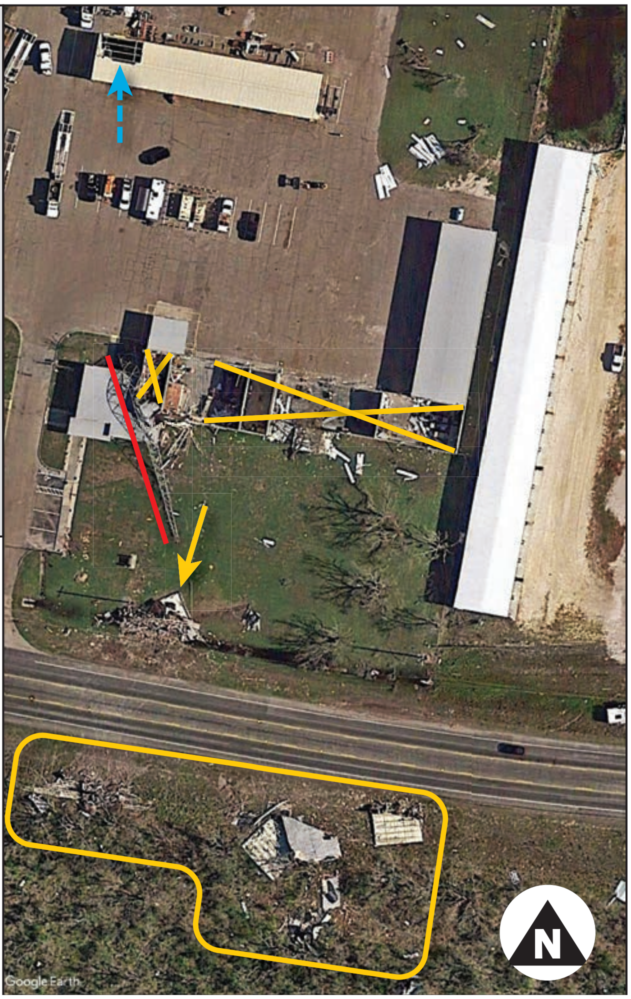


Figure 4-76:
Aerial view of the Texas Department of Transportation maintenance facility showing damage to buildings (Exposure B, with a large open patch adjacent to and north of the building)

One large section of the roof assembly was blown approximately 120 feet, and other portions were blown approximately 250 feet from the building (Figure 4-76). One wind-borne roof assembly flattened a large light fixture (Figure 4-77).

Figure 4-77: Wind-borne roof assembly debris (roof assembly is upside down)

The red arrow indicates a collapsed light fixture.

All of the maintenance bay doors on the windward side of the building were blown into the building (Figure 4-78). Although failure of the large doors increased the internal pressure, the primary cause of roof structure failure was inadequate connection of the steel joists. In some locations, the welds between the joist and bearing plate failed (Figure 4-79). However, the typical failure mode was uplifting of the bearing plate because the plate's studs were not grouted into the bond beam (Figure 4-80).

Figure 4-81 shows the opposite side of the wall shown in Figure 4-78. The exterior windows were protected by storm shutters. The shutters were not labeled. At this building, shutters were not effective at mitigating damage because there were other significant vulnerabilities (e.g., inadequately attached roof joists and decking) that had not been addressed.

The MAT visually evaluated the arc spot welding of the deck to the joists. Similar to observations made by several previous MATs during past events, weld quality varied. Figure 4-82 shows two adjacent deck arc spot welds. One weld was superficial—the deck detached from the weld. The other weld was stronger; a portion of the deck remained attached to the weld.

At the time of the MAT visit, a portable communications tower had been deployed to the site to compensate for the collapsed communication tower (Figure 4-83). Post-event response is more difficult when vital communications towers fail, thus necessitating the deployment of a portable tower.

Figure 4-78: Windward side of the building

The red arrow indicates the collapsed communication tower. Note that the top of the CMU wall is missing (red rectangle). The bond beam did not have vertical reinforcement into the wall.

Figure 4-79: Joist bearing plate that is still attached to a bond beam that blew off

The red lines are left of the welds that attached the joist.

Figure 4-80:
Bearing plate studs that were not grouted into the bearing wall and provided no uplift resistance. This condition was observed at many of the joists

Figure 4-81:
Although the exterior windows were protected with shutters (red arrows), the roof structure failure nullified their effectiveness

IMPORTANCE OF WIND VULNERABILITY ASSESSMENT

The Texas Department of Transportation Maintenance Facility illustrates the importance of performing a wind vulnerability assessment prior to implementing wind mitigation measures, such as installing storm shutters. If a reasonably thorough assessment is not performed before executing mitigation work, there is high potential that mitigating significant vulnerabilities will be overlooked. In addition, as shown in Figure 4-81, the implemented mitigation may not be effective.

The weld in the red circle was superficial; no deck material remained at this location. At the weld in the blue dashed circle, deck material remained.

Figure 4-82: Deck arc spot welds

Figure 4-83: Portable communications tower

4.2.2 Roof Systems and Rooftop Equipment

Roof systems. A variety of roof systems were observed, including built-up roofs (BURs), modified bitumen, single-ply membranes (adhered and mechanically attached), metal panels, asphalt shingles, and tile. Older roof systems generally did not perform well. Several of the newer roof systems did not blow off, but many were punctured by wind-borne debris (much of which was displaced rooftop equipment). Improved wind performance of metal edge flashings and copings in newer construction appeared to be a significant contributor to the reduction in the number of membrane blow-offs. The improved performance of the metal edge flashings and copings is likely due to IBC's reference to ANSI/SPRI/FM 4435/ES-1 2017, *Test Standard for Edge Systems Used with Low Slope Roofing Systems* (ES-1 was first incorporated into the 2003 edition of the IBC).

Rooftop equipment. Common rooftop equipment failures included condenser and HVAC unit blow-off due to lack of or inadequate attachment to curbs, blow-off of HVAC unit access panels, blow-off of HVAC sheet metal unit enclosures (cabinets), blow-off of condensate drain lines, and blow-off of lightning protection systems (LPS). When HVAC units blow off their curbs, rain can freely enter the building. Wind-borne rooftop equipment, including access panels, sheet metal unit enclosures, condensate drain lines, and LPS can puncture and tear roof membranes.

ADDITIONAL GUIDANCE

USVI Recovery Advisory 2, *Attachment of Rooftop Equipment in High-Wind Regions* (2018d), provides guidance for attaching new and existing rooftop equipment, preparations prior to hurricane landfall, and post-event assessment.

Developed by the MAT deployed to the U.S. Virgin Islands, it incorporates findings from the Hurricane Harvey MAT.

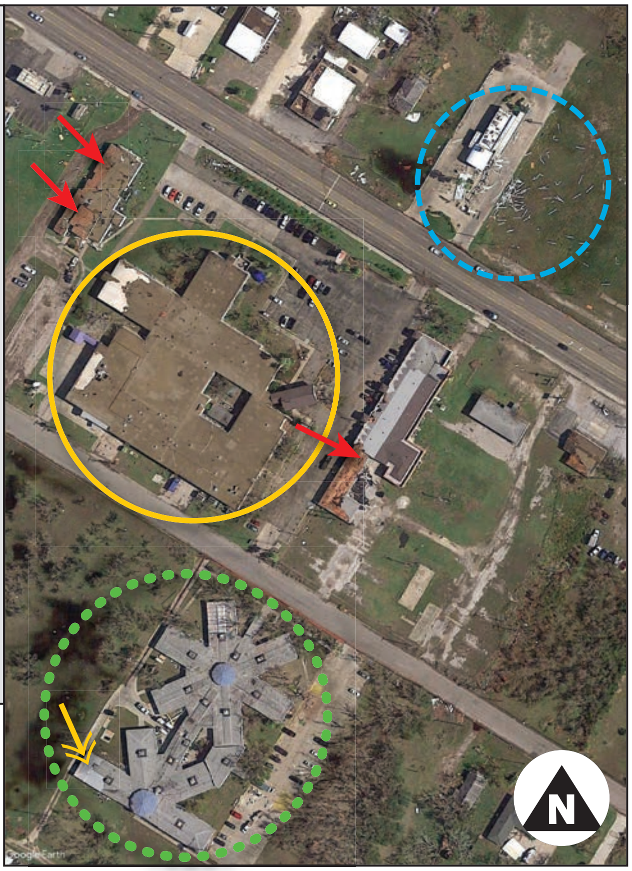
Portions of several roofs were tarped at the time of the MAT observations. It was not possible to determine the cause of damage in many of the tarped areas. Some of the observed roofs only experienced roof membrane or rooftop equipment damage, while others experienced both types of damage. The following subsections provide a synopsis of key observations.

4.2.2.1 Regional Medical Center in Aransas Pass

Figures 4-84 through 4-93 show a regional medical center in Aransas Pass. This older facility had an aggregate surfaced BUR over steel deck and joists. Beginning with the 2006 edition of IBC, aggregate roof surfacing is not permitted in hurricane-prone regions. However, there is no provision in the IBC or International Existing Building Code® (IEBC®) that requires existing aggregate surfaced roofs to be removed. The concern with aggregate surfacing is that wind-borne aggregate has the potential to break unprotected glazing. Also, people arriving at a hospital during a hurricane may be injured by aggregate blowing off the hospital's roof.

Figure 4-84: General view of the regional medical center (Aransas Pass)

A large portion of the roof membrane over the emergency room area blew off (Figures 4-85 and 4-86). In one area, the blow-off appeared to be initiated by the lifting of the top nailer to which the gutter was attached (Figure 4-87). In other areas, gutter uplift initiated the blow-off.



The hospital is in the yellow circle; the two white areas are where the roof membrane blew off. The red arrows indicate roof damage at the medical office buildings. A fast food restaurant and metal roof panel debris from it are in the blue dashed circle. A 170-bed nursing home is in the green dotted circle; the yellow double arrow indicates roof membrane blow-off (tiles were also blown off mansards and steep-slope roofs). The nursing home was shut down at the time of the MAT observations.

Figure 4-85:
Aerial view of the vicinity of the hospital (Exposure B, with open patches to the northwest) (Aransas Pass)

Figure 4-86:
View of emergency repairs to the roof above the emergency room area

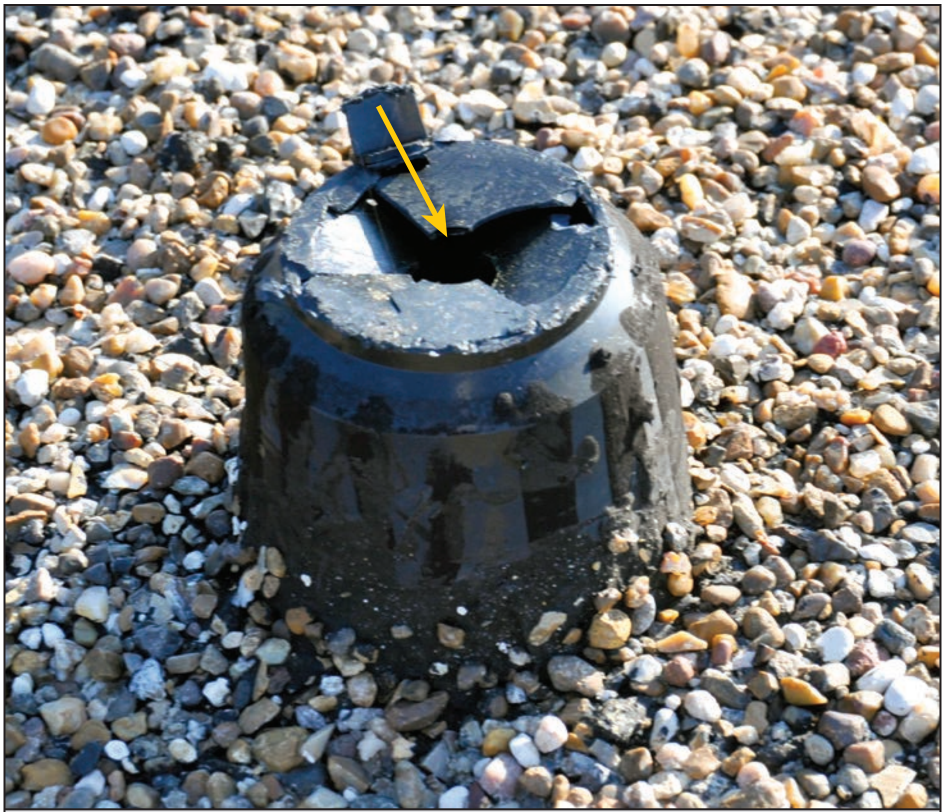
The red arrow indicates a section of metal edge flashing.

Figure 4-87:
Emergency room roof membrane

The red arrow indicates where the top nailer is missing. The blow-off likely initiated in this area. The blue dashed arrow indicates a section of gutter that lifted but remained attached, illustrating the importance of having nailers adequately attached.

Figure 4-88 shows an insulation moisture relief vent. These vents were common in the late 1970s, but their use declined after research found them to be ineffective. The vent's plastic cap is missing. Based on the fact that the top of the vent was fractured, the cap was likely dislodged by wind-borne debris. In this condition, rain was able to enter through the open top of the vent and migrate into the interior of the hospital.

There was extensive damage to rooftop equipment (Figures 4-89 through 4-91). Rain entered the hospital at some of the damaged equipment penetrations, and wind-borne equipment may have punctured the roof membrane in some locations. In some instances, displaced equipment had been attached, but the attachment was inadequate. In other instances, the equipment was not attached at all.



Water was able to enter the hospital at the unprotected vent opening (yellow arrow).

Figure 4-88: Unprotected vent opening

Condenser that was attached to a wood pallet; the pallet simply rested on the roof surface. Metal edge flashing debris is in the lower left.

Figure 4-89: Inadequate attachment of rooftop condenser

The condensers shown in Figure 4-90 were attached to 4x4 wood sleepers that simply rested on the roof surface. This type of equipment support (i.e., lack of anchorage) is inadequate. Portions of the sheet metal unit enclosure (cabinet) at one of the condensers were blown away. Wind-borne sheet metal unit enclosures can puncture roof membranes and break unprotected glazing.

Figure 4-90:
Inadequate attachment of rooftop condensers

Condensers that were attached to wood sleepers, but the sleepers were not attached to the roof.

Figure 4-91 is a view of a displaced satellite dish. Rather than being mechanically attached to the roof structure, the base plates of the satellite dish's support legs simply rested on the roof surface and were ballasted with solid CMUs, which did not provide adequate wind resistance. In 2004, the Hurricane Charley MAT for Florida observed a nearly identical condition (FEMA 488, 2005b). Displaced satellite dishes can rupture roof membranes and cause other damage or injury. FEMA P-577, *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds* (2007b), recommends that ballast not be used to anchor satellite dishes in high-wind areas. Rather, the wind load should be calculated for the dish, and a suitable mechanical attachment to the roof deck or structure should be designed.

Figure 4-91:
Displaced satellite dish (yellow box) and masonry ballast (red dashed box)

At the time of the MAT observations (14 days after the storm), cleanup and drying operations were underway (Figure 4-92). Rain leaking from the roof did not enter all rooms. Where it had entered, the ceiling and gypsum wallboard had been removed.

Figure 4-93 shows one of the piles of debris that had been removed from the hospital.

Evacuation of the hospital began the day before the hurricane made landfall and was completed the next afternoon. As of the date of this report, the facility had not reopened. Repairing the facility was considered, but it was determined that it was more cost-effective to build a new facility.

Figure 4-92:
View down one of the main hospital corridors

At the time of the MAT visit, the ceiling boards and gypsum wallboard had been removed, and temporary ventilation ducts had been installed.

Figure 4-93:
Cabinets and other debris from within the hospital

4.2.2.2 Fisheries Laboratory in Port Aransas

Figures 4-94 and 4-95 show a fisheries laboratory in Port Aransas. This older building had an aggregate surfaced BUR that appeared to be mechanically attached to lightweight insulating concrete over a cast-in-place concrete deck. The roof membrane lifted and peeled in two areas, as shown at Figure 4-94, and some rooftop ductwork was blown away (Figures 4-94 and 4-95). However, only a limited amount of water leaked into the building at damaged rooftop equipment. The cast-in-place roof deck functioned as a secondary membrane and prevented leakage even though the roof membrane blew off in two areas. The laboratory was operational at the time of the MAT observation. This building illustrates the value of providing a secondary membrane, as recommended in FEMA P-424, P-543, and P-577.

Figure 4-94:
Aerial view of the vicinity of the fisheries laboratory (135 mph, Exposure D) (Port Aransas)

The laboratory is in the yellow dotted rectangle; the two white areas are where the roof membrane blew off. The yellow line indicates the vicinity of the damaged ductwork. The red rectangle indicates roof damage at a nearby building. The houses in the west side of the photo had little if any roof damage; the roof on the southern-most house is tile, and the roofs on the other houses are asphalt shingles.

Figure 4-95: Damaged ductwork at the fisheries laboratory

Yellow rectangles indicate the damaged ductwork; the duct openings were temporarily protected when the photo was taken. Yellow arrow shows displaced LPS.

4.2.2.3 Older Building with Aggregate Surfaced BUR

The building in the foreground of Figure 4-96 is an older building with an aggregate surfaced BUR. Figure 4-97 shows the same building. The roof membrane remained in place, but there was extensive aggregate blow-off. The inset in Figure 4-96 shows the back side of an adjacent house; a large tree limb fell onto the roof, and a portion of the roof structure from a nearby house landed on the roof.

Aggregate surfaced BURs normally have a minimum of 4 pounds of aggregate per square foot (psf). Approximately half of the aggregate is typically embedded in the flood coat. The remaining aggregate is loose and therefore susceptible to blow-off. Some adhered aggregate is also sometimes blown off after being struck and dislodged by other wind-borne aggregate, but most of the adhered aggregate typically remains in place. The roof shown in Figure 4-97 was atypical. As shown in the figure, much of the roof surface was bare. At the bare areas, the flood coat was either too cool at the time of aggregate placement or too thin to effectively adhere the aggregate.

Figure 4-96:
Building with aggregate surfaced BUR (Exposure D)

The red arrow indicates the building with the aggregate surfaced BUR. The yellow oval indicates debris that landed on the adjacent house (the inset shows the back side of the house).

Figure 4-97:
Roof of the building shown in Figure 4-96 showing extensive aggregate blow-off

The red arrow indicates aggregate that remained adhered to the roof membrane, and the yellow double arrow indicates bare membrane.

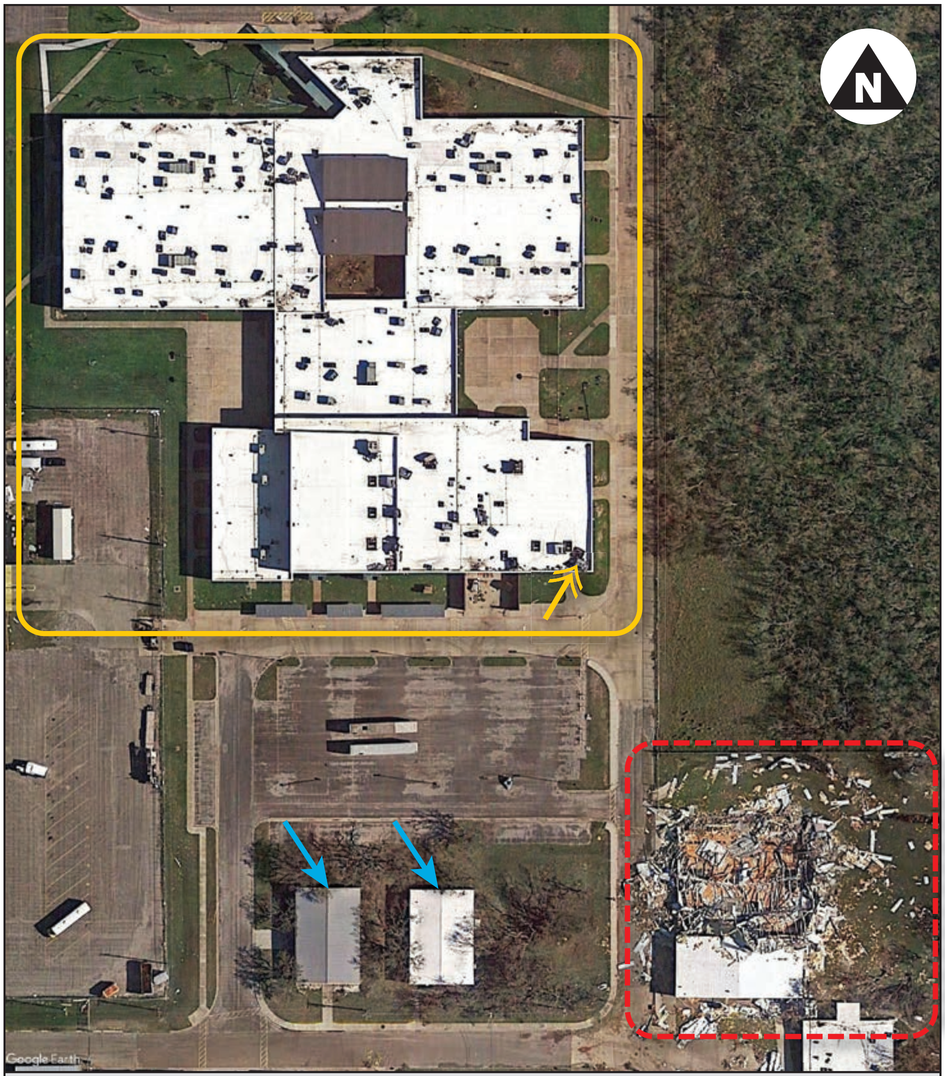
The house adjacent to the aggregate surfaced roof had storm shutters that effectively protected the windows (Figure 4-98).

Figure 4-98:
The red arrow indicates metal storm shutters. The yellow double arrow indicates aggregate blown from the roof shown in Figures 4-96 and 4-97

4.2.2.4 Rockport-Fulton Middle School

Figures 4-99 through 4-105 show the Rockport-Fulton Middle School, which opened in 2001. It had widespread interior water damage that was caused by roof damage. Most or all of the roof damage was caused by HVAC units that blew off their curbs. The displaced equipment punctured or tore the mechanically attached single-ply membrane, which was over insulation over steel deck. Because the membrane was not adhered, once the membrane was punctured or torn by wind-borne debris, water was able to readily enter the roof system. With no secondary membrane over the steel deck, water easily leaked into the interior of the building at equipment curb openings and at membrane punctures and tears.

Figure 4-99:
Rockport-Fulton Middle School. The HVAC units from the roof that were damaged had been moved to the ground after the storm and are shown in the foreground (Rockport)



The yellow rectangle shows the Rockport-Fulton Middle School. The yellow double arrow indicates an HVAC unit that was resting on top of the parapet. A collapsed gym is shown in the red box (see Figure 4-101). The blue arrows indicate metal building systems that had no apparent damage.

Figure 4-100: Aerial view of the Rockport-Fulton Middle School (Exposure B, with open patches adjacent to and west and south of the school)

Figure 4-101: Collapsed, older metal building system shown in the lower right of Figure 4-100

This was a gymnasium that served the nearby high school. The yellow arrow indicates the middle school.

Figure 4-102 shows the northwest roof of the middle school. Other roof areas were similarly damaged. Figure 4-103 shows an HVAC unit that blew off the roof.

Figure 4-102: Damage to northwest roof of middle school

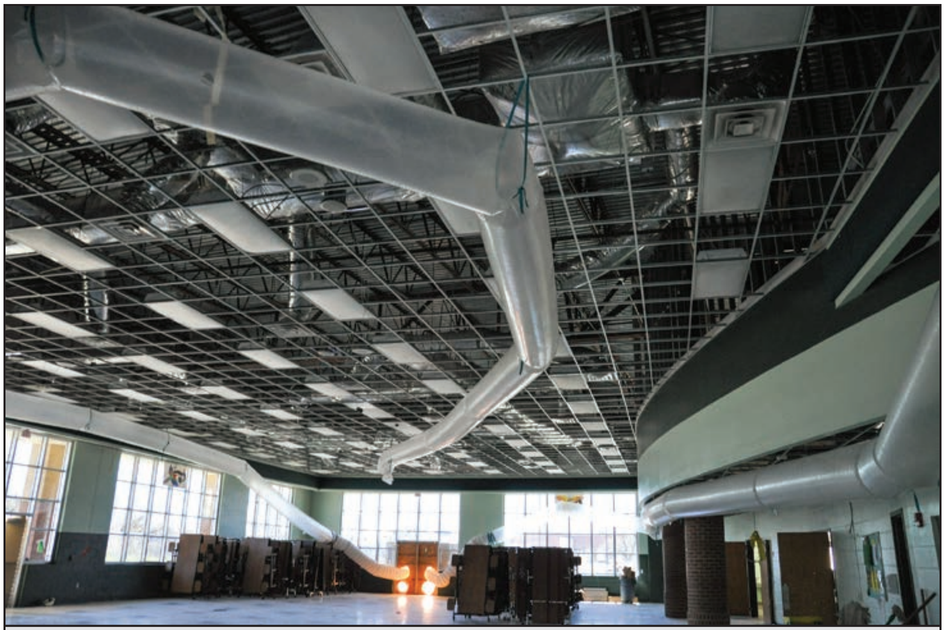
The red arrows indicate where HVAC units were blown off their curbs (the curb openings were temporarily covered with plywood). Emergency patches had been installed at membrane punctures (blue dashed arrow). The gas lines (green dotted arrow) had ruptured.

Figure 4-103: HVAC unit (red arrow) that blew off the roof and a collapsed light fixture next to the school (yellow double arrow; see Figure 4-104)

Figure 4-104: Collapsed light fixture. There was significant corrosion of the tube near the base plate

At the time of the MAT observations (14 days after the storm), approximately 50 people involved in cleanup and drying operations were on site. The entire school was shut down. Rain leaking from the roof did not enter all rooms. Where it had entered, the ceiling had been removed (Figure 4-105).

Figure 4-105:
Interior view of the cafeteria



At the time of the MAT visit, the ceiling boards had been removed and temporary ventilation ducts had been installed.

4.2.2.5 Live Oak Learning Center

Figures 4-106 through 4-113 show the Live Oak Learning Center, which opened in 2013. The mechanically attached single-ply membrane remained attached, even though sections of coping were blown off. The first row of membrane fasteners was 2 feet 3 inches from the parapet (which was 2 feet 8 inches high). The second row was 2 feet 3 inches from the first. Subsequent rows were 6 feet 3 inches on center. The MAT checked the windward corners and perimeter for membrane tearing near the fastener rows and checked some fasteners for backout. Although membrane tearing and/or fastener backout may be caused by dynamic loading induced by hurricanes, the MAT surmised that these problems did not occur during this event in the areas that were checked.

There was interior water damage in portions of the area below the main roof. Most of the water entered where the roof membrane had been punctured or torn by wind-blown debris. Water also entered where an exhaust fan was blown away. The membrane was over insulation, which was over steel deck. Because it was not adhered, once the membrane was punctured or torn by wind-borne debris, water readily entered the roof system. With no secondary membrane over the steel deck, water easily leaked into the interior of the building. At the time of the MAT observations (78 days after the storm), the elementary school was in session.

The red lines on Figure 4-106 indicate where coping was blown off. The blown-off copings appeared to be a major cause of roof membrane punctures and tears. The rooftop mechanical equipment shown in Figure 4-106 consisted of exhaust fans and relief air hoods. In lieu of rooftop HVAC units used at the school shown in Figure 4-100, this school used cooling towers, which were anchored to their supports (Figure 4-107). Hence, this school had far fewer pieces of rooftop equipment.

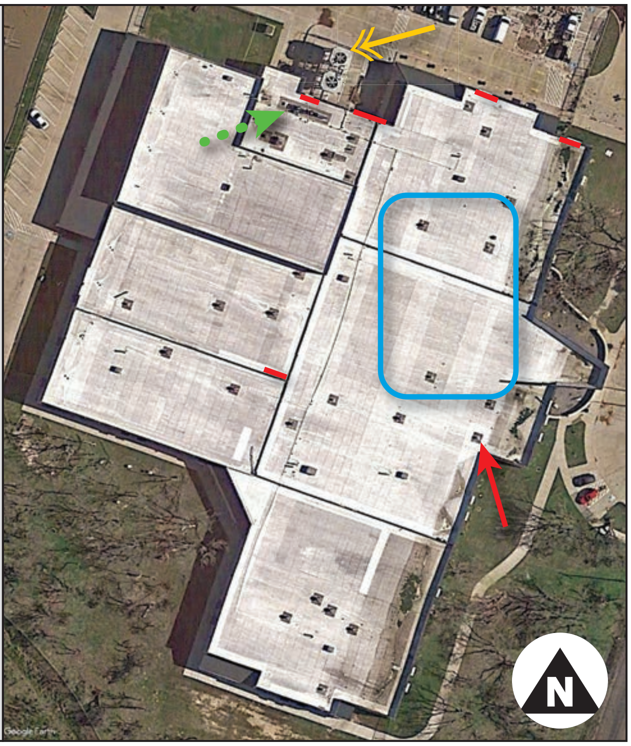
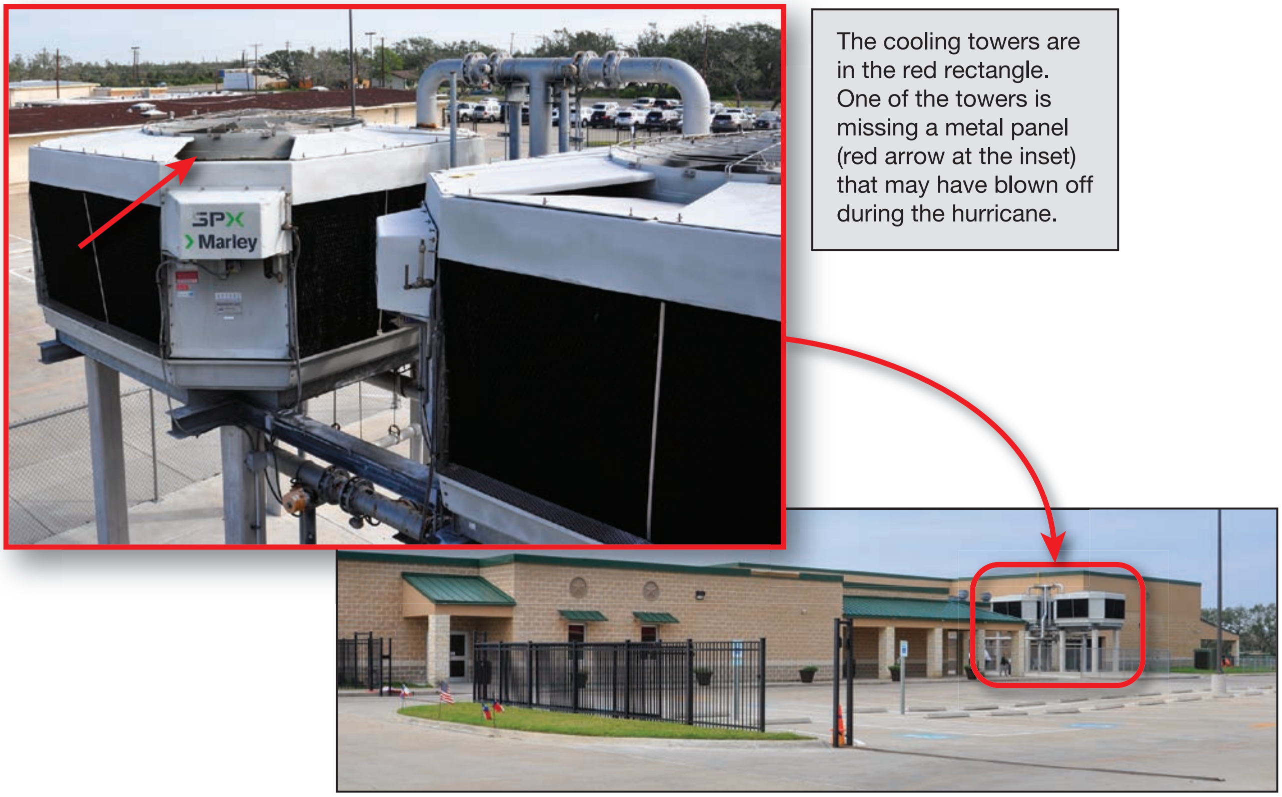


Figure 4-106: Aerial view of the Live Oak Learning Center showing damage (Exposure B, with a large open patch adjacent to and northwest of the school) (Rockport)

The yellow double arrow indicates cooling towers (see Figure 4-107). The red lines indicate blown-off copings (see Figures 4-108 and 4-109). The MAT observed a large number of roof membrane punctures/ tears in the area of the blue rectangle (repair patches are shown in Figure 4-110). The red arrow indicates a damaged exhaust fan (see Figure 4-111). The green dotted arrow indicates a blown-off exhaust fan (see Figure 4-113). The primary wind direction was toward the southeast.



The cooling towers are in the red rectangle. One of the towers is missing a metal panel (red arrow at the inset) that may have blown off during the hurricane.

Figure 4-107: Cooling tower damage

Figure 4-108 shows a coping that blew off a curb at either an expansion joint or a roof area divider. The coping at the parapets and curbs were cleated on both sides of the coping. Typically, when cleats are used, they only occur at the outer leg of the coping, and exposed screws are used to attach the inner leg. Obtaining good coping/cleat interlock is difficult when cleats are used on both legs. The coping did not appear to comply with ANSI/SPRI/FM 4435/ES-1.

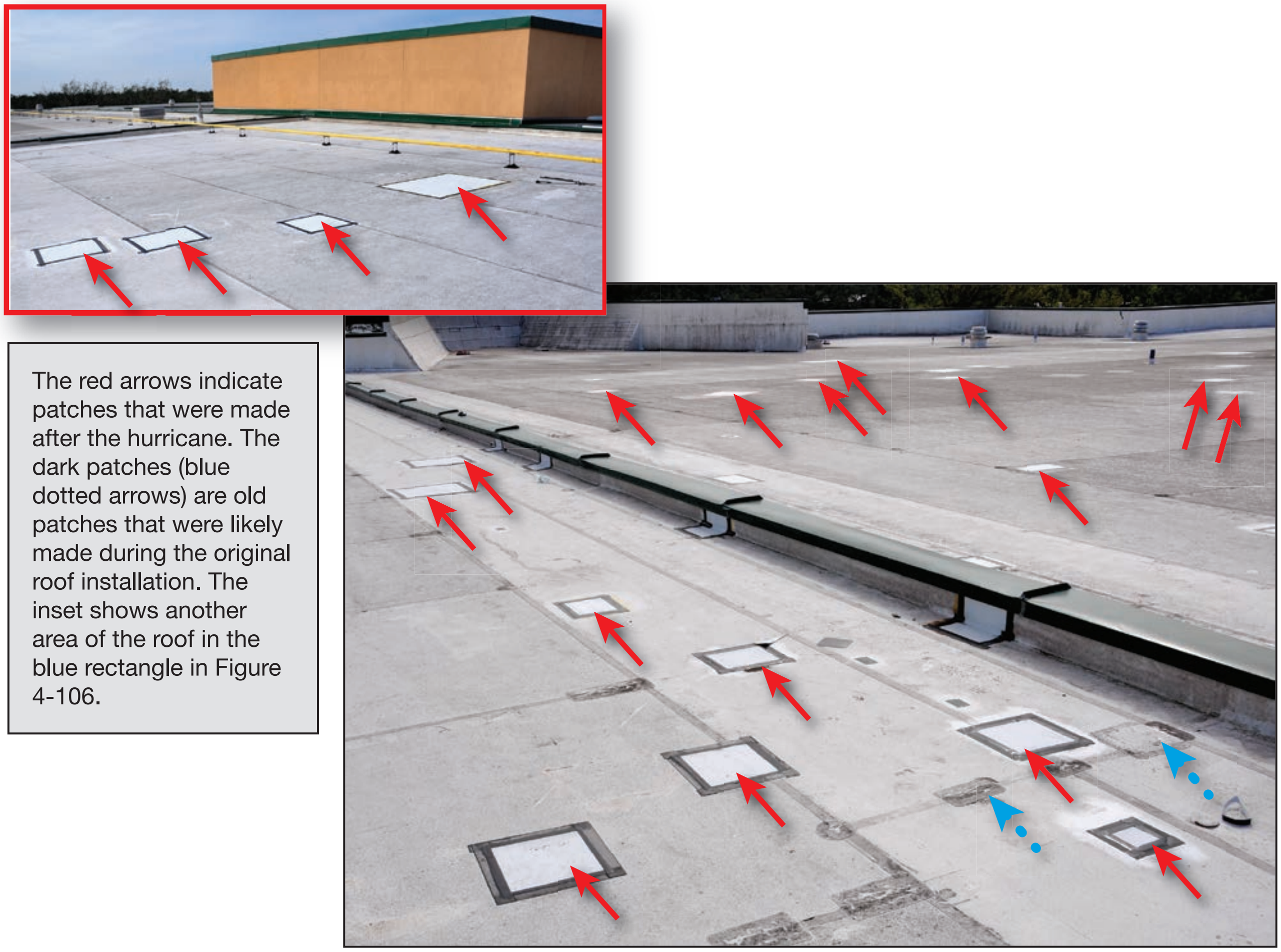
Figure 4-108:
Blown-off coping at a curb. Depending on the curb design, interior water leakage may occur where copings are blown off

Figure 4-109 shows the roof side of the parapet where a coping was blown off. In this area, the cleat nails (example shown in the red circle) were spaced at 14 inches, 8 inches, and 15 inches. Cleat fasteners should be placed as close as possible to the drip break line. When fasteners are located as shown by the red dot, cleat and coping outward rotation due to suction on the roof side of the parapet is minimized, thus reducing the potential for the coping to disengage from the cleat due to cleat deformation.

Figure 4-110 shows a portion of the main roof area with a large number of recent patches at roof membrane punctures/tears. The area shown in Figure 4-110 is within the blue rectangle shown in Figure 4-106. Roof areas south and west of the blue rectangle were not checked because of time limitations. After initial patching was completed, leaks were reported after subsequent rains. The subsequent leaks occurred at punctures/tears that were not initially patched (small tears can be difficult to find). Note that water that enters a roof system may travel laterally before leaking into the interior of the building. Hence, the location where water enters the roof system may not coincide with the interior leakage location, thus complicating the identification of membrane puncture and tear locations.

The red circle shows location of cleat nail, and the red dot shows the idealized location for the cleat fastener.

Figure 4-109: Cleat where a coping blew off



The red arrows indicate patches that were made after the hurricane. The dark patches (blue dotted arrows) are old patches that were likely made during the original roof installation. The inset shows another area of the roof in the blue rectangle in Figure 4-106.

Figure 4-110: Main roof damage

Figure 4-111 shows an exhaust fan that was struck by wind-borne debris. The location of the fan is indicated by a red arrow in Figure 4-106. The fan was attached to the curb with two screws at each side of the fan. The attachment of the fan to the curb and attachment of the curb to the roof structure were adequate to resist the impact load. For an easy-to-use attachment schedule for fans and other small equipment, see Table 6-1 in FEMA P-424 (2010a). For this school, the attachment schedule recommends three screws at each side of the fan, rather than two per side as installed at this fan.

Figure 4-111: Exhaust fan struck by wind-borne debris

The red arrow indicates the direction of travel (toward the southeast).

The exhaust fan shown in Figure 4-112 was attached with only two screws (one screw on opposite sides of the fan). In addition, the screw heads were not in contact with the fan. If the debris that struck the fan shown in Figure 4-111 had struck this fan, it would likely have been knocked off the curb, thus allowing rain entry into the school.

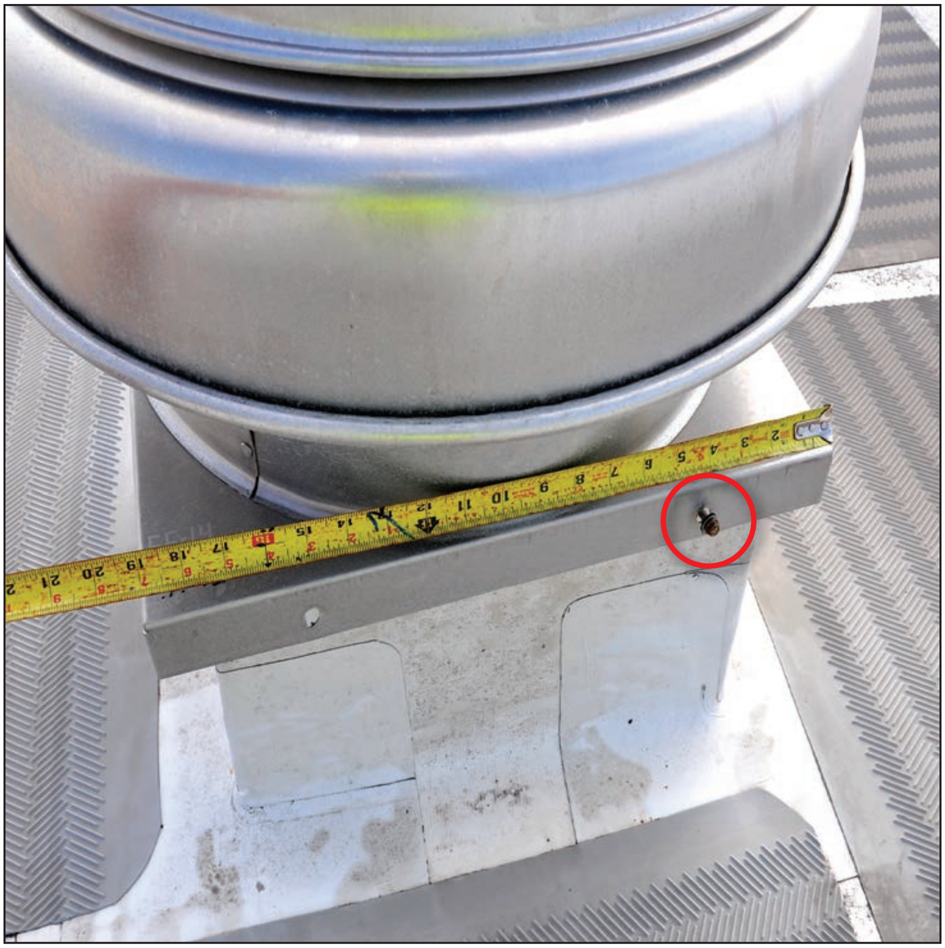


Figure 4-112: Exhaust fan attached with only two screws (red circle shows one of the screws)

Figure 4-113 shows where an exhaust fan was blown off the curb. Rain was able to leak into the building until the opening was temporarily protected. The nearby natural gas pipe support did not provide uplift resistance. FEMA's U.S. Virgin Island (USVI) Recovery Advisory 2, *Attachment of Rooftop Equipment in High-Wind Regions* (2018d), shows a support detail that provides lateral and uplift resistance for gas pipes, condensate drain lines, and conduits.

Figure 4-113:
Blown off exhaust fan

The red arrow indicates where an exhaust fan blew off. The blue dashed arrow indicates where a section of coping blew off. The yellow double arrow indicates a gas pipe support.

4.2.2.6 Fulton Learning Center

Figure 4-114 shows the Fulton Learning Center. A large addition to this older elementary school opened in 2013. The addition had a mechanically attached single-ply membrane. The original building had an older, mechanically attached single-ply membrane. The older and new roof membranes remained attached, even though sections of coping were blown off in several areas of the addition (Figure 4-115). The newer coping did not appear to comply with ANSI/SPRI/FM 4435/ES-1.

The older and newer roof membranes were punctured and torn by wind-borne debris. Most of the damage occurred at the older roof. The membrane was over insulation, which was over steel deck. Because the membrane was not adhered, once it was punctured or torn by wind-borne debris, water readily entered the roof system. With no secondary membrane over the steel deck, water easily leaked into the interior of the building. Water also leaked into the building where rooftop equipment blew off its curbs.

The red arrows indicate the 2013 addition to the Fulton Learning Center. The yellow double arrow indicates the original building. At the time of the MAT observations (14 days after the storm), cleanup and drying operations were underway.

Figure 4-114: Fulton Learning Center (Fulton)

The cleat's metal nail-in anchor pulled out of the brick. See the discussion of Figure 4-109 regarding cleat fastener location.

Figure 4-115: Area where a section of newer coping blew off

There were several condensers on the older roof; all were supported by 4x4 wood sleepers that rested on the roof membrane. Because of the lack of load path, many of the condensers were displaced (Figure 4-116). Wind-borne rooftop equipment was a major source of wind-borne debris damage at the older roof.

Figure 4-116:
Displaced condensers

The red arrow indicates where an HVAC unit used to be.

4.2.2.7 Port Aransas Schools

Figure 4-117 is an aerial view of the Port Aransas elementary, middle, and high schools. All of the schools experienced significant roof system damage and interior damage due to roof leakage. At the time of the MAT observations (77 days after the storm), the damaged buildings were shut down. School was in session in portable classrooms that had been moved on site.

Figure 4-118 shows the elementary and middle schools. Interior and rooftop observations were not made because of time limitations.

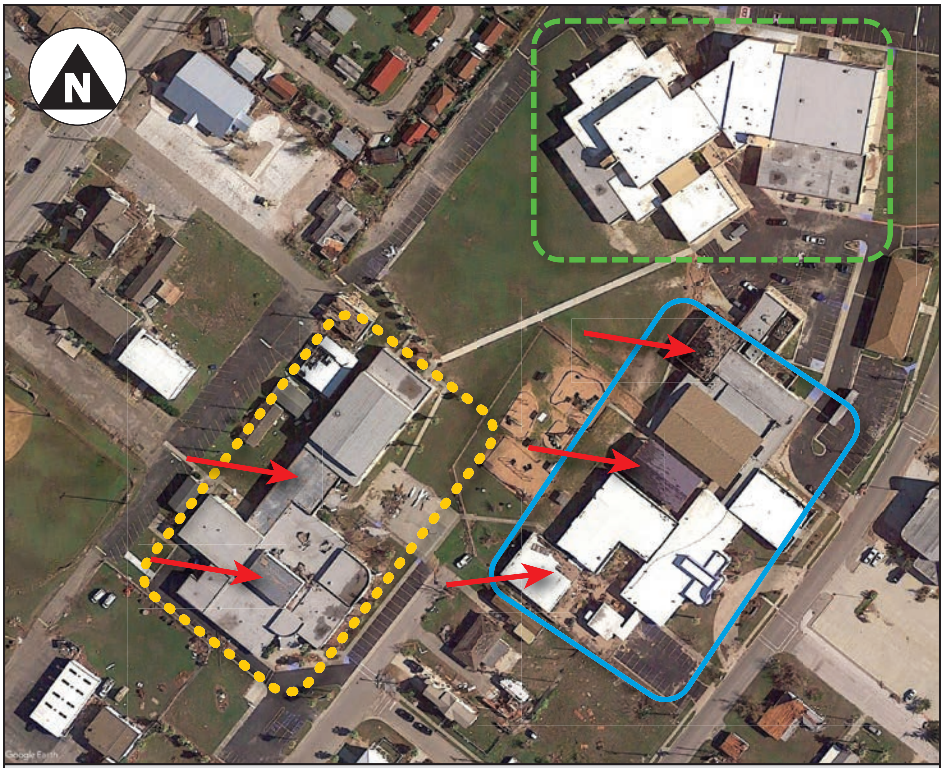


Figure 4-117: Aerial view of the Port Aransas schools showing roof damage (135 mph)

The elementary school is indicated by the blue outline, the middle school is indicated by the yellow dotted outline, and the high school is indicated by the green dashed outline. Red arrows indicate areas of noticeable roof damage. This photo was taken before portable classrooms were moved on site.

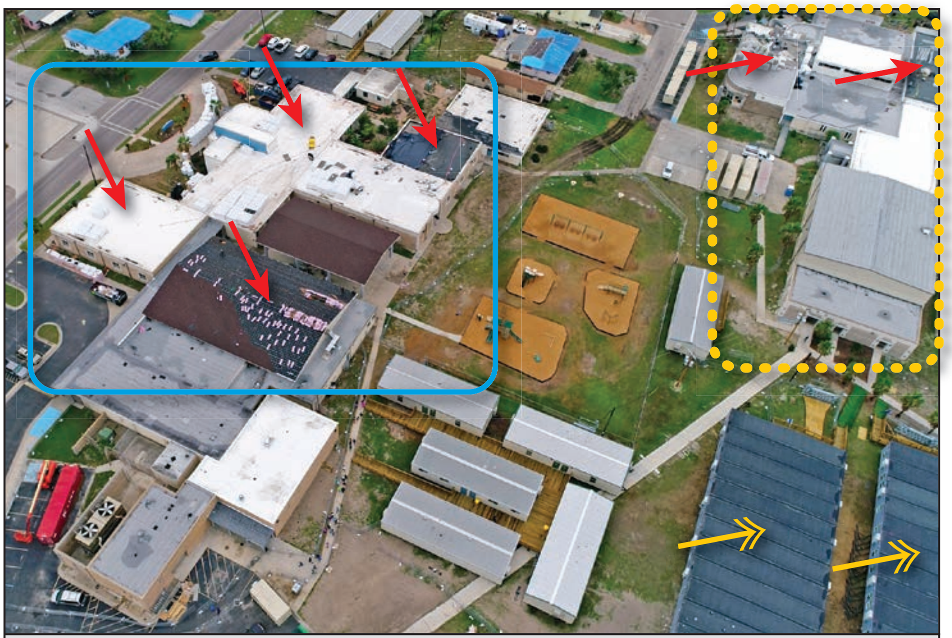


Figure 4-118: Aerial view of the Port Aransas elementary (blue outline) and middle school (yellow dotted outline) [DRONE IMAGE]

Red arrows indicate areas where reroofing was underway. The yellow double arrows indicate portable classrooms brought in after the hurricane.

Figure 4-119 shows the high school. The MAT made only limited interior observations because of time limitations. Damage was not apparent in the first floor areas that were observed.

Figure 4-119: Aerial view of the Port Aransas high school

[DRONE IMAGE]

Red arrows indicate areas where reroofing was underway. The green dotted arrow indicates a modified bitumen membrane roof with no apparent damage. The blue dashed arrow indicates the stair tower shown in Figure 4-120. The yellow double arrows indicate portable classrooms brought in after the hurricane.

Figure 4-120 shows an area where the mechanically attached single-ply membrane was punctured in several areas by brick veneer that fell from the stair tower wall. The nearby modified bitumen membrane roof had no apparent damage. Also, there was no apparent damage to the few pieces of rooftop equipment on that roof area.

Figure 4-121 shows signage, brick veneer, and soffit damage. The soffit was stucco supported by metal framing. The main consequences of the soffit damage were the cost of repair and the potential for it to become wind-borne debris.

Figure 4-120:
Brick veneer failure at a stair tower

The black areas are emergency repairs. The red arrow indicates the modified bitumen membrane roof with no apparent damage.

Figure 4-121:
Signage, brick veneer, and soffit (yellow oval) failure

4.2.2.8 Pharmacy

Figure 4-122 shows a pharmacy that was opened in 2014. A large portion of the single-ply membrane blew off, which resulted in significant roof leakage. A mobile pharmacy was set up in the parking lot and used until the pharmacy reopened on April 22, 2018.

Figure 4-122:
Aerial view of a pharmacy with roof damage (135 mph) (Port Aransas)

The red circle shows the location of the pharmacy. Red arrows indicate areas of noticeable roof covering damage at nearby buildings. Under greater magnification, asphalt shingle damage is visible on several other buildings.

4.2.2.9 Port Aransas Hotel

Figure 4-123 shows a hotel that had a substantial portion of its modified bitumen membrane blown off. Some wall louvers at packaged terminal air conditioners (PTACs) were also blown off (Figure 4-124). A portion of the gypsum board soffit at the porte cochere was blown away; the gypsum board was attached directly to the wood structural framing.

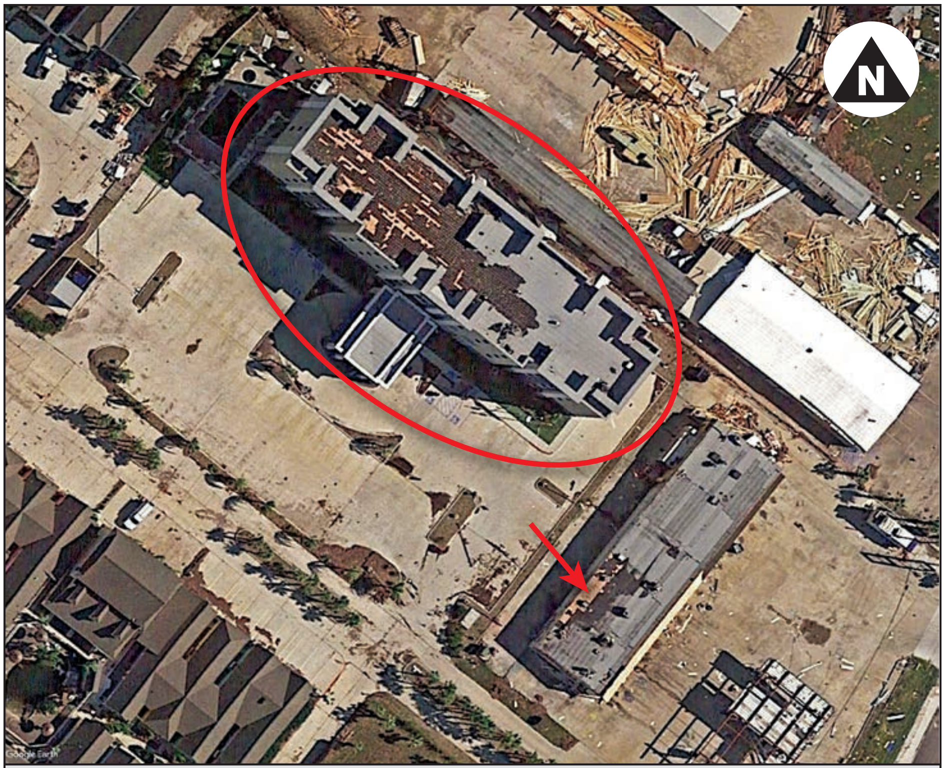


Figure 4-123: Aerial view of a four-story hotel with roof damage (Port Aransas)

The red oval shows the location of the hotel. The red arrow indicates roof covering damage at an older nearby building. There was no apparent damage to the asphalt shingle roofs at the southwest corner of the photo.

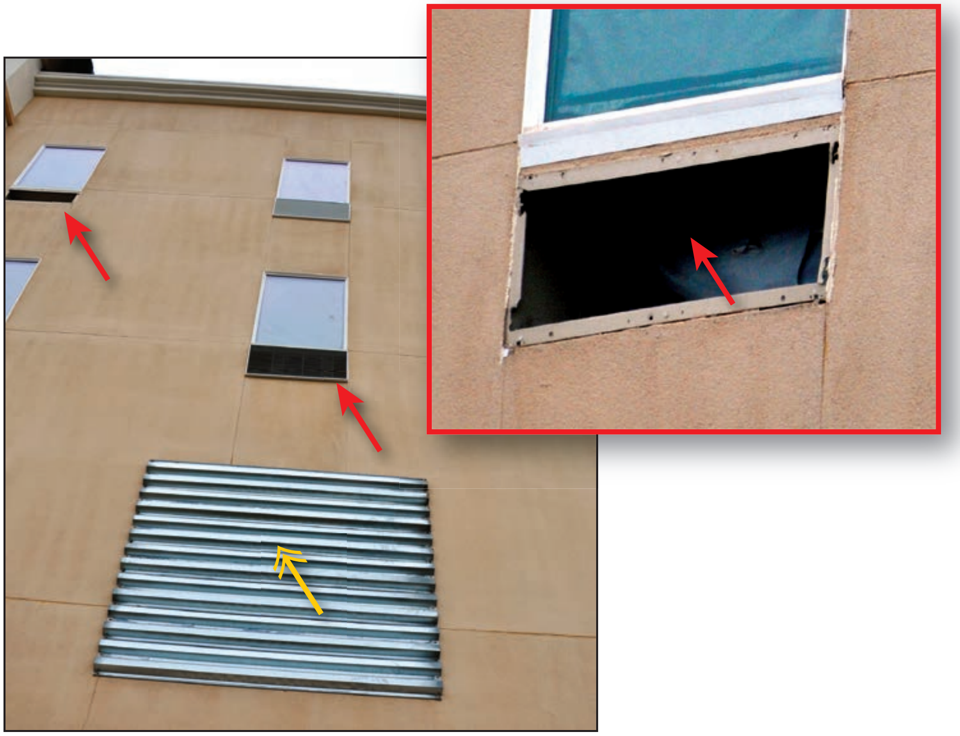


Figure 4-124:
The red arrows indicate where PTAC wall louvers were blown away. The lower level windows were protected with metal shutters (yellow double arrow)

4.2.2.10 Rockport Hotels

Figure 4-125 shows two Rockport hotels that experienced significant roof covering and interior water damage. The northern hotel had a modified bitumen membrane. Portions of the membrane blew off, unanchored condensers were displaced (Figure 4-126), and a fan cowling and HVAC unit access panel were blown off. Figure 4-126 shows the displaced condenser at the northern hotel. Figure 4-127 shows the interior of the first floor of the northern hotel. At the time of the MAT observations (76 days after the storm), the hotel was shut down.

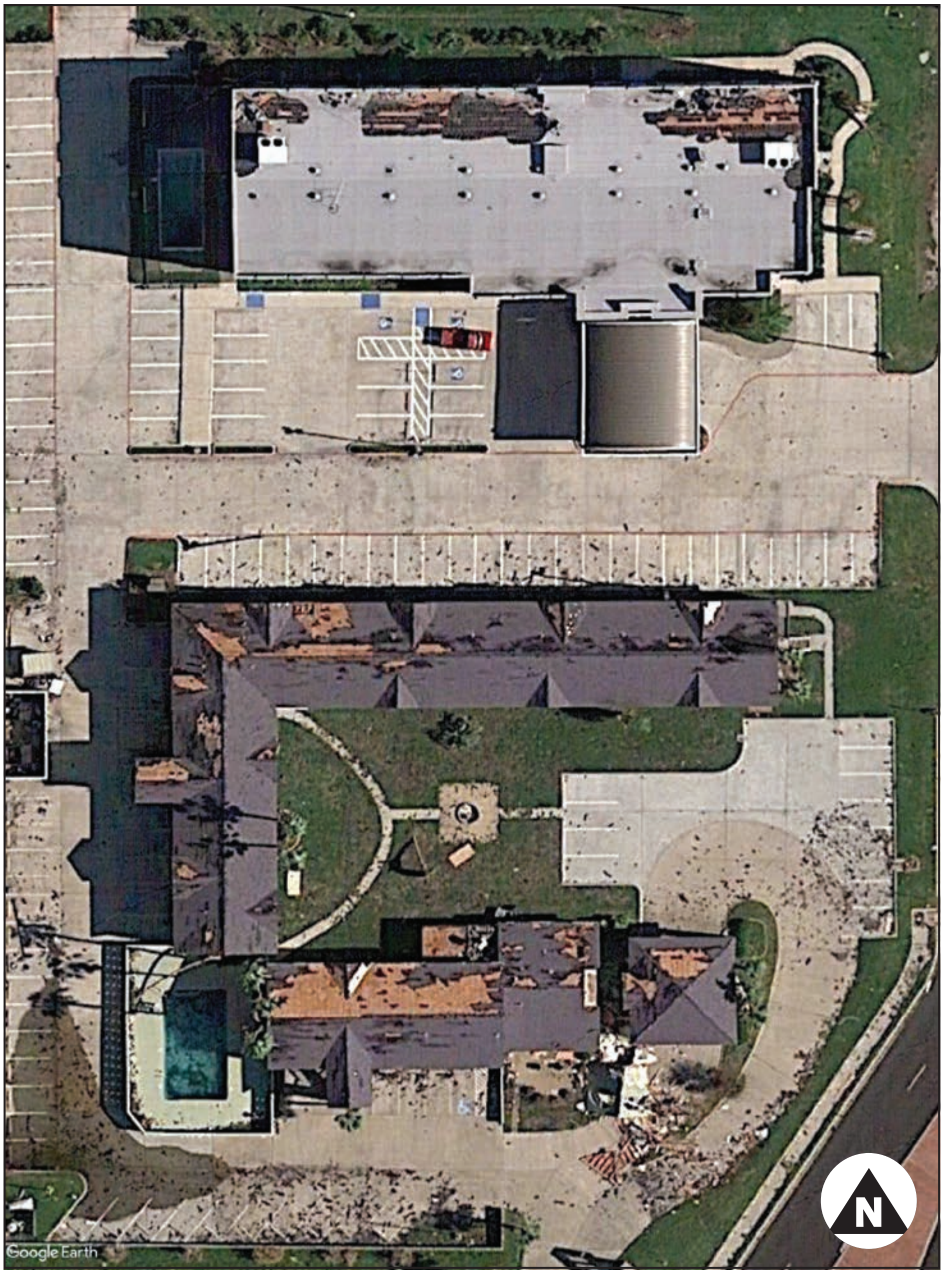
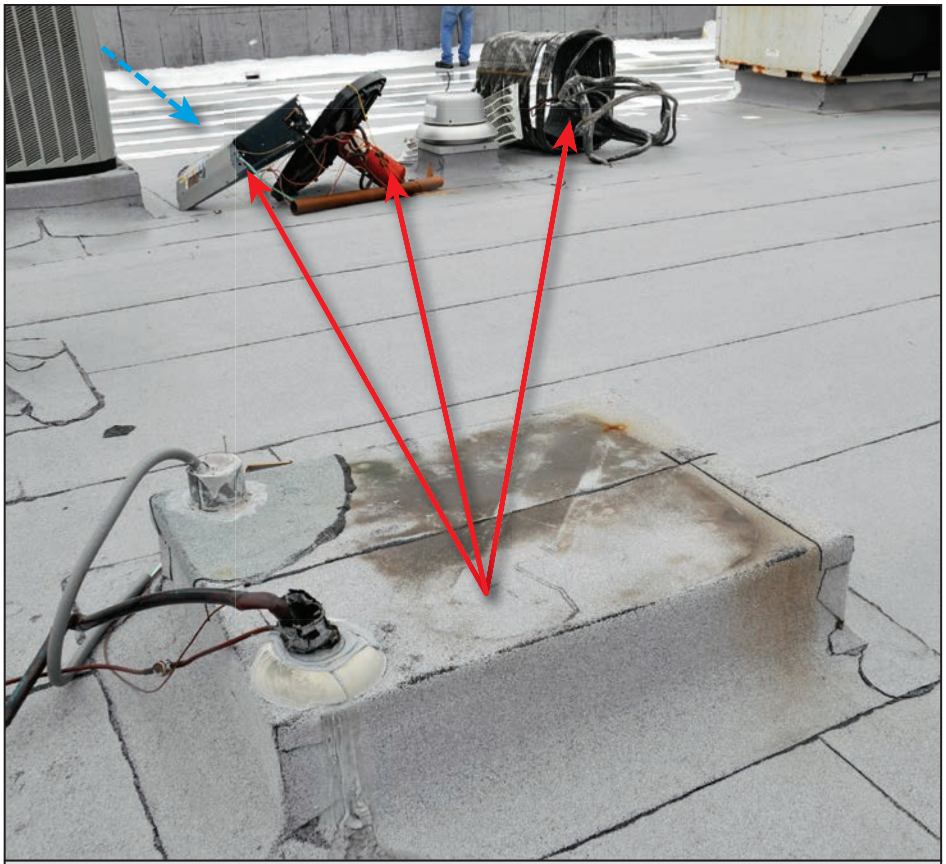


Figure 4-125:
Aerial view of roof covering damage at two hotels. The northern building is three stories and the southern building is two stories. (Exposure D) (Rockport)



The condenser at this hotel had rested on the curb. The red arrows show the location of the condenser after Hurricane Harvey. The blue dashed arrow indicates an emergency repair where the roof membrane had blown off.

Figure 4-126: Displaced condenser at hotel (Rockport)

Figure 4-127: First floor corridor of a hotel (Rockport)

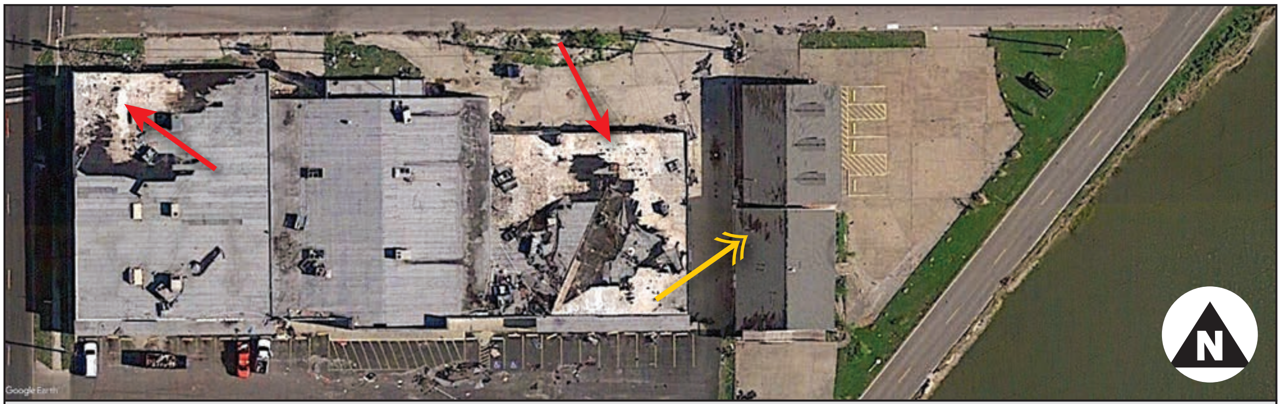
Note that the gypsum wallboard near the floor had been removed. On the upper floors, all of the gypsum wallboard had been removed at the rooms below the damaged roof.

4.2.2.11 Older Rockport Retail Building

Figure 4-128 shows an older retail building that experienced roof membrane and rooftop equipment blow-off. A portion of the parapet was also damaged (Figure 4-129).

The roof assembly was composed of a modified bitumen membrane over gypsum poured over a metal deck. The membrane's base sheet was attached to the gypsum with spreading fasteners. A large number of fasteners pulled out of the deck in the roof area shown in Figure 4-130. However, it appeared that uplift of the edge flashing nailer initiated the blow-off in this area.

Figure 4-131 shows a damaged HVAC unit. The unit was strapped to a sheet metal curb adaptor, which sat on a curb. The connection of the unit to the curb adaptor and the connection of the adaptor to the curb were stronger than the wind resistance of the unit itself.



The red arrows indicate roof membrane blow-off areas. The yellow double arrow indicates asphalt shingle damage at a nearby building.

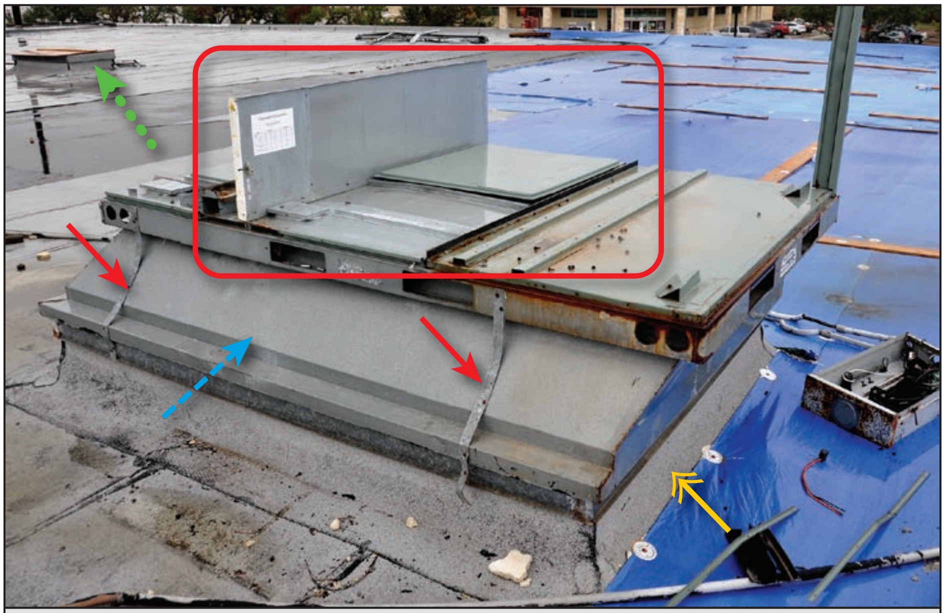
Figure 4-128: Aerial view of an older retail building (Exposure D) (Rockport)

Figure 4-129: Damaged parapet; Exterior Insulation and Finish System (EIFS) over metal framing

Figure 4-130:
Underside of the base sheet (yellow oval)

The red arrows indicate metal edge flashing nailers. The yellow double arrow indicates the gypsum.

Figure 4-131:
Disintegrated HVAC unit



Red rectangle shows the HVAC unit. The blue dashed arrow indicates the curb adaptor, and the yellow double arrow indicates the curb. The red arrows indicate straps connecting the unit, curb adaptor, and curb. The green dotted arrow indicates an HVAC unit that blew off its curb.

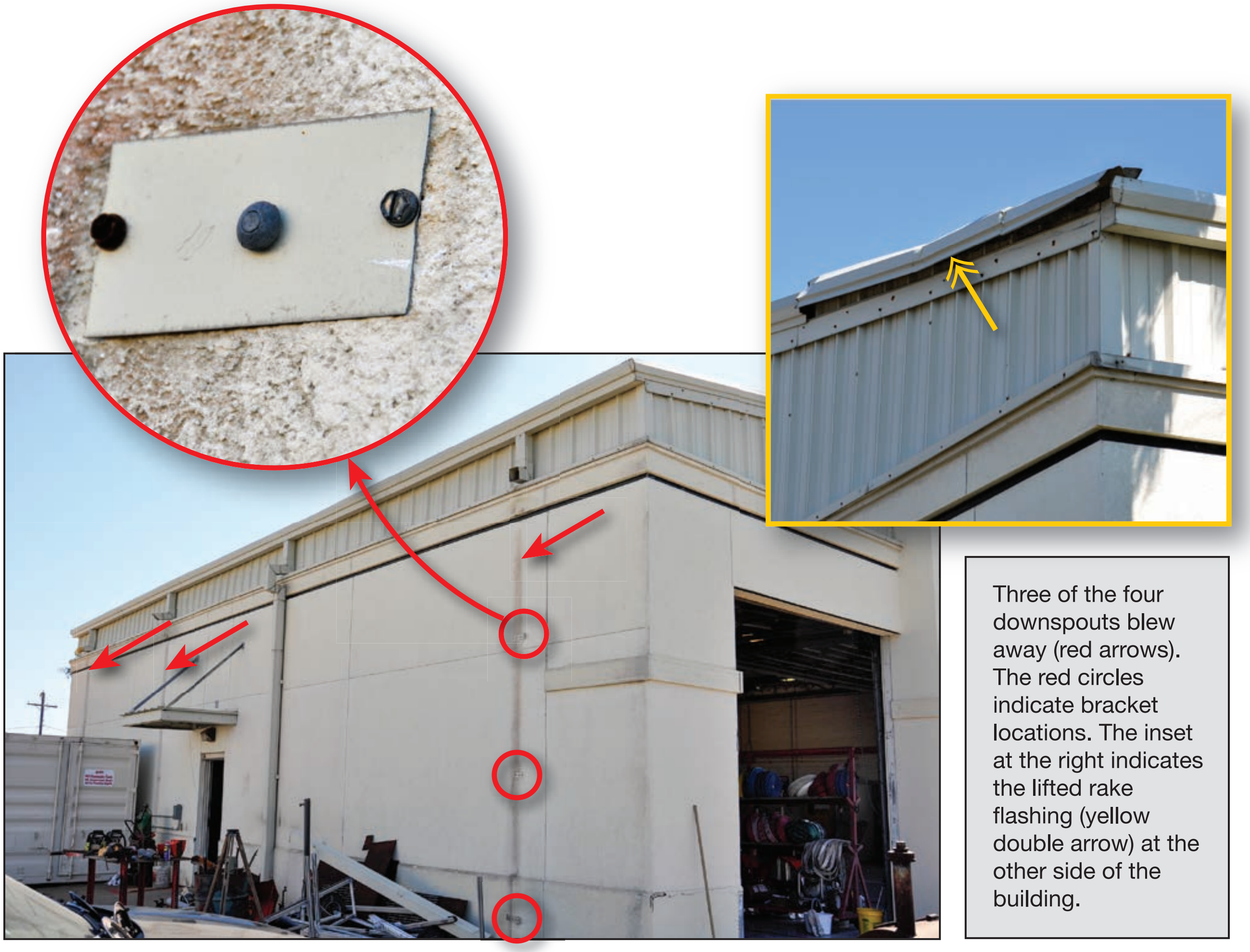
The roof damage resulted in significant interior water damage (Figure 4-132). At the time of the MAT observations (76 days after the storm), rain was leaking into the building.

The red arrows indicate rainwater on the floor.

Figure 4-132: Inside the building under the area shown at Figure 4-130

4.2.2.12 Metal Building System in Aransas Pass

Figure 4-133 shows a metal building system (formerly known as "pre-engineered metal building") fire station in Aransas Pass. The only apparent damage was lifting of some rake flashing and blow-off of some downspouts. The IBC currently does not have criteria regarding wind resistance of gutters and downspouts. The downspouts were anchored with U shaped sheet metal brackets at 4 feet 7 inches on center. One, or in some instances both, of the bracket legs failed at the downspouts that blew away. Displaced downspouts can become damaging wind-borne debris.



Three of the four downspouts blew away (red arrows). The red circles indicate bracket locations. The inset at the right indicates the lifted rake flashing (yellow double arrow) at the other side of the building.

Figure 4-133: Metal building system fire station (Aransas Pass)

4.2.3 Non-Load-Bearing Walls, Wall Coverings, and Soffits

A variety of non-load-bearing wall, wall covering, and soffit systems were observed. Pertinent observations are discussed below.

4.2.3.1 Refugio Church

Figure 4-134 shows brick veneer failure at a church in Refugio, where the estimated wind speed was a little more than 120 mph per Figure 1-11. Although this site is far inland, the brick ties were significantly corroded. Section 4.1.2.3 offers examples and discussion of brick veneer failure for residential buildings.

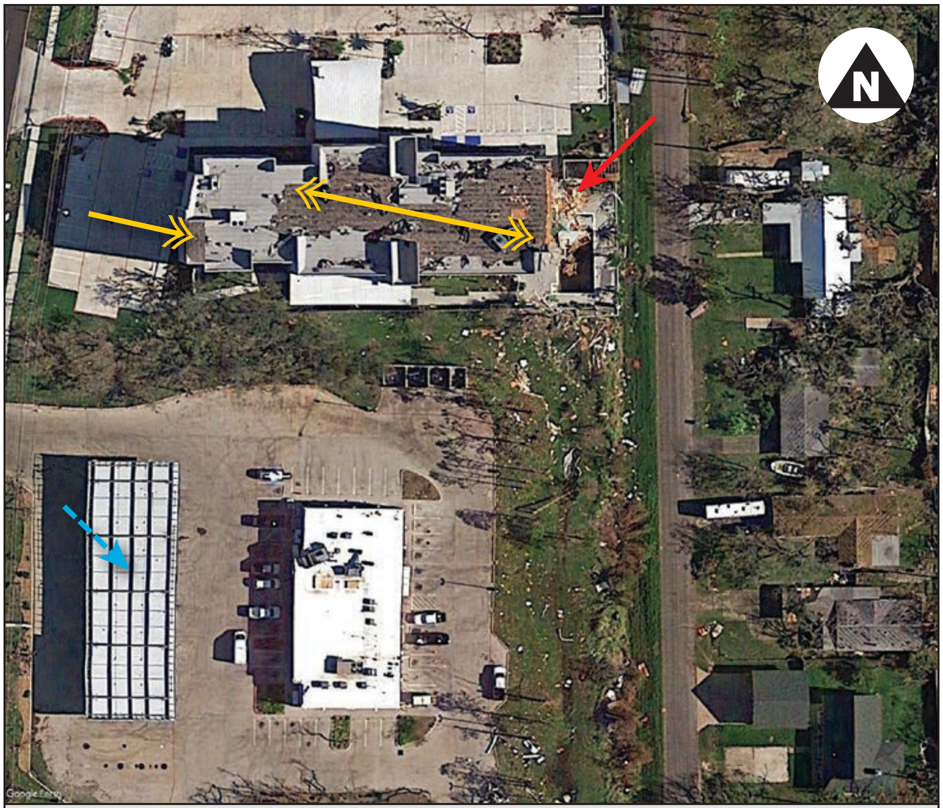
The inset shows corroded brick ties.

Figure 4-134: Brick veneer failure (Refugio)

4.2.3.2 Rockport Hotel

Figure 4-135 shows a Rockport hotel that was approximately 1 year old at the time of the hurricane. A substantial portion of the roof membrane blew off, which resulted in extensive interior water damage. The hotel was reportedly occupied during the hurricane.

Figure 4-135:
Aerial view of a newer hotel (Rockport)



The yellow double arrows indicate roof membrane blow-off areas. The red arrow indicates debris from a collapsed end wall (Figure 4-136). The blue dashed arrow indicates a gas station canopy.

Figure 4-136 shows failure of an exterior wall, including the parapet on the side wall portion of the hotel. The exterior wall framing detached from its supports at the roof and floor diaphragm levels. The other exterior walls, including framing that extended above the roof line to form the parapet, did not exhibit this failure. Most of the studs were not gravity load bearing, but some stud packs in the wall appeared to be load bearing. Lack of access precluded a comprehensive evaluation of the wall failure.

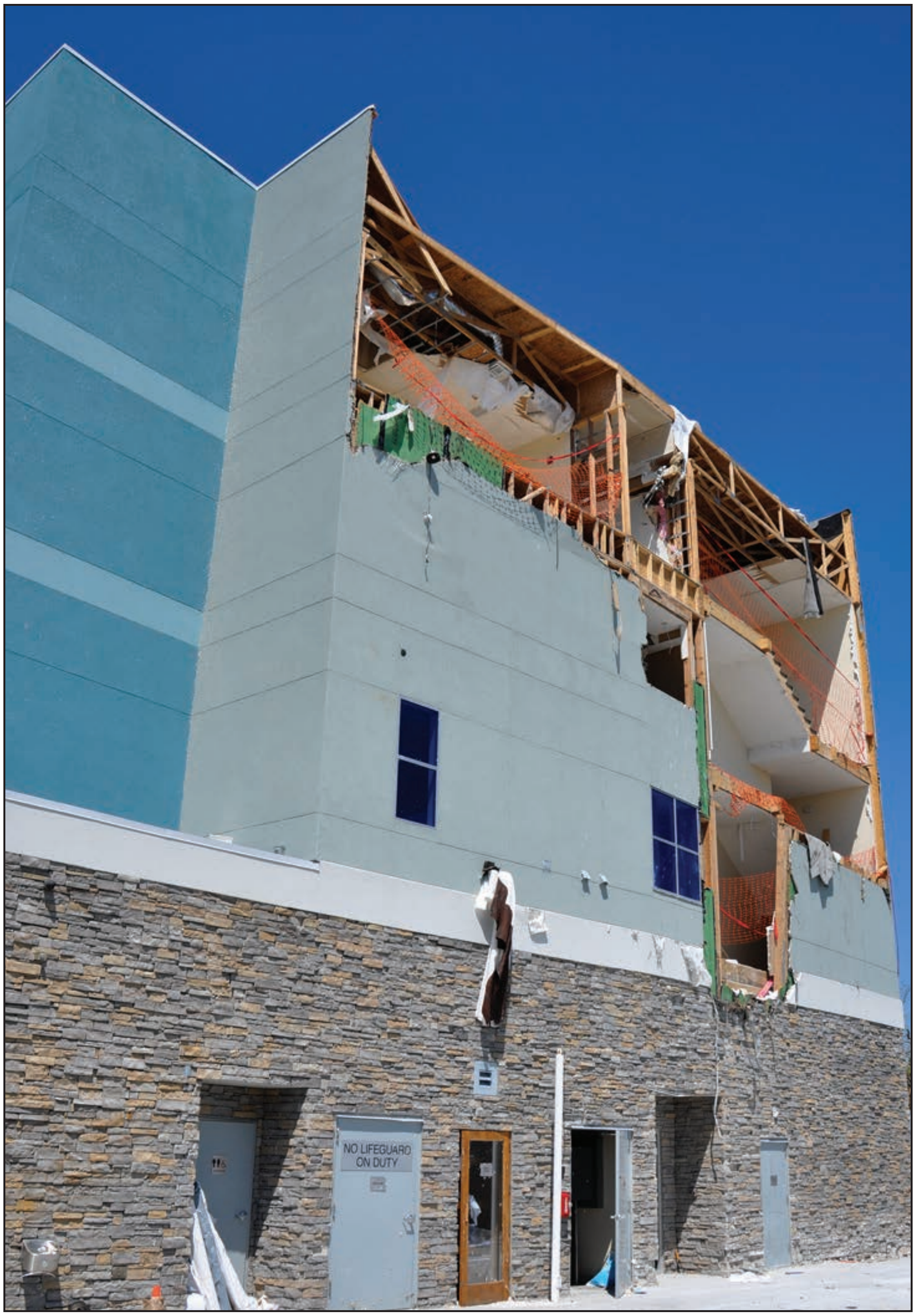
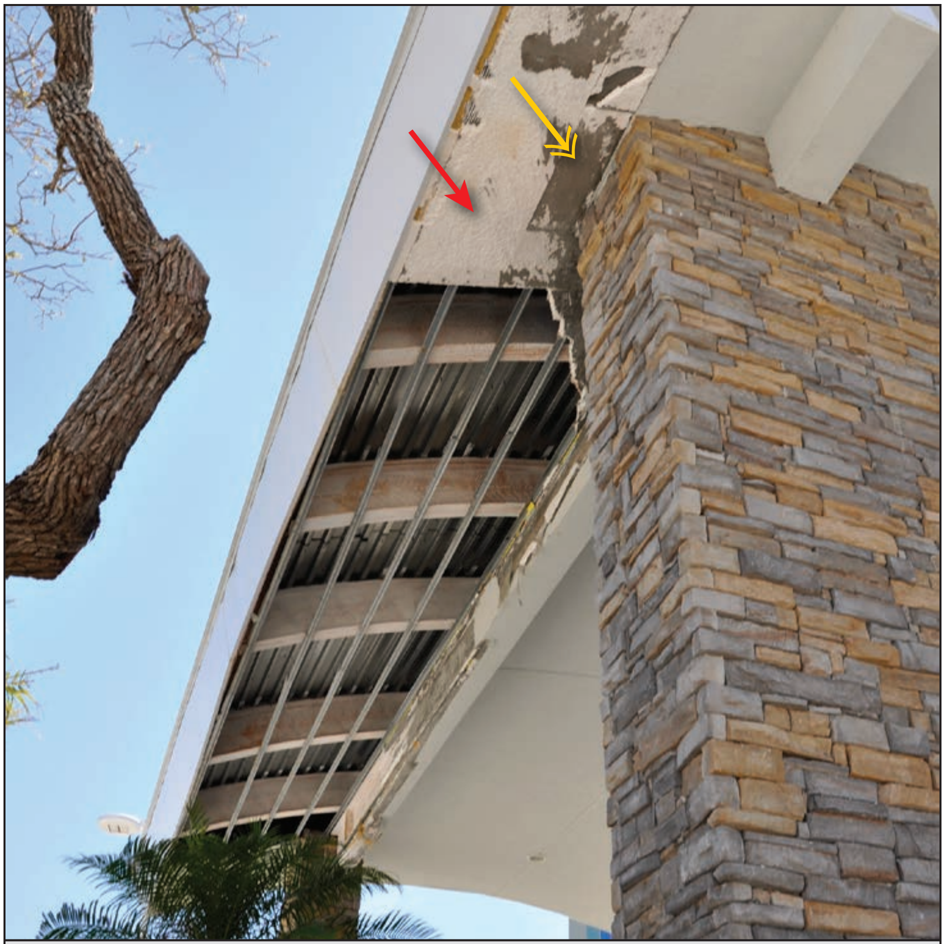


Figure 4-136: End wall failure at hotel (Rockport)

Figure 4-137 shows soffit failure at the porte cochere. The soffit had an EIFS over metal framing. The main consequences of this damage were the cost of repair and the potential for the soffit material to become wind-borne debris.

Figure 4-138 shows some of the ramifications of the roof and end wall damage. The two large debris boxes are full of ceiling, wall covering, and other water-damaged debris from the hotel.

Figure 4-137:
Soffit failure at the porte cochere



The red arrow indicates molded expanded polystyrene foam insulation. The yellow double arrow indicates gypsum board. The primary failure mode was detachment of the gypsum board from the metal framing.

Figure 4-138:
Debris from the interior of the hotel

The red arrow indicates wet mattresses, and the blue dashed arrow indicates wet furniture

4.2.3.3 Metal Building System at Rockport High School

Figure 4-139 shows an older metal building system at the Rockport high school. The high school is near the middle school shown in Figure 4-100. This large high school was constructed over many years using a variety of structural and building envelope materials. Much of the school experienced building envelope damage, and one of the gymnasiums collapsed (Figures 4-100 and 4-101. At the gymnasium shown in Figure 4-139, a precast non-load-bearing wall panel collapsed, and several metal roof and wall panels were blown away.

Figure 4-139: High school gymnasium damage (Rockport)

The blue arrow indicates the collapsed precast wall panel at the gymnasium. The blue circle indicates the connection shown in Figure 4-140.

The precast wall panels sat on the foundation, and weld plates were cast into the wall panel. The plates were welded to the frames to provide lateral resistance (Figure 4-140). However, the welds were insufficient to resist the wind load.

**Figure 4-140:
Precast panel connection to the steel frame**

The red arrow indicates a weld plate cast into the panel. The yellow double arrow indicates a plate that was welded to the frame and the panel weld plate.

Figure 4-141 shows the windward end wall. The girts supporting the wall panels were pushed inward. The girts likely failed because the metal stands supporting condensers were blown against the wall.

**Figure 4-141:
End wall failure**

The yellow double arrows indicate condensers; their stands rotated into the wall. The red arrow indicates the collapsed precast wall panel.

Figure 4-142 shows a collapsed light fixture pole (standard) at the athletic field.

Figure 4-142:
Collapsed light fixture pole (high school buildings are in the background)

4.2.3.4 Civic Center in Aransas Pass

Figure 4-143 is a view of the porte cochere at the civic center in Aransas Pass, which opened in 2008. Most of the soffit was constructed of metal panels attached to metal framing. In some areas, the panels blew away, and in others, both the metal framing and panels blew away. The main consequences of this damage were the cost of repair and the potential for the soffits to become wind-borne debris.

Figure 4-143:
Soffit damage of the porte cochere at the civic center (Aransas Pass)

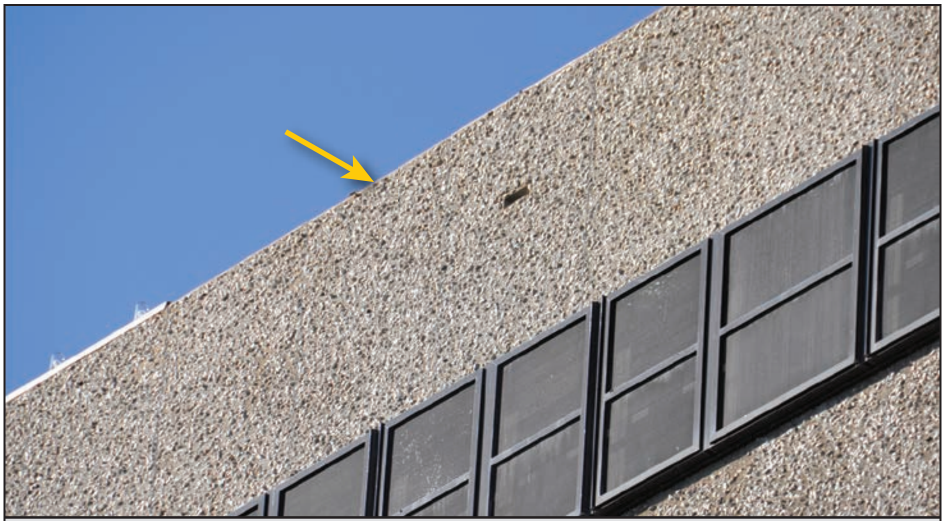
In some areas, the metal panels blew away (yellow double arrows). In other areas, the metal framing that supported the panels also blew away (green dotted outline).

4.2.4 Doors, Windows, and Shutters

The MAT did not observe personnel doors that were damaged by wind pressure or wind-borne debris. For the doors that were observed, the MAT did not determine whether wind-driven rain entered the building between the door and frame. The only large doors (i.e., sectional or rolling doors) that were observed are the ones shown in Figure 4-78. Those older doors were from an era when large doors typically had limited wind resistance. The MAT observed storm shutters of various types, as shown at Figures 4-81, 4-98, and 4-124.

Storm shutters were also observed at two hospitals in Corpus Christi. They were major glazing mitigation projects. At both facilities, accordion shutters were installed at glazed entry doors, and permanently mounted wind-borne debris-resistant screens were installed at windows (Figure 4-144). With permanently mounted screens, deployment and demobilization time and costs associated with most other types of shutters are eliminated. The accordion shutters and screens had labels indicating that they had been tested. However, the labels did not indicate the level of the test missile (i.e., D or E as specified in ASTM E1996). At one of the hospitals, screens had blown off during previous storms.

The roof of one of the hospitals had been at least partially mitigated, wherein a previous aggregate surfaced BUR was replaced with a modified bitumen roof system. Attention had also been given



The yellow arrow indicates where a coping blew off (see Figure 4-145).

Figure 4-144: Permanently mounted screens at a hospital (Corpus Christi)

to anchorage of some of the rooftop equipment. However, the hospital shown in Figure 4-145 still had an old aggregate surface BUR. With the modest wind speeds at this site and the presence of a relatively tall parapet, the aggregate probably did not blow off. However, it would have been prudent to replace the aggregate surfaced roof in conjunction with the glazing mitigation project. Several sections of coping blew off the parapet of the aggregate surfaced roof.

The sections of coping that blew off, landed on the roof (yellow arrow). The copings did not blow off the roof because the wind speeds were modest.

Figure 4-145: Sections of coping blew off at various locations along the parapet

4.2.5 Building Operations

Building damage inflicted by Hurricane Harvey had significant impacts on the operations of many non-residential buildings, including critical facilities, as summarized below.

- One regional hospital was taken out of service.
- Several nursing homes in the greater Rockport area, and as far inland as Refugio (where the estimated wind speed was 105 mph, Figure 4-146), were taken out of service.
- All of the public schools in Rockport and Port Aransas were closed for weeks.
- Several hotels in the greater Rockport area and Port Aransas were taken out of service. The damaged hotels were not available to residents who had to vacate their houses/apartments because of damage nor were they available to workers who came into the area to provide emergency response and recovery services.
- Damaged retail buildings resulted in loss of local services and jobs.

Figure 4-146:
Although located far inland, this nursing home was shut down as a result of building envelope damage and subsequent water infiltration (Refugio)

4.3 Wind Performance of Solar Panel Systems

This section discusses observations of ground- and rooftop-mounted solar panels, also known as photovoltaic (PV) panels.

Ground-Mounted Solar Array

The MAT observed one ground-mounted array (Figure 4-147). The panels were attached with T-bolted compression panel clips to extruded aluminum rails. Fifteen panels were blown away, and one was damaged by wind-borne debris. For further information on ground-mounted PV arrays, refer to the MAT report, FEMA P 2021, *Hurricanes Irma and Maria in the U.S. Virgin Islands* (2018i).

Figure 4-147: Ground-mounted array

The yellow arrows indicate 13 missing panels. Two other missing panels are outside the view of the photo.

Rooftop-Mounted Solar Arrays

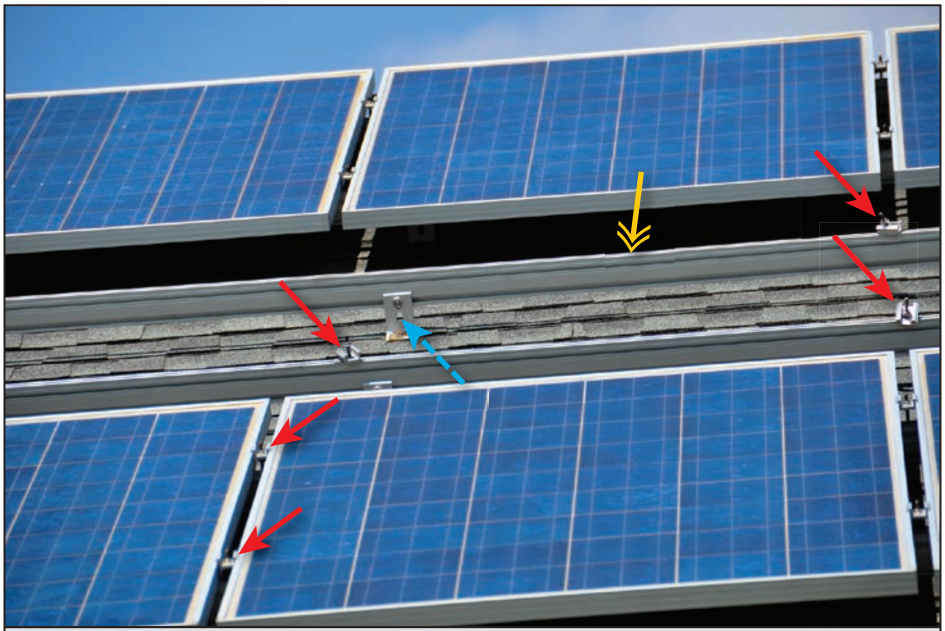
Two rooftop-mounted solar arrays were observed. Figures 4-148 and 4-149 show an array that had four rows of panels, with eight panels per row. The entire middle row blew away.

Figure 4-148: Aerial view of the vicinity of a rooftop solar array (Exposure D)

Yellow circle shows the location of the rooftop solar array. There was no apparent roof covering damage at some of the houses, while there was at others; at one house, one roof structure blew off and another collapsed.

Figure 4-149: The yellow arrow indicates the row of missing solar panels

The panels were attached with T-bolted compression panel clips to extruded aluminum rails, which were attached with clip angles to the structure (Figure 4-150). The panels, bolts, clips, and rails were similar to a large number of arrays that were observed in the U.S. Virgin Islands after Hurricanes Irma and Maria in 2017.



The red arrows indicate panel clips. The yellow double arrow indicates a rail, and the blue dashed arrow indicates a clip angle that attached the rail to the structure.

Figure 4-150: Damage to a rooftop-mounted solar array

Figure 4-151 shows another rooftop solar array. Asphalt shingles and roof sheathing were blown off this house. At the time of the MAT's observation, the house had been reroofed, but the solar panels had not been reinstalled. This house illustrates the importance of conducting a wind vulnerability assessment of the roof assembly and mitigating significant vulnerabilities before installing solar panels.

Figure 4-151: Aerial view of a damaged rooftop solar array

Yellow outlines show the solar array. The red arrows indicate roof structure damage.

For further information on rooftop solar panels, refer to FEMA's USVI Recovery Advisory 5, *Rooftop Solar Panel Attachment: Design, Installation and Maintenance* (2018l).

5

Conclusions and Recommendations

The conclusions and recommendations are intended to help reduce future damage and impacts from flood and wind events such as Hurricane Harvey.

The conclusions and recommendations presented in this report are based on the MAT's observations in the areas studied; evaluations of relevant codes, standards, and regulations; and meetings with local officials, facility representatives, design professionals, and contractors.

The recommendations are intended to assist the State of Texas, communities, businesses, and individuals in the reconstruction process, and to help reduce future damage and impacts from flood and wind events such as Hurricane Harvey. The recommendations will also help FEMA assess the adequacy of building codes and standards as they relate to dry floodproofing and floodplain management requirements and determine whether changes are needed, or additional guidance related to reducing hurricane damage is required.

Section 5.1 is a summary of the conclusions and recommendations based on the MAT's observations. Section 5.2 discusses general conclusions and recommendations. Section 5.3 discusses conclusions and recommendations related to building codes, standards, and regulations. Section 5.4 includes flood-related building performance conclusions and recommendations. Section 5.5 includes wind-related building performance conclusions and recommendations. Section 5.6 provides conclusions and recommendations on FEMA technical publications and guidance. Section 5.7 provides a summary of the conclusions and recommendations in a tabular format.

5.1 Summary of Conclusions and Recommendations

The recommendations are presented as guidance to the State of Texas and those who are involved with the design, construction, and maintenance of the built environment in the State. The entities involved in the reconstruction and mitigation efforts should consider these recommendations in conjunction with their existing priorities and resources when determining how they can or will be implemented.

Overall, in areas where recent codes were adopted and enforced, newer construction sustained much less damage than older construction, so the requirements incorporated under the TDI Windstorm Inspection Program, as well as floodplain management regulations and building code requirements, appear to be effective at improving building performance. Flood-related building damage was primarily attributable to non-elevated or low elevation buildings (legal non- conforming), dry floodproofing failures, the use of non-flood damage-resistant materials below the BFE, the lack or failure of sewer backflow prevention devices, and widespread flooding outside the SFHA. Wind-related building damage was primarily attributable to using improper materials in hurricane-prone regions; design deficiencies; poor installation or failure to follow installation guidelines for wall coverings, windows, and doors in high-wind zones; and inadequate attachment of roof coverings and roof-mounted equipment.

LEGAL NON-CONFORMING CONSTRUCTION

Legal non-conforming construction is a structure that complied with floodplain management requirements when permitted, but BFEs or flood zones have since changed.

The MAT's conclusions and recommendations are prioritized within each subsection by those that may be most important for the State, community, or interested party to implement. Specifically, recommendations of note from each section include:

Recommendation TX-1a (Section 5.2). Continue providing training to Windstorm Inspection Program inspectors and building code enforcement staff, placing emphasis on changes reflected in the latest adopted edition of the building code.

Recommendation TX-3a (Section 5.3). TDI should adopt the 2018 IBC and IRC as the model codes for its Windstorm Inspection Program.

Recommendation TX-5a (Section 5.4). Communities and building owners should consider elevating new and Substantially Improved/Substantially Damaged buildings above the NFIP elevation requirements to protect them from flooding.

Recommendation TX-14a (Section 5.5). Building owners and/or facility managers should ensure roof-mounted equipment is adequately anchored.

Recommendation TX-23a (Section 5.6). FEMA should complete *Guidelines for Wind Vulnerability Assessments for Critical Facilities.*

5.2 General Conclusions and Recommendations

Conclusion TX-1

Building codes and floodplain management requirements were inconsistently enforced. Inconsistencies in code compliance and enforcement were observed throughout sites the MAT visited. Although there was evidence of good practices in some communities, the most common and routine inconsistencies observed included, among other things, improper load paths, not requiring products that are on the approved and tested list (e.g., the TDI Product Evaluation Index), and a lack of flood openings in enclosures below the lowest floor of buildings in the SFHA.

Recommendation TX-1a. Continue providing training to Windstorm Inspection Program inspectors and building code enforcement staff, placing emphasis on changes reflected in the latest adopted edition of the building code. Communities that have adopted building codes and the TDI should work with the Texas State Collaborative, the International Code Council, and FEMA to provide building officials, plan examiners, and inspectors with training materials on the model building codes to ensure they are up to date on current wind provisions in the model building codes and standards and associated local amendments. The training should emphasize discrepancies observed between building code requirements and completed construction following Hurricane Harvey. For example, in newer/ongoing construction, the MAT observed the load path from the foundation to the top plate was generally sufficient, but there were concerns with the design and execution of load paths in the roof framing. TDI should consider providing additional training for Windstorm Inspection Program inspectors to more effectively review plans and enforce proper load path connections to meet roof framing requirements. Both Windstorm Inspection Program inspectors and building code enforcement staff should inspect the building's structural integrity and identify any deficiencies in the design and construction process.

Recommendation TX-1b. The Texas Water Development Board and other stakeholders should develop/modify training on the flood provisions in model building codes and/or floodplain management ordinances. The Texas Water Development Board, which is the designated Texas NFIP State Coordinating Agency, in conjunction with FEMA and the Texas Floodplain Management Association, should develop training related to flood damage-resistance provisions in the model building codes and include content on a model code-coordinated floodplain management ordinance. Based on observations following Harvey, the training materials should emphasize the use of flood damage-resistant materials and flood openings in enclosures below the BFE. The target audience for the training materials should be builders, developers, floodplain administrators, building officials, and building inspectors.

Conclusion TX-2

Some high-occupancy and critical facility building owners have a limited awareness of hurricane hazard risks and vulnerabilities. The quality of planning and preparedness for Hurricane Harvey at the non-residential buildings visited by the MAT, particularly some schools, nursing homes, and medical centers along the coast, varied greatly. These variations may have been due to the information sources used to identify risks and vulnerabilities to wind and flood events, as well as local government recommendations about whether to close the facilities during the event. Many building managers and owners may not have been aware of the higher risks to their buildings from such severe hurricane events.

> **Recommendation TX-2. Facility and building owners should perform vulnerability assessments.** Prior to hurricane season, facility and building owners should consider having a vulnerability assessment conducted by a team of knowledgeable professionals to help determine available options to mitigate hazards and risks for buildings, critical facilities and key assets, and other structures that may be damaged by a flood or wind event. Owners should identify vulnerabilities and include mitigation measures in short- and long-term facility maintenance and capital improvement programs to realistically address the vulnerabilities over time, where possible. Facility owners and operators should work with key internal staff and design professionals to analyze their facilities, key systems and components, operational assumptions, and operations plans to determine a path forward for developing project priorities and funding capital improvements that maximize facility and operational resiliency. FEMA P-424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds* (2010a); FEMA P-1000, *Safer, Stronger, Smarter: A Guide to Improving School Natural Hazard Safety* (2017); FEMA P-543, *Design Guide for Improving Critical Facility Safety from Flooding and High Winds* (2007a); and FEMA P-577, *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings* (2007b) are building-use-specific guidance documents that include multi-hazard vulnerability assessment checklists for schools, critical facilities, and hospitals, respectively.

5.3 Building Codes, Standards, and Regulations

Conclusion TX-3

The TDI Texas Windstorm Inspection Program requirements are based on compliance with the 2006 IBC and IRC, which are outdated. Based on observations in Texas and other areas the 2017 Hurricane MAT visited, buildings that had been designed or mitigated to resist high-wind loads in accordance with modern building codes performed substantially better than buildings constructed to earlier codes. In addition, the IBC and IRC have been through four code cycles since 2006, including incorporating two revisions to ASCE 7.

> **Recommendation TX-3a. TDI should adopt the 2018 IBC and IRC as the model codes for its Windstorm Inspection Program.** These codes and referenced standards include up-to-date design and construction provisions and create consistency across industry standards. When TDI adopts the model code and standards, minimum criteria should be kept intact or exceeded. Upon adopting any new requirements, TDI and communities should provide training to local design professionals, contractors, and inspectors on the requirements of the latest adopted codes.

Recommendation TX-3b. TDI should consider developing a more stringent high-wind retrofit program. In addition to adopting the 2018 IBC and IRC and referenced standards, TDI should consider developing a residential wind retrofit program that complies with or exceeds its current requirements to address wind vulnerabilities of existing residential buildings, as well as model building code requirements for existing residential buildings. TDI should consider using FEMA P-804, *Wind Retrofit Guide for Residential Buildings* (2010d), which was developed in conjunction with the Insurance Institute for Business and Home Safety FORTIFIED for Existing Homes™ Program. Note that any wind retrofit projects of one- and two-family residential buildings funded under the FEMA Hazard Mitigation Assistance (HMA) program must be completed in conformance with FEMA P-804. Individual insurance companies should provide discounts as an incentive for homeowners to invest in retrofit projects.

Conclusion TX-4

Portions of local floodplain management ordinances and building codes in communities visited by the MAT conflict with some of the requirements in model ordinances and building codes. The MAT identified inconsistencies while reviewing local floodplain management ordinances and flood provisions in locally adopted building codes.

Recommendation TX-4a. Harris County should review and update its floodplain management regulations. In the Regulations of Harris County for Floodplain Management, add a definition for “Substantial Damage,” ensure proper use of the term “lowest floor” (rather than “habitable floor”), require non-residential buildings to be elevated or dry floodproofed as high as residential buildings (18 inches above the BFE), and use “market value” in Substantial Improvement/Substantial Damage (rather than “value of structure”).

Recommendation TX-4b. The City of Houston should review and update its floodplain management ordinance and guidance. Chapter 19 of the Code of Ordinances for the City of Houston contains the City’s floodplain ordinance. The City should consider more clearly specifying the height of dry floodproofing when owners of non-residential buildings elect this option (at least the BFE plus 1 foot). The City produces companion guidelines for Chapter 19 that should be revised to update references to out-of-date editions for a number of FEMA technical bulletins (Chapter 19 references the 1993 version of Technical Bulletin 1 instead of the 2008 version).

Recommendation TX-4c. The City of Bellaire should review and update its flood damage prevention ordinance and guidance. Article II-A of Chapter 9 in the City of Bellaire’s Code of Ordinances addresses flood damage prevention. The City also enforces building codes that contain requirements for buildings in flood hazard areas. Review and update the definition of “lowest floor” to refer to the non-elevation requirements of Article II-A instead of NFIP regulations, and require non-residential buildings to be elevated or dry floodproofed as high as residential buildings (at least the BFE plus 1 foot). Correct the description of how lowest floors are determined and eliminate the implication that basements (areas below grade on all sides) are allowed. In addition, work with FEMA to revise the City’s guidance that explains which costs must be included in Substantial Improvement/Substantial Damage interpretations (a sample packet for this purpose is included in Appendix D of FEMA P-758, *Substantial Improvement/ Substantial Damage Desk Reference* [2010c]).

Recommendation TX-4d. The City of Port Aransas should review and update its flood damage prevention ordinance. Chapter 8 of the City of Port Aransas' Code of Ordinances addresses flood damage prevention. The City should ensure that any temporary, post-hurricane regulatory relief does not have the effect of waiving floodplain management requirements related to repair of buildings that incur Substantial Damage. Review and update the definition of "lowest floor" to refer to the non-elevation requirements of Chapter 8 rather than NFIP regulations.

Recommendation TX-4e. All Texas communities should consider reviewing and updating their local floodplain management ordinances. The Texas Water Development Board, in conjunction with FEMA, should consider reviewing previously adopted floodplain management ordinances for consistency with NFIP requirements and model building codes. The Texas Water Development Board should utilize FEMA's model floodplain ordinance to help them develop a model ordinance that seamlessly integrates with the I-Codes. The model ordinance can be utilized by all Texas communities when updating their ordinance.

5.4 Flood-Related Building Performance

Conclusion TX-5

Many non-elevated or low-elevation buildings sustained flood damage. Forty percent of flood-damaged buildings were located outside of the 0.2-percent-annual-chance probability floodplain. Buildings elevated above the Hurricane Harvey flood level on strong foundations sustained little or no flood damage.

Recommendation TX-5a. Communities and building owners should consider elevating new and Substantially Improved/Substantially Damaged buildings above the NFIP elevation requirements to protect them from flooding. Communities should consider requiring new buildings, those determined to have incurred Substantial Damage, and those that will undergo Substantial Improvement to be elevated in accordance with the I-Codes and ASCE 24, which exceed the NFIP elevation requirements. In some communities, Hurricane Harvey inundation levels rose higher than the BFE; therefore, communities should consider adopting elevation requirements that exceed ASCE 24 (i.e., more than the ASCE 24 minimum freeboard of 1 foot).

Recommendation TX-5b. Communities should incorporate the best available flood hazard data wherever they are available. For example, Nueces and Aransas Counties, TX, have preliminary FIRMs available that should be compared to effective FIRMs to require new buildings, Substantial Improvements, Substantially Damaged buildings, and reconstructed buildings to be elevated relative to the higher BFE. While a preliminary FIRM is not regulatory until adopted, using the latest flood hazard information is a best practice.

Recommendation TX-5c. Communities should consider future conditions in zoning, building code, and floodplain management requirements. While the model building codes and standards limit new construction in High-Risk Flood Hazard Areas, including areas prone to erosion and high-velocity flow areas, the DFE requirements (which exceed the minimum NFIP requirements) do not provide the same level of protection in all geographic areas. For example, 1 foot of additional elevation above the BFE on the FIRM may be equivalent to the 0.5-percent-annual-chance probability flood in one area and the 0.2-percent-annual-chance probability flood in another. As specified in ASCE 24, reasons for adopting higher flood elevations include anticipated future conditions (including predicted upland development, subsidence, or sea level rise), accommodating the flood of record, and compensating for uncertainties inherent in determining flood frequencies and flood elevations for other flood events. Communities should evaluate all of these factors, especially the future conditions, and consider adopting DFEs that best reflect the anticipated flood conditions over the life of the building.

Conclusion TX-6

Dry floodproofing measures often failed under less than design flood conditions. Following Tropical Storm Allison in June 2001, several buildings throughout the Houston area were dry floodproofed (with and without FEMA grant funding). The MAT visited approximately 20 dry floodproofed sites following Hurricane Harvey and identified several lessons learned from dry floodproofing failures under less than design flood conditions. The MAT also identified best practices from successfully implemented dry floodproofing measures.

Recommendation TX-6a. Local floodplain administrators, design professionals, and building owners should follow the guidance in FEMA's Texas Recovery Advisory 1 (2018g) and Florida Recovery Advisory 1 (2018f). Texas Recovery Advisory 1, *Dry Floodproofing: Planning and Design Considerations* (2018g), and Florida Recovery Advisory 1, *Dry Floodproofing: Operational Considerations* (2018f) have guidance related to dry floodproofing methods and procedures based on MAT observations made during and after Hurricanes Irma and Harvey. The MAT observations illustrate that designing and implementing dry floodproofing for buildings is complicated. Therefore, guidance based on recent events should be incorporated into the design and implementation of new and existing dry floodproofing. Specific considerations from the recovery advisories include:

- Conduct a thorough vulnerability assessment, including a survey of all potential water entry points, as part of the design process.
- Incorporate freeboard into the DFE based on the building use.
- Treat flood barriers like firewall assemblies—label them and minimize modifications and penetrations.
- Evaluate utility components and penetrations through walls and floors as potential water entry points.
- Install check valves in floor drain systems and require ejector systems with check valves/ backflow preventers for stormwater and sanitary sewers.
- Provide waterstops at the seals in foundation walls and floor slabs where those spaces are intended to remain dry and are located below the DFE.

Recommendation TX-6b. Local floodplain administrators, design professionals, and building owners should ensure sump pumps, with a floor drain system to collect seepage, are included as part of all dry floodproofing systems. To satisfy the performance expectations for dry floodproofed buildings when NFIP compliance is required, NFIP Technical Bulletin 3, *Non-Residential Floodproofing—Requirements and Certification* (1993) and ASCE 24 require sump pumps to remove seepage; emergency power should be provided to run the pumps as well. Most dry floodproofed buildings visited did not have sump pumps, which contributed to failure or heavy damage, so incorporating them should be emphasized.

Conclusion TX-7

Dry floodproofed buildings that were considered substantially impermeable sustained damage that resulted in significant loss of function while repairs were completed. In some cases, redundant mitigation measures within dry floodproofed buildings, such as compartmentalizing critical functions or elevating utility systems, helped reduce the loss of function. In particular, the use of flood damage-resistant materials on the interior of dry floodproofed portions of buildings reduced damage as well as loss of function.

> **Recommendation TX-7. Flood damage-resistant materials should be used below the DFE inside dry floodproofed buildings when possible.** Local floodplain administrators, design professionals, and building owners should consider encouraging the use of flood damage-resistant materials below the DFE inside dry floodproofed buildings. Using flood damage-resistant materials is considered a best practice and helps minimize damage and time needed to remove and replace interior finishes.

Conclusion TX-8

Dry floodproofed buildings where building managers had instilled a culture of preparedness sustained less damage than other dry floodproofed buildings. The scope and detail of operations, maintenance, and testing plans was an indicator of dry floodproofing system performance.

> **Recommendation TX-8a. Facility managers should develop an emergency operations plan (EOP) for severe weather.** An EOP that outlines how to prepare the building when severe weather events are expected should be developed by facility managers. Each dry floodproofed facility should have an EOP with action items or an implementation checklist based on a timeline keyed to official severe weather warnings and watches. ASCE 24 Chapter 6 contains requirements for and discussion of EOPs.

> **Recommendation TX-8b. Facility managers should routinely re-evaluate dry floodproofing designs and plans as required by codes and standards.** After each deployment of a dry floodproofing system, including training exercises, the overall design of dry floodproofing systems and EOPs for severe weather should be revisited to resolve any deficiencies identified while systems were being tested, installed, or subjected to floodwater. ASCE 24 Chapter 6 requires periodic practice of installing shields as well as testing of sump pumps and other drainage measures.

> **Recommendation TX-8c. Facility managers should take reasonable measures to instill a culture of preparedness.** Facility managers should conduct annual training exercises during which dry floodproofing measures are installed, taking note of the time to install each portion of the system and the total time to install the entire dry floodproofing system. The commentary in ASCE 24 indicates persons responsible for installing or implementing the measures must be familiar with the procedures and equipment. Therefore, training exercises should include building maintenance and engineering staff along with other building staff that may be needed to install dry floodproofing systems with little warning time. Maintenance of dry floodproofing system components should be conducted annually, as well as during training exercises and following deployment for a flood event. To ensure system functionality, periodic maintenance should include checking gaskets and seals, installation hardware and fasteners, and the condition of building elements to which dry floodproofing components will be attached.

Consider creating a video recording of manual dry floodproofing installations, especially the complex steps, so the video can be referenced later if untrained staff are required to assist.

Conclusion TX-9

Non-flood damage-resistant materials were used below the BFE in elevated buildings and had to be replaced. The MAT observed several instances of non-flood damage-resistant materials being removed from garages and crawlspaces below newer elevated buildings (new construction since floodplain management requirements were adopted). While the total flood insurance claims for these buildings were typically about $10,000 to $15,000, compared to $120,000 to $150,000 for adjacent non-elevated buildings, even those lower claims and relatively minor damage would likely have been avoided, or at least considerably reduced, if the appropriate flood damage-resistant materials had been used as required by local floodplain management regulations.

Recommendation TX-9. Local floodplain administrators must enforce, and design professionals and builders must comply with, the requirement to use flood damage-resistant materials below an elevated building's DFE. When communities issue permits for new construction, Substantial Improvement, and repair of Substantially Damaged buildings, the NFIP requires all building materials below the BFE to be flood damage-resistant, regardless of the expected or historical flood duration. Model building codes and ASCE 24 require flood damage-resistant materials to be used below the lowest floor. Refer to NFIP Technical Bulletin 2, F*lood Damage-Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the National Flood Insurance Program* (2008b), for the classification of specific materials.

Conclusion TX-10

Damage to buildings not designed and constructed to current building code requirements was noticeably greater than damage to NFIP-compliant buildings. Buildings that incorporated the best available flood hazard data along with requirements from consensus-based building codes and standards promulgated by the International Code Council and the ASCE sustained less damage than those that did not. Although buildings both inside and outside of the SFHA were flooded, those within the SFHA that sustained the most damage were designed and built before communities joined the NFIP and began regulating development in SFHAs. In Houston, the average NFIP flood insurance claim for pre-FIRM buildings (pre-1980) was double that of post-FIRM buildings. Some of the pre-FIRM buildings also flooded in 2015, 2016, and other significant rainfall events.

Recommendation TX-10a. When and where possible, FEMA should consider updating the NFIP standards to be at least equivalent to the consensus-based codes. The model building codes require freeboard above the BFE. FEMA should update the minimum NFIP requirements to include freeboard, or at least require freeboard as a minimum criterion to participate in the NFIP's CRS, described in Section 2.1.1.4. While the consensus-based codes are periodically updated (currently every 3 years), the NFIP building requirements have not significantly changed in the 50 years of the program.

Recommendation TX-10b. FEMA and communities should re-evaluate the criteria for Substantial Improvement/Substantial Damage. In light of the number of "Existing"[1] and legal non-conforming (see text box in Section 5.1) buildings that were inundated, FEMA and communities should re-evaluate the criteria for Substantial Improvement/Substantial Damage. Under the CRS program, communities earn points for higher regulatory standards when counting improvements cumulatively or having a Substantial Improvement threshold lower than 50 percent. The purpose of Substantial Improvement/Substantial Damage is to reduce the number of non-conforming buildings that are exposed to flood damage. Communities should consider adopting a threshold lower than 50 percent and consider developing requirements specific to repetitively flooded properties. FEMA should require having a Substantial Improvement threshold lower than 50 percent and/or using the Severe Repetitive Loss definition to trigger Substantial Damage (regardless of the 50 percent threshold) as a minimum criterion to participate in the NFIP's CRS.

Conclusion TX-11

The State and communities did not receive (or did not receive in a timely manner) data on buildings that appeared to have incurred Substantial Damage. When buildings appeared to have incurred Substantial Damage, the State and communities either did not receive requested data submitted by NFIP claims adjusters, or did not receive the information in a timely manner.

Recommendation TX-11. FEMA should develop an effective and timely means to deliver the Adjuster Preliminary Damage Assessment data. When NFIP claims adjusters identify claims that, based on available data, appear to have incurred Substantial Damage, the adjusters submit data using FEMA Form 086-0-020, *Adjuster Preliminary Damage Assessment* (2018a). The form indicates FEMA and communities can use the data to identify potentially Substantially Damaged buildings. FEMA P-758, *Substantial Improvement/Substantial Damage Desk Reference* (2010c) (Section 7.4.1), describes using the data for screening purposes only, especially after flood events that damage large numbers of buildings. FEMA should develop an effective and timely means to deliver data submitted by NFIP claims adjusters to States and communities.

Conclusion TX-12

The MAT observed widespread flood damage both within and outside the regulatory floodplain. In the City of Houston, approximately 48,850 buildings located in the SFHA were damaged and approximately 35,000 buildings located in the 0.2-percent-annual-chance floodplain were damaged. Another 70,000 buildings situated outside the 0.2-percent-annual-chance floodplain were damaged. Hundreds of these properties, including those outside the SFHA, have received repetitive claim payments from the NFIP. In some cases, historical flood insurance claims in specific areas indicated a flood risk that was not reflected on the FIRM (i.e., there were repetitive claims for properties outside the SFHA).

Recommendation TX-12a. FEMA should make NFIP policy information, especially data related to historical claims, available to help supplement flood hazard data on the FIRM. The number of active policies and historical claim information should be made public at a street

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[1] The NFIP uses the term "Existing" as follows: Existing Construction is a structure built before the community had adopted a Flood Insurance Rate Map (FIRM).

or community level and updated periodically to show historical trends versus one-time events. Generally, the public relies on FIRMs to identify risk, yet in many areas in Houston, claims are a better measure of risk and would supplement the FIRM. Property owners, including those outside the SFHA who are not required to carry flood insurance but are eligible for preferred risk policies, should have access to historical claims to supplement their flood insurance coverage decision-making process. FEMA should perform a study to help determine acceptable methods for making claims information more readily available without compromising privacy information. The analysis should include alternatives with advantages and disadvantages, along with a recommended path forward.

Recommendation TX-12b. Owners of buildings located near but outside the SFHA should consider implementing flood risk reduction measures. Aside from critical facilities (e.g., fire and police stations, hospitals), most model building code and floodplain management requirements do not apply to buildings near but outside the SFHA. Building owners, especially those located immediately adjacent to the SFHA where flooding has occurred, should evaluate their flood hazard when constructing or renovating their building and consider implementing flood risk reduction measures (e.g., elevating, wet floodproofing, dry floodproofing).

Conclusion TX-13

Contractors and designers have insufficient guidance on elevated slab projects. The MAT observed several ongoing residential elevated slab projects. The single-family buildings were typically being elevated on segmented concrete piles using a variety of methods to reinforce the slab and establish a load path between the slab and the columns. While each site and slab was unique, there were inconsistencies in existing slab reinforcement, and the design standard or method being applied to evaluate the slabs and determine whether each slab had sufficient capacity to support itself once elevated was unclear.

Recommendation TX-13. Continue ongoing research on the performance of elevated slab foundations and develop related outreach material. The University of Texas at Arlington has an ongoing research project related to the performance of elevated slab foundations. The purpose of the research is to support structural engineers in evaluating existing slab foundations, estimating the amount of strengthening required to meet the loading requirements, and providing suggested methods for strengthening slabs. Although FEMA P-312, *Homeowner's Guide to Retrofitting: Six Ways to Protect Your Home From Flooding* (2014), and other guidance exists related to elevated slab projects, this research will provide engineers with technical data to support their evaluations and designs based on testing representative concrete slabs that are typically constructed to be continuously supported by the ground. Considering the number of existing slab foundations and the potential for numerous elevated slab projects, the State of Texas may want to consider supplementing the ongoing research with FEMA Hazard Mitigation Grant Program funds or other funding to support this type of research. Outreach materials related to this research should be developed and distributed to elevation contractors and design professionals to consider and incorporate into elevated slab projects.

5.5 Wind-Related Building Performance

Conclusion TX-14

Roof-mounted equipment lacked adequate attachments. Inadequate attachment of roof-mounted equipment was responsible for much of the wind damage to non-residential buildings incurred during Hurricane Harvey.

> **Recommendation TX-14a. Building owners and/or facility managers should ensure roof-mounted equipment is adequately anchored.** Building owners should perform a vulnerability assessment and place more emphasis on anchoring roof-mounted equipment throughout the State, especially in the hurricane-prone regions. FEMA P-424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds* (2010a); FEMA P-543, Design Guide for *Improving Critical Facility Safety from Flooding and High Winds* (2007a); FEMA P-577, *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings* (2007b); and USVI Recovery Advisory 2, *Attachment of Rooftop Equipment in High-Wind Regions* (2018d), contain building-use-specific guidance for performing vulnerability assessments. Securing items on the roof should be a continued area of emphasis throughout the life of the building, including when roof-mounted equipment is replaced. In addition, owners should ensure equipment tie-downs lead to a proper load path so as not to cause more extensive damage to the roof. If the equipment cannot be adequately mounted on the roof, then the equipment should be moved elsewhere on the site instead of the roof.

> **Recommendation TX-14b. FEMA should ensure that securing roof-mounted equipment is incorporated into eligible Public Assistance Hazard Mitigation Proposals**. Appendix J of the FEMA *Public Assistance Program and Policy Guide* (PAPPG; 2018j) lists securing roof-mounted equipment via a continuous load path using tie-downs, straps, or other anchoring systems to resist expected wind forces as a cost-effective hazard mitigation measure. All eligible facilities with damage caused by inadequately attached equipment should incorporate securing roof-mounted equipment as a hazard mitigation measure under the Public Assistance grant when technically feasible and cost-effective.

Conclusion TX-15

Windows (glazed openings) on most existing buildings are vulnerable to damage and failure from wind pressures and wind-borne debris. The MAT observed that buildings of all types with unprotected glazing on exterior walls were vulnerable to failure from wind pressures and wind-borne debris. When these glazed openings fail, the buildings are exposed to additional internal wind pressures, and the building interior also becomes exposed to the wind and rain associated with the event. These failures were observed in all building types visited, including residential and non-residential.

> **Recommendation TX-15a. Building owners should consider protecting the glazed openings on their existing buildings.** Owners of existing buildings should consider protecting glazed window systems and doors with rated opening protection systems (i.e., storm shutters) or retrofitting the building with impact-resistant glazing. When those options are cost prohibitive, homeowners should consider constructing and maintaining plywood panels that are cut and sized to cover each window or glass door at the home (per the wood panel design criteria for opening

protection set forth in the IRC). FEMA USVI Recovery Advisory 4, *Design, Installation, and Retrofit of Doors, Windows, and Shutters* (2018e), provides guidance on the installation and protection of windows and doors. When evaluating opening protection systems, building owners should consider passive versus active alternatives, along with their capacity to maintain and implement the mitigation measure.

Recommendation TX-15b. FEMA should ensure that opening protection is incorporated into eligible Public Assistance Hazard Mitigation Proposals. Appendix J of the FEMA PAPPG lists replacing doors, door frames, hinges, and hardware with wind-resistant units; strengthening windows; replacing glass with impact-resistant material; and installing shutters on windows as cost-effective hazard mitigation measures. All eligible facilities with glazing damage should incorporate glazing protection as a hazard mitigation measure under the Public Assistance grant when technically feasible and cost-effective.

Conclusion TX-16

The loss of wall coverings on residential buildings was widespread and, in some cases, served as an initiation point for progressive damage. The MAT observed evidence of inadequate resistance to wind pressures for certain wall coverings of residential buildings. The lack of face nailing on fiber cement siding in areas visited throughout Aransas and Nueces Counties led to extensive loss of wall covering on residential buildings. The loss of vinyl siding in newer construction was commonly due to not selecting siding appropriate for the designated wind speed; improper fasteners and/or improper fastener spacing were also a common factor.

Recommendation TX-16a. Design professionals should specify, and contractors should use, face nails on fiber cement siding. Unless the product has been tested and the manufacturer's installation instructions do not require face nails based on the wind hazard at the building location, design professionals should specify, and contractors should use, face nails instead of blind nails for fiber cement siding in all three zones of the TDI-designated Catastrophe Area. Refer to Technical Fact Sheet 5.3, "Siding Installation in High-Wind Regions" in FEMA P-499 (2010b). In addition, contractors should consider sealing the free siding edge with a continuous bead of sealant as a best practice. At a minimum the manufacturer's installation requirements for fastener type, size, and spacing should be followed (requirements vary based on the wind hazard for the building location).

Recommendation TX-16b. Windstorm inspectors and local building officials should enforce the use of approved materials in high-wind regions and ensure they are installed in accordance with the manufacturer's requirements. The TDI maintains a list of products that comply with the adopted standards for the Windstorm Inspection Program. The MAT observed that improper materials were used in new construction that sustained damage. Design professionals, contractors, construction material suppliers, and inspectors should only use/allow products that are on the approved and tested list and ensure they are installed in accordance with industry and manufacturers' recommendations for high-wind zone installations. For example, high-wind siding should be used instead of standard siding in areas with a design wind speed greater than 110 mph per ASCE 7-05, or 139 mph per ASCE 7-10/16.

Conclusion TX-17

Asphalt shingle roof damage was observed throughout high-wind regions. The MAT observed many wind performance problems with asphalt shingles, including shingles that had been recently installed. Asphalt shingles rated less than that required by TDI were observed in new construction, as well as on project sites that were being re-roofed following Hurricane Harvey.

> **Recommendation TX-17. Contractors should use and inspectors should enforce the use of asphalt roof shingles rated for high-wind regions and follow special installation methods to increase wind resistance.** Texas Recovery Advisory 2, *Asphalt Shingle Roofing for High-Wind Regions* (2018c), provides guidance on installing asphalt roof shingles that will enhance wind resistance in high-wind regions. When asphalt shingles are used, the TDI should require shingles based on wind resistance determined by test method ASTM D 7158, which calls for Class G shingles in Inland Zone I (basic wind speed 120 mph) and Inland Zone II (basic wind speed 110 mph), and Class H shingles in the Seaward Zone (basic wind speed 130 mph).

Conclusion TX-18

Many soffits lacked adequate wind resistance, typically because the wrong material was used for the region or it was improperly installed. The MAT observed widespread loss of soffits in residential and non-residential construction, generally due to improper materials, lack of fasteners, and/or inadequate framing, and wind-driven rain infiltrated some areas where soffits were displaced or lost. The loss of soffit vents can allow hurricane winds to drive large amounts of water through the openings and soak insulation, which can lead to mold growth and, in some cases, the collapse of ceilings.

> **Recommendation TX-18. Designers, contractors, and inspectors should place more emphasis on proper soffit installation in high-wind regions.** Wind-driven rain should be limited from entering building envelopes and damaging building interiors through proper soffit installation. Florida Recovery Advisory 2, *Soffit Installation in Florida* (2018m), provides soffit installation guidance.

Conclusion TX-19

Brick veneer failures were common. The MAT observed numerous brick veneer failures throughout the Hurricane Harvey-damaged areas, including several mid-rise condominiums. The common issues observed were randomly spaced brick ties and corrosion or minimal embedment of many corrugated ties.

> **Recommendation TX-19. Design professionals and contractors should improve installation of brick veneer in high-wind regions**. Model codes prior to 1995 permitted brick veneer in any location, with no wind speed restrictions. Current building requirements and referenced standards, including TMS 402/602, *Building Code Requirements for Masonry Structures* (2016) (formerly the ACI 530), provide design and construction guidance for the installation of brick veneer. Technical Fact Sheet 5.4, "Attachment of Brick Veneer in High-Wind Regions" in FEMA P-499 (2010b), provides additional guidance on properly attaching brick veneer in high-wind regions. Design professionals and contractors should place more emphasis on proper construction of brick veneer wall systems to limit potential damage.

Conclusion TX-20

The performance of high-wind-rated sectional and rolling doors was noticeably better than those that were not designed for use in high-wind regions. The MAT observed many non-rated sectional doors that failed during Hurricane Harvey. On the other hand, very few hurricane-rated sectional doors failed.

> **Recommendation TX-20. Building owners in the hurricane-prone regions should have sectional and rolling doors evaluated and replace existing doors that lack adequate resistance.** Sectional and rolling doors should be installed and reinforced in accordance with industry and manufacturer's recommendations for hurricane-prone region installations to prevent catastrophic door failure and building pressurization. While most non-rated sectional and rolling doors observed by the MAT appeared to pre-date TDI Windstorm Inspection Program requirements, building owners, designers, and contractors should ensure any new doors are on the approved product evaluation list.

Conclusion TX-21

The improved wind performance of metal edge flashings and copings in new construction contributed to the reduced number of roof membrane blow-offs. The improved performance is likely due to the IBC's reference to the American National Standards Institute/Single Ply Roofing Industry/FM Approvals (ANSI/SPRI/FM) 4435/ES-1 2017, *Test Standard for Edge Systems Used with Low Slope Roofing Systems* (ES-1 was first incorporated into the 2003 edition of the IBC).

> **Recommendation TX-21. Building owners with single-ply roof membranes should ensure their metal edge systems are properly installed.** Metal edge flashing and coping on roofs with single-ply roof membranes should be installed in accordance with ANSI/SPRI/FM 4435/ES-1 2017 and manufacturer's recommendations for hurricane-prone region installations should be followed to prevent roof cover loss.

Conclusion TX-22

Current testing standards may need to further consider debris impact. In multiple locations, the MAT observed broken laminated glass that remained in the frame, but allowed water infiltration; the leakage may have been related to flashing deficiencies, glass breakage, or both. The MAT also observed one instance where a window subframe blew out of the main window frame because wind-borne debris impacted a jack stud; the stud was pushed inward, which caused the main window frame to twist. While the products observed were tested for the region in which they were installed, the damage indicates the performance measures in current testing requirements may need to be re-evaluated and adjusted, especially with respect to limiting infiltration of wind-driven rain.

> **Recommendation TX-22a. FEMA should work with industry partners to evaluate whether ASTM testing requirements for debris impacts and wind pressures should be adjusted.** Using damage observations made after Hurricane Harvey, the FEMA Building Science Branch should collaborate with industry partners and identify trends in damages (e.g., interior finishes subject to water intrusion/wind driven rain) that are potentially a result of inadequate testing requirements. For example, ASTM E1886, the standard for glazing protection systems impacted

by missiles and exposed to cyclic pressure differentials, does not consider water leakage after debris impact, nor does it consider debris impact to the framing around the opening. The current testing standard evaluates missile impacts to the window, but the framing around the glazing is not impacted during testing.

Recommendation TX-22b. Industry groups and/or academia should study debris generation and strikes to protective systems during hurricanes to determine whether the wind speed triggers for the ASCE 7 wind-borne debris region are appropriate. Industry groups and/or academia should study debris generation and associated debris strikes to protective systems from the 2017 hurricane, as well as for future storms, to determine whether the current wind speed triggers for the wind-borne debris region as defined in ASCE 7 are appropriate. Data collected and analyzed during the study can be used to make recommendations on ASCE 7-required protection of windows and glazed doors.

5.6 FEMA Technical Publications and Guidance

Conclusion TX-23

Select FEMA Building Science technical guidance publications are becoming increasingly incongruent with current building codes and do not include lessons learned from recent MATs. The Building Science Branch at FEMA HQ develops and maintains over 200 publications and resources that provide technical guidance on how to assess risk; identify vulnerabilities; better understand the NFIP and the regulatory environment with respect to building codes and standards; and describe best practices and mitigation measures that can be taken to reduce vulnerabilities to flood, wind, and seismic hazards. Some of the FEMA Building Science technical guidance publications do not reflect advanced requirements in current building codes nor do they include new lessons learned from recent MAT reports.

The 2017 hurricane season brought landfalling hurricanes on the island territories and the continental United States. There were many valuable and important damage observations and lessons learned from this and other events, and the observed damage might have been avoided if the guidance from these documents had been incorporated at different building locations. However, while the approaches and theories in these publications are still accurate, many of the building codes have been updated in the last 8 to 10 years and may impact the current approaches outlined in these documents.

Recommendation TX-23a. FEMA should complete *Guidelines for Wind Vulnerability Assessments for Critical Facilities*. FEMA's Building Science Branch has been developing guidance to assess wind vulnerabilities of critical facilities. FEMA should include lessons learned from the 2017 hurricane season in finishing this publication, which would greatly benefit many stakeholders in the U.S.

Recommendation TX-23b. FEMA should update select FEMA Building Science publications that affect coastal construction. The FEMA Building Science Branch should consider updating or producing a supplement for its key hurricane technical guidance publications to include lessons learned from the 2017 hurricane season and reflect updates to building codes since the publications' latest releases. These publications might include, but are not necessarily limited to, the following:

- FEMA P-55, *Coastal Construction Manual* (2011)
- FEMA P-499, *Home Builder's Guide to Coastal Construction* (2010b)
- FEMA P-762, *Local Officials Guide for Coastal Construction* (2009b)
- FEMA P-804, *Wind Retrofit Guide for Residential Buildings* (2010d)

Recommendation TX-23c. FEMA should update the FEMA Risk Management Series guidance publications for natural hazards. The FEMA Building Science Branch, working with other FEMA and DHS entities, should consider updating or producing a supplement to select technical documents from the FEMA Natural Hazard Risk Management Series to include lessons learned from the 2017 hurricane season and reflect updates to building codes since the publications' latest releases. These publications might include, but are not limited to, the following:

- FEMA P-424, *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds* (2010a)
- FEMA 543, *Design Guide for Improving Critical Facility Safety from Flooding and High Winds* (2007a)
- FEMA 577, *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds: Providing Protection to People and Buildings* (2007b)

Conclusion TX-24

Post-Tropical Storm Allison Public Assistance Hazard Mitigation Proposals did not require post-construction certification to a specific requirement or standard. The MAT observed dry floodproofing failures at several sites where the dry floodproofing measure had been installed using Public Assistance funding. The Public Assistance Mitigation Proposal for these measures did not reference or require compliance with NFIP Technical Bulletin 3, *Non-Residential Floodproofing—Requirements and Certification* (1993) or ASCE 24-98.

Recommendation TX-24a. FEMA should make the requirements for projects developed under the FEMA Public Assistance and the Hazard Mitigation Assistance programs consistent between the programs. The FEMA PAPPG allows buildings to be dry or wet floodproofed as a hazard mitigation measure without specific requirements (unless the measure triggers a code requirement), whereas the FEMA HMA guidance requires mitigation grant recipients to design all dry floodproofing projects in accordance with ASCE 24. When applicable, FEMA should incorporate consensus standards (ASCE 24), testing standards (ANSI, ASTM, etc.), or other best practice guidance when identifying cost-effective mitigation measures in the PAPPG.

Recommendation TX-24b. Hazard Mitigation Proposals for dry floodproofing under the Public Assistance program should be required to reference ASCE 24. All Public Assistance Hazard Mitigation Proposals that include dry floodproofing as a mitigation measure should require design and construction to be completed in accordance with ASCE 24. In addition, dry floodproofing design and construction should incorporate guidance from Texas Recovery Advisory 1, *Dry Floodproofing: Planning and Design Considerations* (2018g), and Florida Recovery Advisory 1, *Dry Floodproofing: Operational Considerations* (2018f).

Conclusion TX-25

Future dry floodproofing design and construction can benefit from observed failures and successes. The MAT visited about 20 dry floodproofed sites following Hurricane Harvey and observed several lessons learned from dry floodproofing failures under less than design flood conditions, as well as best practices from successes. For example, dry floodproofed facilities that had undergone a comprehensive flood vulnerability assessment prior to the design and construction of the floodproofing measures and had a thorough EOP that was regularly exercised were much less likely to have flood damage.

Recommendation TX-25a. FEMA should update dry floodproofing guidance. Based on the varying performance of dry floodproofing measures observed, FEMA should revise existing dry floodproofing guidance to include data and observations from recent events. In particular, NFIP Technical Bulletin 3, *Non-Residential Floodproofing—Requirements and Certification* (1993), should be updated to improve guidance on planning, design and construction, and emergency operations, as well as maintenance planning requirements. Specific points of emphasis include:

- For new construction, recommend using ACI 350, *Code Requirements for Environmental Engineering Concrete Structures* (2006) for designing concrete that will be constructed below the required dry floodproofing elevation (ACI 350 concrete design reduces the crack width in concrete and increases the fineness of the concrete matrix to reduce concrete permeability rates).
- For both new construction and retrofits to existing structures, include information on the use of products certified by the National Flood Barrier Testing and Certification Program and the applicability of the ANSI 2510 standard for flood barrier products (ANSI 2510 establishes performance standards for perimeter barriers, opening barriers, backflow valves, and flood abatement pumps).
- Consider limiting the amount of allowable building envelope that is not permanently substantially impermeable. Generally, passive dry floodproofing measures were more effective than active measures at reducing flood damage. However, the number of active measures and time required to implement them was typically a better indicator of performance; buildings with fewer active dry floodproofing measures performed better than those with more. As a result, the extent of temporary protective measures, whether passive or active, would be limited to the length of the perimeter required for egress (pedestrian and vehicular in the case of parking structures and loading docks).

FEMA should also consider updating FEMA P-936, *Floodproofing for Non-Residential Buildings* (2013), with relevant lessons learned from the 2017 hurricane season.

Recommendation TX-25b. FEMA should evaluate existing dry floodproofing guidance and post-flood investigations to develop a recommendation for inclusion in ASCE 24. FEMA should review recommendations, fact sheets, and recovery advisories related to dry floodproofing included in other MAT reports to develop a comprehensive recommendation for dry floodproofing design, limitations, testing, and maintenance and operations requirements for consideration by the ASCE 24 committee charged with revising Chapter 6, "Dry Floodproofing and Wet Floodproofing."

Conclusion TX-26

Many communities have difficulty implementing the Substantial Improvement/Substantial Damage requirements, especially after major disasters. Several thousand flood-damaged buildings in SFHAs flooded by Hurricane Harvey were designed and built before communities joined the NFIP and began regulating development in SFHAs. Enforcing the NFIP requirements to bring Substantially Improved and Substantially Damaged buildings into compliance continues to be one of the more difficult challenges for floodplain administrators and building officials. Updated guidance on administering the Substantial Improvement/Substantial Damage requirements in forms accessible by local officials, design professionals, builders, and property owners is needed. When flood-damaged buildings are insured by the NFIP, local officials must determine whether a building was Substantially Damaged in order for policyholders to qualify for Increased Cost of Compliance.

Recommendation TX-26a. FEMA should update FEMA P-758; at the same time, FEMA 213 should be updated to be consistent with FEMA P-758. FEMA P-758, *Substantial Improvement/Substantial Damage Desk Reference* (2010c) should be updated. Updates should include lessons learned, and recommended guidance and clarifications since it was published in 2010. At the same time, FEMA 213, A*nswers to Questions about Substantially Improved/Substantially Damaged Buildings* (2018b) should be updated to be consistent with FEMA P-758. Outreach material should be developed as part of the publication updates.

Recommendation TX-26b. FEMA should consider expanding existing training materials related to Substantial Improvement/Substantial Damage. FEMA should consider developing a webinar format training for distribution to NFIP State Coordinators and other entities related to Substantial Improvement/Substantial Damage. The materials should incorporate lessons learned after Hurricane Harvey and other recent flood events and should include a unit that focuses on the local official's role in helping insured property owners satisfy requirements to qualify for Increased Cost of Compliance claims and in issuing permits for mitigation measures eligible for use of those claim payments.

5.7 Summary of Conclusions and Recommendations

Table 5-1 is a matrix listing the conclusions and recommendations cross-referenced to the sections of the report that describe the supporting observations. The recommendations provided in the table have also been cross-referenced to Recovery Support Functions (RSFs) supported by FEMA through the National Disaster Recovery Framework (NDRF). FEMA developed the RSFs with the objective of facilitating the identification, coordination, and delivery of Federal assistance needed to supplement recovery resources and efforts by local, State, tribal, and territorial governments, as well as private and nonprofit sectors. The MAT has identified RSFs for the recommendations provided in this report to assist Texas with accelerating the process of recovery, redevelopment, and revitalization.

NATIONAL DISASTER RECOVERY FRAMEWORK AND RECOVERY SUPPORT FUNCTIONS

FEMA developed the National Disaster Recovery Framework (NDRF) to create a common platform and forum by which the whole community builds, sustains, and coordinates delivery of recovery capabilities. FEMA guidance states:

> Resilient and sustainable recovery encompasses more than the restoration of a community's physical structures to pre-disaster conditions. The primary value of the NDRF is its emphasis on preparing for recovery in advance of disaster. The ability of a community to accelerate the recovery process begins with its efforts in pre-disaster preparedness, including coordinating with whole community partners, mitigating risks, incorporating continuity planning, identifying resources, and developing capacity to effectively manage the recovery process, and through collaborative and inclusive planning processes. Collaboration across the whole community provides an opportunity to integrate mitigation, resilience, and sustainability into the community's short- and long-term recovery goals.

The Recovery Support Functions compose the coordinating structure for key functional areas of assistance in the NDRF. Their purpose is to support local governments by facilitating problem solving; improving access to resources; and fostering coordination among State and Federal agencies, nongovernmental partners, and stakeholders.

The list of Recovery Support Functions and the leading coordinating agencies is presented below (and available on line at www.fema.gov/recovery-support-functions):

- Community Planning and Capacity Building (CPCB) Recovery Support Function (U.S. Department of Homeland Security/FEMA)
- Economic Recovery Support Function (U.S. Department of Commerce)
- Health and Social Services Recovery Support Function (U.S. Department of Health and Human Services)
- Housing Recovery Support Function (U.S. Department of Housing and Urban Development)
- Infrastructure Systems Recovery Support Function (U.S. Army Corps of Engineers)
- Natural and Cultural Resources Recovery Support Function (U.S. Department of the Interior)

Table 5-1: Summary of Conclusions and Recommendations

Observations	Conclusions	Recommendations	Recovery Support Function
Chapter 4 (Section 4.1)	**TX-1** Building codes and floodplain management requirements were inconsistently enforced.	**TX-1a.** Continue providing training to Windstorm Inspection Program inspectors and building code enforcement staff, placing emphasis on changes reflected in the latest adopted edition of the building code.	CPCB, Housing
Chapter 3 (Section 3.1)		**TX-1b.** The Texas Water Development Board and other stakeholders should develop/modify training on the flood provisions in model building codes and/or floodplain management ordinances.	CPCB
Chapters 3 and 4	**TX-2** Some high-occupancy and critical facility building owners have a limited awareness of hurricane hazard risks and vulnerabilities.	**TX-2.** Facility and building owners should perform vulnerability assessments.	CPCB, Health and Social Services, Housing
Chapter 4 (Section 4.1)	**TX-3** The TDI Texas Windstorm Inspection Program requirements are based on compliance with the 2006 IBC and IRC, which are outdated.	**TX-3a.** TDI should adopt the 2018 IBC and IRC as the model codes for its Windstorm Inspection Program.	CPCB, Housing
		TX-3b. TDI should consider developing a more stringent high-wind retrofit program.	
Chapter 2 (Section 2.1.3)	**TX-4** Portions of local floodplain management ordinances and building codes in communities visited by the MAT conflict with some of the requirements in model ordinances and building codes.	**TX-4a.** Harris County should review and update its floodplain management regulations.	CPCB
		TX-4b. The City of Houston should review and update its floodplain management ordinance and guidance.	
		TX-4c. The City of Bellaire should review and update its flood damage prevention ordinance and guidance.	
		TX-4d. The City of Port Aransas should review and update its flood damage prevention ordinance.	
General MAT Field Observation		**TX-4e.** All Texas communities should consider reviewing and updating their local floodplain management ordinances.	
Chapter 3 (Section 3.1)	**TX-5** Many non-elevated or low-elevation buildings sustained flood damage.	**TX-5a.** Communities and building owners should consider elevating new and Substantially Improved/ Substantially Damaged buildings above the NFIP elevation requirements to protect them from flooding.	CPCB, Housing
Chapter 3		**TX-5b.** Communities should incorporate the best available flood hazard data wherever they are available.	
		TX-5c. Communities should consider future conditions in zoning, building code, and floodplain management requirements.	

Table 5-1: Summary of Conclusions and Recommendations (continued)

Observations	Conclusions	Recommendations	Recovery Support Function
Chapter 3 (Section 3.2)	**TX-6** Dry floodproofing measures often failed under less than design flood conditions.	**TX-6a.** Local floodplain administrators, design professionals, and building owners should follow the guidance in FEMA's Texas Recovery Advisory 1 (2018g) and Florida Recovery Advisory 1 (2018f).	CPCB, Infrastructure
		TX-6b. Local floodplain administrators, design professionals, and building owners should ensure sump pumps, with a floor drain system to collect seepage, are included as part of all dry floodproofing systems.	
	TX-7 Dry floodproofed buildings that were considered substantially impermeable sustained damage that resulted in significant loss of function while repairs were completed.	**TX-7.** Flood damage-resistant materials should be used below the DFE inside dry floodproofed buildings when possible.	CPCB, Infrastructure
	TX-8 Dry floodproofed buildings where building managers had instilled a culture of preparedness sustained less damage than other dry floodproofed buildings.	**TX-8a.** Facility managers should develop an emergency operations plan (EOP) for severe weather.	CPCB, Infrastructure
		TX-8b. Facility managers should routinely re-evaluate dry floodproofing designs and plans as required by codes and standards.	
		TX-8c. Facility managers should take reasonable measures to instill a culture of preparedness.	
Chapter 3 (Section 3.1)	**TX-9** Non-flood damage-resistant materials were used below the BFE in elevated buildings and had to be replaced.	**TX-9.** Local floodplain administrators must enforce, and design professionals and builders must comply with, the requirement to use flood damage-resistant materials below an elevated building's DFE.	CPCB
Chapter 3	**TX-10** Damage to buildings not designed and constructed to current building code requirements was noticeably greater than damage to NFIP-compliant buildings.	**TX-10a.** When and where possible, FEMA should consider updating the NFIP standards to be at least equivalent to the consensus-based codes.	CPCB, Housing
		TX-10b. FEMA and communities should re-evaluate the criteria for Substantial Improvement/Substantial Damage.	CPCB
General MAT Field Observation	**TX-11** The State and communities did not receive (or did not receive in a timely manner) data on buildings that appeared to have incurred Substantial Damage.	**TX-11.** FEMA should develop an effective and timely means to deliver the Adjuster Preliminary Damage Assessment data.	CPCB

Table 5-1: Summary of Conclusions and Recommendations (continued)

Observations	Conclusions	Recommendations	Recovery Support Function
Chapter 3	**TX-12** The MAT observed widespread flood damage both within and outside the regulatory floodplain.	**TX-12a.** FEMA should make NFIP policy information, especially data related to historical claims, available to help supplement flood hazard data on the FIRM.	CPCB
		TX-12b. Owners of buildings located near but outside the SFHA should consider implementing flood risk reduction measures.	CPCB, Housing
Chapter 3 (Section 3.1)	**TX-13** Contractors and designers have insufficient guidance on elevated slab projects.	**TX-13.** Continue ongoing research on the performance of elevated slab foundations and develop related outreach material.	CPCB
Chapter 4 (Section 4.2)	**TX-14** Roof-mounted equipment lacked adequate attachments.	**TX-14a.** Building owners and/or facility managers should ensure roof-mounted equipment is adequately anchored.	CPCB, Health and Social Services, Housing
		TX-14b. FEMA should ensure that securing roof-mounted equipment is incorporated into eligible Public Assistance Hazard Mitigation Proposals.	
Chapter 4	**TX-15** Windows (glazed openings) on most existing buildings are vulnerable to damage and failure from wind pressures and wind-borne debris.	**TX-15a.** Building owners should consider protecting the glazed openings on their existing buildings.	CPCB, Health and Social Services, Housing
		TX-15b. FEMA should ensure that opening protection is incorporated into eligible Public Assistance Hazard Mitigation Proposals.	
Chapter 4 (Section 4.1)	**TX-16** The loss of wall coverings on residential buildings was widespread and, in some cases, served as an initiation point for progressive damage.	**TX-16a.** Design professionals should specify, and contractors should use, face nails on fiber cement siding.	CPCB, Housing
		TX-16b. Windstorm inspectors and local building officials should enforce the use of approved materials in high-wind regions and ensure they are installed in accordance with the manufacturer's requirements.	CPCB
	TX-17 Asphalt shingle roof damage was observed throughout high-wind regions.	**TX-17.** Contractors should use and inspectors should enforce the use of asphalt roof shingles rated for high-wind regions and follow special installation methods to increase wind resistance.	CPCB
Chapter 4	**TX-18** Many soffits lacked adequate wind resistance, typically because the wrong material was used for the region or it was improperly installed.	**TX-18.** Designers, contractors, and inspectors should place more emphasis on proper soffit installation in high-wind regions.	CPCB

Table 5-1: Summary of Conclusions and Recommendations (continued)

Observations	Conclusions	Recommendations	Recovery Support Function
Chapter 4 (Section 4.1)	**TX-19** Brick veneer failures were common.	**TX-19.** Design professionals and contractors should improve installation of brick veneer in high-wind regions.	CPCB
	TX-20 The performance of high-wind-rated sectional and rolling doors was noticeably better than those that were not designed for use in high-wind regions.	**TX-20.** Building owners in the hurricane-prone regions should have sectional and rolling doors evaluated and replace existing doors that lack adequate resistance.	CPCB
Chapter 4 (Section 4.2)	**TX-21** The improved wind performance of metal edge flashings and copings in new construction contributed to the reduced number of roof membrane blow-offs.	**TX-21.** Building owners with single-ply roof membranes should ensure their metal edge systems are properly installed.	CPCB
Chapter 4	**TX-22** Current testing standards may need to further consider debris impact.	**TX-22a.** FEMA should work with industry partners to evaluate whether ASTM testing requirements for debris impacts and wind pressures should be adjusted.	CPCB, Housing
		TX-22b. Industry groups and/or academia should study debris generation and strikes to protective systems during hurricanes to determine whether the wind speed triggers for the ASCE 7 wind-borne debris region are appropriate.	
General MAT Field Observation	**TX-23** Select FEMA Building Science technical guidance publications are becoming increasingly incongruent with current building codes and do not include lessons learned from recent MATs.	**TX-23a.** FEMA should complete *Guidelines for Wind Vulnerability Assessments for Critical Facilities*.	CPCB, Health and Social Services
		TX-23b. FEMA should update select FEMA Building Science publications that affect coastal construction.	CPCB, Housing
		TX-23c. FEMA should update the FEMA Risk Management Series guidance publications for natural hazards.	CPCB, Health and Social Services

Table 5-1: Summary of Conclusions and Recommendations (concluded)

Observations	Conclusions	Recommendations	Recovery Support Function
Chapter 3 (Section 3.2)	**TX-24** Post-Tropical Storm Allison Public Assistance Hazard Mitigation Proposals did not require post-construction certification to a specific requirement or standard.	**TX-24a.** FEMA should make the requirements for projects developed under the FEMA Public Assistance and the Hazard Mitigation Assistance programs consistent between the programs.	CPCB, Health and Social Services
		TX-24b. Hazard Mitigation Proposals for dry floodproofing under the Public Assistance program should be required to reference ASCE 24.	CPCB, Health and Social Services, Infrastructure
	TX-25 Future dry floodproofing design and construction can benefit from observed failures and successes.	**TX-25a.** FEMA should update dry floodproofing guidance.	CPCB, Infrastructure
		TX-25b. FEMA should evaluate existing dry floodproofing guidance and post-flood investigations to develop a recommendation for inclusion in ASCE 24.	
General MAT Field Observation	**TX-26** Many communities have difficulty implementing the Substantial Improvement/ Substantial Damage requirements, especially after major disasters.	**TX-26a.** FEMA should update FEMA P-758; at the same time, FEMA 213 should be updated to be consistent with FEMA P-758.	CPCB
		TX-26b. FEMA should consider expanding existing training materials related to Substantial Improvement/ Substantial Damage.	

ASCE = American Society of Civil Engineers
BFE = base flood elevation
CPCB = Community Planning and Capacity Building
DFE = design flood elevation
EOP = emergency operations plan
FEMA = Federal Emergency Management Agency
FIRM = Flood Insurance Rate Map
IBC = International Building Code
IRC = International Residential Code
MAT = Mitigation Assessment Team
NFIP = National Flood Insurance Program
SFHA = Special Flood Hazard Area
TDI = Texas Department of Insurance

Appendix A: Acknowledgments

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David Alamia, MPA CEM
Harris County Office of Emergency Management

Scott Aldridge
CDM Smith

Courtney Alters
Riverview Reality Partners

Robert Azimi
FM Approvals

Randy Behm, PE, CFM
U.S. Army Corps of Engineers

Chad Berginnis, CFM
Association of State Floodplain Managers

Matthew Berkheiser, DrPh, CIH, CSP
The University of Texas MD Anderson Cancer Center

Jason Berrio
Thermal Energy Corporation (TECO)

Bill Blanton, CFM
FEMA Headquarters

John Bourdeau, Jr., CFM, PMP
FEMA Region VI

Dana Bres, PE
U.S. Department of Housing and Urban Development

Adam Briones
Harris County Sheriff's Office

Lindsay Brugger, AIA
American Institute of Architects

Jose Campos
Hicks Ventures

Abel Carrillo
Port Aransas Building Official

Paul Carter
Harris County Engineering Department
Facilities & Property Maintenance

Bill Coulbourne, PE, F.SEI, F.ASCE
AECOM

Paul Croas
Harris County Sheriff's Office

Richard Driscoll
Floodbreak

FEMA Modeling Working Group

Gina Filippone, CFM
AECOM

Jacob Frazell, PMP, CFM, LEED GA
Harris County Engineering Department
Facilities & Property Maintenance

Fanny Frederick
The University of Texas MD Anderson
Cancer Center

Jose Garcia, PE, CEM
Thermal Energy Corporation (TECO)

Rose Grant
State Farm

Zane Gifford
Riverview Reality Partners

Ram Goonie, CEM
Thermal Energy Corporation (TECO)

Bert Gumeringer
Texas Children's Hospital

Carlos Gutierrez, PE, MLSE
CSF Consulting LP

Lisa Hargrove
Houstonfirst

Leslie Chapman-Henderson
Federal Alliance for Safe Homes, Inc.

Micah Hennings
Harris County Engineering Department
Facilities & Property Maintenance

Andrew Hoyns
Hicks Ventures

Greg Hudgins
The University of Texas MD Anderson
Cancer Center

John Ingargiola, EI, CFM, CBO
FEMA Headquarters

Insurance Institute for Business & Home Safety

International Code Council

Samantha Krautwurst, PE
AECOM

Edward Laatsch, PE
FEMA Headquarters

Donald Leifheit Jr., CFM
FEMA Region VI

Marc Levitan, PhD
National Institute of Standards and
Technology

Tom Little, CFM, CGP
Smartvent

Rachel Minnery, FAIA
American Institute of Architects

James Mitchell
Texas Children's Hospital

Judith Mitrani-Reiser, PhD
National Institute of Standards and
Technology

Karen Mooney, MBA, ACC
The University of Texas MD Anderson
Cancer Center

Rock Morille, MBA, BSME
Baylor College of Medicine

Devina Patel
The University of Texas MD Anderson
Cancer Center

Tim Peglow, PE, CCE, SASHE
The University of Texas MD Anderson
Cancer Center

John "Bud" Plisich
FEMA Region IV

Carol Porter, DNP, RN, FAAN
The University of Texas MD Anderson Cancer Center

James Power
The University of Texas MD Anderson Cancer Center

Oscar Rangel
The University of Texas MD Anderson Cancer Center

James Reddington
City of Houston

Michael Rimoldi, MPA, CBO, CFM
Federal Alliance for Safe Homes, Inc.

David B. Roueche, PhD
Auburn University

Bob Roy
Center Point Energy

Lance Rumfield
Center Point Energy

Elex Sanchez
Texas Children's Hospital

Sheldon Schroeder, AIA
Freeman Schroeder Architects

Rodney Smalligan
The University of Texas MD Anderson Cancer Center

Michael Staley
Harris Heath Ben Taub Hospital

Benny Stansbury
Harris Heath Ben Taub Hospital

Steve Suter
The University of Texas MD Anderson Cancer Center

Biv Taylor, PE
Houston Energy Corridor Facilities Manager

Steve Thompson, PE
TX Department of Insurance

Amanda Torres
Rockport Community Planner

Raymond Tirado
Four Leaf Towers

Bruce Turner, PE, CPE
Thermal Energy Corporation (TECO)

Roksan Okan-Vick, FAIA
Houstonfirst

Peter Vickery, PhD, PE, F.SEI, F.ASCE
Applied Research Associates

Larry Voice
FEMA Region VI

Ronald C. Wanhanen, PE
FEMA Region VI

Chad Wleczyk
Center Point Energy

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– Technical Fact Sheet 4.1, "Load Paths"

– Technical Fact Sheet 4.3, "Use of Connectors and Brackets"

– Technical Fact Sheet 5.3, "Siding Installation in High-Wind Regions"

– Technical Fact Sheet 5.4, "Attachment of Brick Veneer in High-Wind Regions"

– Technical Fact Sheet 6.2, "Protection of Openings – Shutters and Glazing"

– Technical Fact Sheet 7.3, "Asphalt Shingle Roofing for High-Wind Regions"

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Appendix C: Recovery Advisories

FEMA has prepared new Recovery Advisories (RAs) that present guidance to engineers, architects, homeowners, and local officials on mitigation measures that can be taken to minimize building damage in a hurricane event. Two advisories are referenced in this appendix:

FL-RA1: *Dry Floodproofing: Planning and Design Considerations*

FL-RA2: *Asphalt Shingle Roofing for High-Wind Regions*

These advisories are online at https://www.fema.gov/media-library/assets/documents/158123

Dry Floodproofing: Planning and Design Considerations

FEMA

HURRICANE HARVEY IN TEXAS *Recovery Advisory 1, April 2018*

Purpose and Intended Audience

The purpose of this Recovery Advisory is to provide guidance on the design of dry floodproofing measures to reduce flood damage and limit interruption of building services. This advisory incorporates observations made by the Federal Emergency Management Agency (FEMA) Mitigation Assessment Teams (MATs) in Texas and Florida after Hurricanes Harvey and Irma. It describes best design practices and successful implementation of dry floodproofing, as well as lessons learned from failures. The information in this advisory is directed toward existing and new non-residential facilities.

This guidance, along with other FEMA publications related to dry floodproofing, should be used by building owners and design professionals examining ways to reduce future risk. It will also be useful to communities and building owners preparing designs and proposals for FEMA Section 404 Hazard Mitigation grants and hazard mitigation elements included in recovery funding available through FEMA Section 406 Public Assistance. To improve resiliency in future flooding events, lessons learned and best practices from the MATs can be incorporated into retrofits when dry floodproofing measures are applied to existing buildings and when designing dry floodproofing systems for new buildings.

The audience for this advisory includes building owners, operators, and managers; architects; engineers; building officials; contractors; and local government officials responsible for public building planning, design, and maintenance.

Key Issues

The key issues identified by the MATs during field visits in Texas and Florida are shown in Table 1. A number of these key issues are discussed in detail in other FEMA publications (see the list of references and resources in this advisory) and not in this advisory. This advisory focuses on key issues to help fill information gaps or supplement guidance in other FEMA publications.

Dry Floodproofing

Dry floodproofing is a combination of measures that result in a structure, including its attendant utilities and equipment, being watertight, with all elements substantially impermeable to the entrance of floodwater and with structural components having the capacity to resist flood loads (ASCE 24; ASCE 2014).

The image below shows an example of dry floodproofing where a passive opening protection deployed to protect a below-grade loading dock was threatened by rising floodwaters.

Photograph courtesy of Andrew Hoyns, Hicks Ventures

FEMA Public Assistance Program Funding for Dry Floodproofing Projects

In addition to funding for repair and recovery projects, FEMA Public Assistance (PA) Program funding may be available for cost-effective hazard mitigation measures that increase resilience, such as dry floodproofing projects. For more information, refer to Chapter 2 Section VII.C., "Hazard Mitigation" of FEMA's Public Assistance Program and Policy Guide (2018).

Table 1: Key Issues Identified by MATs

Key Topic Areas	Discussed in this Advisory?	Additional FEMA Sources of Information
Backup power	**Yes**	FEMA P-1019 FEMA P-348 (Chapter 5) Iowa Floods of 2016 RA5
Building penetration elevations relative to base/design flood elevations	**Yes**	FEMA P-936 (Sections 2.6.3, 3.4, 3.9, and 3.10) FEMA P-259 (Chapter 5D)
Flood barrier penetrations and seepage control	**Yes**	FEMA P-312 (Chapters 7 and 8) FEMA P-936 (Section 3.4.3)
Issues with sewer system and stormwater systems (ejector pumps with back-flow preventers)	**Yes**	FEMA 259 (Sections 5D.10 and 5W.12) FEMA P-348 (Section 5.3) FEMA P-936 (Sections 2.2 and 3.7)
Rainfall behind the flood barrier	**Yes**	FEMA P-312 (Section 3.4.2; Chapters 7 and 8) FEMA P-936 (Sections 2.2.8 and 3.7)
Seepage disposal	**Yes**	FEMA P-936 (Sections 2.2.7 and 3.7)
Use of flood damage-resistant materials	**Yes**	FEMA TB 2 FEMA P-936 (Sections 3.2 and 3.9) See also *
Use of redundant systems and compartmentalization/layered protection	**Yes**	FEMA P-348 (Chapter 5)
Design flood elevation requirements	**No**	Hurricane Sandy RA5 Iowa Floods of 2016 RA1
Hydrostatic forces and buoyancy	**No**	Hurricane Sandy RA2 FEMA P-936 (Section 2.2)
Performance of critical building systems	**No**	Hurricane Sandy RA2, RA4, and RA6 Iowa Floods of 2016 RA3 FEMA P-348 (Chapter 5) FEMA P-936 (Section 2.6.3)

Note: Complete titles and URLs for each publication are presented at the end of this advisory

RA = Recovery Advisory; TB = Technical Bulletin

*Refer also to *Floodproof Commercial Construction: Working for Coastal Communities* (Oak Ridge National Laboratory 2011)

This Recovery Advisory Addresses

- Observations of dry floodproofing system failures
- Flood vulnerability assessments
- Planning and pre-design considerations
- Design considerations

A companion advisory, titled *Dry Floodproofing: Operational Considerations* (Hurricane Irma in Florida, FL-RA1, 2018) describes deployment considerations (deployment, operations, maintenance, testing) for dry floodproofing.

Observations of Dry Floodproofing System Failures

Hurricanes Harvey and Irma caused numerous failures in dry floodproofing systems used to protect non-residential buildings, which led to extensive damage to mechanical, electrical, and plumbing system components, as well as building and interior finishes, and occasionally structural components. Based on the observations of FEMA's MATs deployed after the hurricanes, the performance of dry floodproofing measures was highly variable, ranging from effective to completely ineffective. Observed failures at dry floodproofed buildings included overtopping of flood walls or barriers, failure of the opening protections, structural failure of flood barriers, failure to identify lowest point of floodwater entry, seepage issues, and sanitary sewer and stormwater system issues.

As a result of these failures, critical building systems located in basements and first floors were damaged and rendered inoperable. Even where opening protection succeeded in holding back most of the floodwater, seepage through the flood barrier and water entry through penetrations resulted in significant damage to interior finishes and building systems. In addition to failures, there were numerous observations of "near misses" where dry floodproofing measures and human intervention prevented widespread flood damage. If flood levels had been only slightly higher or if building managers had not taken action before the onset of flooding, many observed successes would have become failures. This section describes the types of failure modes the MATs observed after Hurricanes Harvey and Irma.

Key Terminology

Flood Barrier: The physical barrier, composed of opening protection, floor slab, and wall system, that separates floodwater from the dry floodproofed portion of the building.

Opening Protection: A cover, shield, or door that covers a window, doorway, loading dock access, or other opening in a building wall or floor. Sometimes called "closure device."

Floodwall: A constructed barrier of flood damage-resistant materials to keep water away from or out of a specific area. Floodwalls surround a building and are typically offset from the exterior walls of the building; some floodwalls can be integrated into the building envelope. Floodwalls are considered a component of the overall flood barrier.

Flood Entry Point: Any opening, joint, gap, crack, low point, or other location through or over which floodwater can enter the dry floodproofed area.

Overtopping

Floodwalls and opening protection were overtopped in locations where the water surface elevation (WSE) exceeded that of the top of the flood barrier.

Failure of Opening Protection

Opening protection failed either because it was not properly sealed against its frame or because hydrostatic or hydrodynamic forces exceeded the structural capacity of the barrier. Figure 1 shows a submarine door that failed at its midpoint due to hydrostatic forces.

Structural Failure of Flood Barrier

Flood barriers failed in locations where the hydrostatic forces exceeded the capacity of the wall system. Other failures occurred in areas where abandoned building openings were infilled with materials, typically unreinforced masonry, that could not resist hydrostatic forces.

Figure 1: Structural failure of a submarine door from hydrostatic forces; the door failed along a weld in the door panel adjacent to a stiffener (red circle)
Photograph courtesy of Carlos Gutierrez, CSF Consulting

Failure to Identify and Protect Lowest Point of Entry

Buildings were flooded when dry floodproofing measures were incomplete and did not adequately protect the lowest point of entry from floodwater. Figure 2 shows a building where the low point in the flood barrier was not identified or protected, allowing floodwater to overtop the low point in the flood barrier.

Failure to Maintain Structural Integrity of the Flood Barrier

Basements and other below-grade areas were flooded due to large openings being cut through the foundation walls during construction or capital improvement projects. These openings were sealed without re-establishing structural integrity or impermeability. Sealing these openings without making them substantially impermeable and not re-establishing an adequate structural load path left a weakness in the flood barrier, making it vulnerable to floodwater entry and flood damage when exposed to hydrostatic forces. Figure 3 shows a 6-foot by 6-foot opening cut into a foundation wall to provide access for a construction project. After construction was completed, the opening was filled in with timber framing and gypsum wall board. During Hurricane Harvey, the timber-framed infill wall failed and allowed floodwater to fill the building.

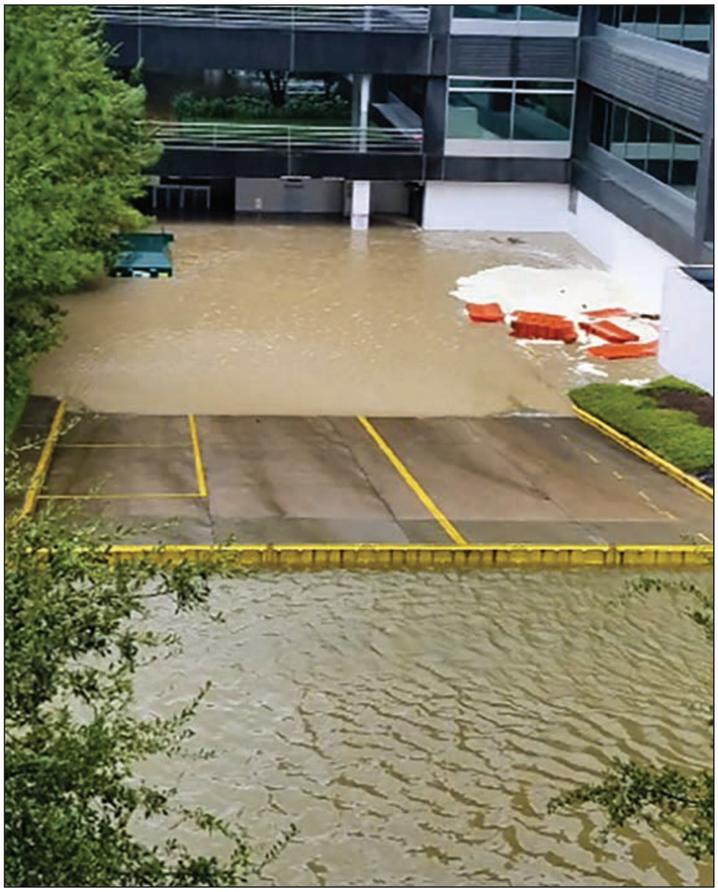


Figure 2: Building where floodwater overtopped the unidentified and unprotected low point in the flood barrier; overtopping location is obscured by the tree on the left-hand side of the image

Substantially Impermeable

According to the U.S. Army Corps of Engineers (USACE), a wall is considered substantially impermeable if it limits water accumulation to 4 inches in a 24-hour period (USACE 1995). In addition, sump pumps are required to control any seepage, and flood damage-resistant materials must be used in all areas where seepage is likely to occur. This standard is the minimum requirement; it is possible to achieve lower seepage rates, which is strongly encouraged by FEMA, particularly in new construction.

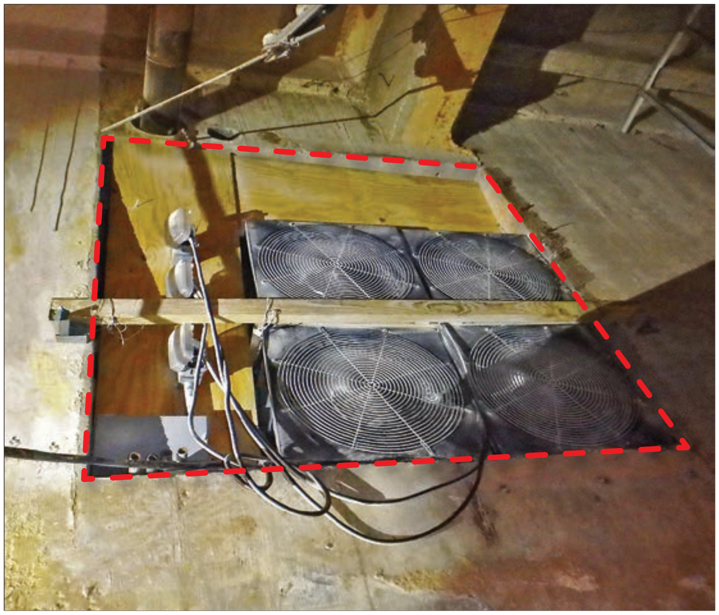


Figure 3: Floodwater entered the building through a large opening cut into a foundation wall; opening is located approximately 12 feet above the floor

Seepage Issues

The MAT observed several types of seepage issues, described below.

Failure to remove seepage through flood barriers. Numerous buildings experienced damage to interior finishes as a result of water seeping through the flood barrier. Buildings that were not equipped to remove the seepage had several near misses as water came within inches of critical building systems. In addition to damaging building finishes, water leaking into buildings required basements to be evacuated, caused failures in pump control panels for sump pumps and potable water supply pumps, and damaged elevator systems. Figure 4 shows an example of water seepage at a submarine door.

Unsealed penetrations through flood barriers. The MAT observed instances of improperly sealed or unsealed penetrations in flood barriers, such as for utilities, failing and allowing floodwater to enter buildings. Even buildings with extensive and redundant dry floodproofing systems were flooded because of penetrations for utilities passing through the flood barrier not being properly waterproofed and sealed. Figure 5 shows an example of unsealed penetrations that allowed floodwater to enter and flood a subgrade tunnel. Floodwater eventually filled the tunnel to the ceiling, causing 2 inches of water to leak into the basement of a connected building.

Another significant source of water infiltration was conduits from utility vaults or electrical pull boxes outside of the flood barrier that penetrated the flood barrier to interior spaces. Water from inside the vault or pull box was able to flow inside the conduit, often entering the building inside the electrical room or control room.

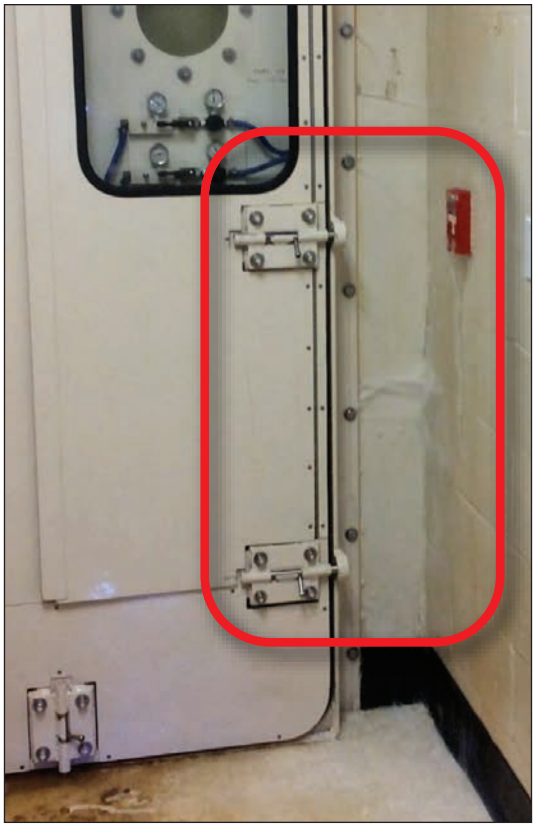


Figure 4: Water seepage at a submarine door
Photograph courtesy of Facilities and Property Maintenance, Harris County Engineering Department

Figure 5: Unsealed conduit and utility penetrations through the flood barrier (yellow circles, left) allowed subgrade tunnel to fill with water (yellow arrow, right); the penetrations (shown on left image) are on the other side of the door at the end of the tunnel (shown on right image). The utility penetrations were sealed after the flooding, prior to the MAT visit)
Photograph on the right courtesy of Facilities and Property Maintenance, Harris County Engineering Department

Failure to waterproof joints in the building envelope. The MAT observed numerous instances where significant water seepage originated from unsealed joints in the building envelope. Most water seepage through unsealed joints occurred where the concrete foundation wall stopped, typically 6 inches above surrounding grade, but significantly below the base flood elevation (BFE), design flood elevation (DFE), and WSE. Figure 6 shows an unsealed joint between the concrete foundation wall and the reinforced masonry wall with granite facade; if the joint is left unsealed, water can seep into the building. Another common area for water seepage was unsealed joints between the concrete foundation slab and foundation wall.

Figure 6: Unsealed joint (red arrow) between concrete foundation wall and a reinforced masonry wall with granite facing panel

Sanitary Sewer or Stormwater System Flows

Failures associated with backflow from sanitary sewers and stormwater conveyance systems resulted in significant damage to building finishes and critical building systems throughout the areas affected by the hurricanes. While most of the buildings had some type of check valve or backflow preventer, the system configuration, pressure rating of the piping, age of the piping, and the building function all contributed to backflow issues. At one location, the issues were the result of occupants remaining in buildings and using its sanitary systems even after the check valves had been closed as a result of the main lines becoming surcharged by water pressure generated by floodwater. For buildings that did not have ejector pumps as part of the sanitary system, sewer water originating from within the building could not overcome the pressure in municipal lines and backflowed into the interior space.

Other damage occurred when there were no check valves installed on floor drains connected to stormwater drainage networks. When stormwater overwhelmed other components in the drainage network, water was able to backflow though floor drains and fill dry floodproofed areas from within the building.

Flood Vulnerability Assessments

Unless flood provisions were incorporated into their design, existing buildings are vulnerable to flooding if they are located in or near areas subject to flooding. Numerous buildings sustained flood damage as a result of building owners or managers not fully understanding the flood hazard for the building and/or failure to identify and protect all potential sources of water entry. Flooding can cause damage ranging from minor inconvenience to complete closure of and significant damage to the building. To reduce the likelihood of such damage in future events, building owners and managers should consider performing a flood vulnerability assessment to identify equipment and systems vulnerable to flooding and take actions to reduce their vulnerability to flooding. The information obtained during the flood vulnerability assessment, combined with building function and staff or tenant capabilities to deploy dry floodproofing measures, should be used to design the dry floodproofing measures.

Vulnerability Assessments

Additional guidance on conducting flood vulnerability assessments is outlined in Appendix C of FEMA P-936, *Floodproofing Non-Residential Structures*.

Prior to performing a flood vulnerability assessment, the floodwater source with corresponding 10-percent-, 2-percent-, 1-percent-, and 0.2-percent-annual-chance (10-, 50-, 100-, and 500-year) WSE and the enforced DFE should be identified for the building. The assessment should determine if the code minimum should be applied or whether a higher freeboard is cost effective and should be incorporated into the DFE. Assessments should account for the fact that once a floodproofing barrier is overtopped, a dry floodproofed building is impossible to keep dry and could negate all floodproofing efforts.

Vulnerability assessments should be conducted by a team of architects and engineers working closely with building managers, operators, and maintenance staff. It is highly recommended that a surveyor be incorporated into the team to identify the grades adjacent to the building and the elevations of all pertinent openings and entrances into the building, the first floor and subgrade floors, any utility penetrations into the building, and all critical building systems. The vulnerability assessment should identify the following:

Freeboard

Freeboard is a factor if safety, usually feet above a flood level, used to compensate for unknown factors that can contribute to flood heights greater than calculated heights. Providing freeboard in excess of code minimums is often a cost-effective means of limiting future damage. FEMA National Flood Insurance Program (NFIP) regulations require a minimum of 1 foot of freeboard. The American Society of Civil Engineers (ASCE) 24-14, *Standard for Flood Resistant Design and Construction,* and Hurricane Sandy Recovery Advisory 5 provide additional guidance and considerations related to flood risk and determining how much freeboard to incorporate into a design.

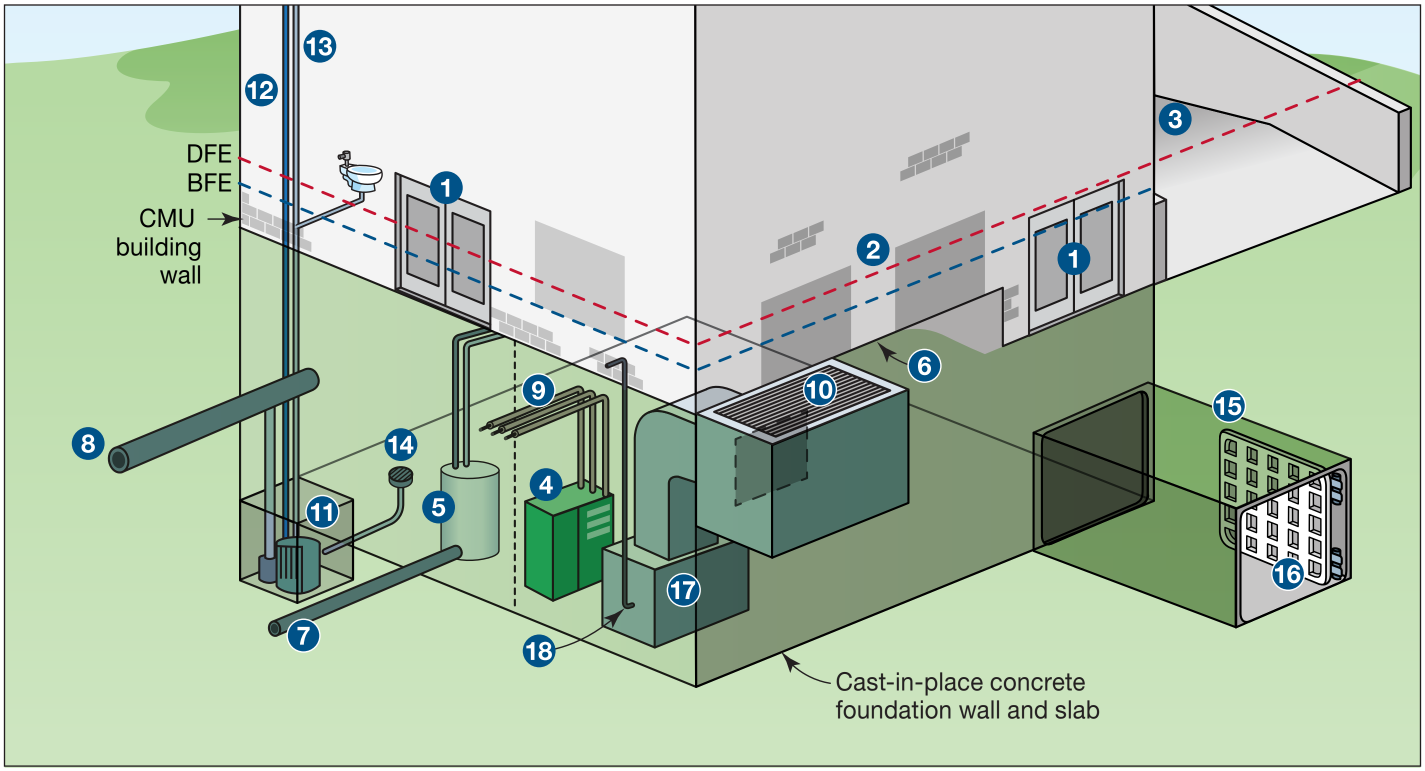
- Locations and elevations of building entrances, such as personnel and overhead doors
- Locations and elevations of openings, such as windows, vents, and louvers
- Locations and elevations of utility (electrical, potable water, sanitary sewer, stormwater, chill water, steam, etc.) conduits entering or exiting the building
- Locations and elevations of any unsealed construction joints where water can enter
- The components of the sanitary sewer and stormwater systems, i.e., whether there is an ejector pump system or a gravity system, if there is a backflow preventer on the discharge piping, if the system is connected to backup power, and the location of the pump control panel. Additionally, it would be beneficial to determine the maximum surcharge level in the municipal system.
- Locations and elevations of the backup power systems, taking note of the building systems connected to backup power, size and location of fuel tank, and location of exhaust ductwork
- Locations and elevations of critical building systems, i.e., building electrical components, steam and chill water, electrical control panels, fire pumps, etc.

In addition to determining flood entry points, the team should consider the effects of water entry. Specifically, if the flood barrier is penetrated, what areas of the building or building systems would be exposed to floodwater. Clarifying the path floodwater will take upon entering the building will identify optimal locations for installing drains to collect water seepage or submarine doors to form a redundant barrier. The use of flood damage-resistant materials in these areas, and below the DFE, will help minimize damage and reduce downtime after the floodwater recedes.

Figure 7 is an illustration of an existing building with examples of the types of openings and penetrations that should be identified during a flood vulnerability assessment.

National Flood Barrier Testing and Certification Program

This program, a partnership among the Association of State Floodplain Managers, U.S. Army Corps of Engineers, and FM Approvals, currently tests and certifies four types of products to meet ANSI/FM 2510: temporary (perimeter) barriers, closure devices (opening protection), backwater valves, and mitigation (flood abatement) pumps. Testing and certification standards are currently being developed for semi-permanent barriers and sealants. A list of certified products can be found at www.nationalfloodbarrier.org.



Component

① Building entrance
② Windows
③ Access ramp to loading dock
④ Electric service equipment room
⑤ Building central plant equipment room
⑥ Construction joint
⑦ Water service
⑧ Sewer line
⑨ Utility power
⑩ Ventilation grill
⑪ Sump pit with sump pump
⑫ Stormwater drain
⑬ Waste line
⑭ Floor drain
⑮ Access tunnel to adjacent building
⑯ Submarine door
⑰ Backup generator with fuel tank
⑱ Fuel line

Figure 7: Example of an existing building with multiple openings and penetrations below the BFE and DFE; blue numbered circles indicate a small sample of the types of openings and penetrations that should be identified during a flood vulnerability assessment and protected by the flood barrier

Planning and Pre-Design Considerations

After the flood vulnerability assessment and prior to design, each identified opening should be evaluated to determine the appropriate method of opening protection. Opening protection systems should come from a reputable manufacturer and be compliant with a testing standard such as ANSI/FM 2510 that includes, among other requirements, performance standards for hydrostatic test strength, impact and wear resistance, system leakage (seepage), environmental corrosion, abrasion resistance, and tear and puncture resistance. If the system is not tested in accordance with ANSI/FM 2510, opening protection systems should, at a minimum, have a demonstrated ability to resist hydrostatic forces associated with the DFE. Homemade barriers should not be used. After the components of the flood barrier have been installed, it is highly recommended that they be tested to ensure water tightness.

Key considerations. The pre-design process for flood protection systems should be comprehensive, ensuring that all opening protection components for the entire building can be installed based on the implementation timeframe used in the building's emergency operations plan (for more information, refer to the companion FL-RA1, *Dry Floodproofing: Operational Considerations).* Key considerations should include, but not necessarily be limited to:

- The timing and rate of anticipated floodwater rise, availability of staff and equipment to install the opening protection, building occupancy classification, daily use of the openings, and maintenance requirements.

- The amount of traffic, whether vehicular or pedestrian. Traffic may affect the selection of opening protection systems, since gaskets on shields or doors may need to be protected against damage during day-to-day use.
- The type of gasket—inflatable or compression—should be considered when selecting opening protection systems. Inflatable gaskets tend to be composed of thinner material and are generally more susceptible to cracking under prolonged exposure to weather and sunlight.

Active versus passive protection. The rate of floodwater rise and anticipated amount of advance warning are often the most important considerations in determining whether to use active (requiring human intervention) or passive (automatic) opening protection (see text box).

Active and Passive Opening Protection

Active: A dry floodproofing opening protection system that requires human intervention to install the physical barrier. These systems are effective only if there is enough warning time to mobilize the labor and equipment necessary to implement them and then safely evacuate.

Passive: A dry floodproofing opening protection system that does not require human intervention to deploy the physical barrier.

Openings at elevations that can flood during frequent flood events (e.g., 10-percent-annual-chance [10-year] flood events or strong downpour) may require passive opening protection (see Figure 8). Another important consideration is the presence of 24/7 on-site support staff—owners of buildings without continuous support staff should also consider passive opening protection since there may not be enough time for a contractor crew to arrive and install active opening protection systems. On the other hand, passive opening protection measures require regular maintenance, as their components are exposed to the elements.

If active protection is selected, designers need to determine if the opening protection will be permanently attached (using hinges or rails) or detached (such as bolted-on shields or flood logs). It is recommended that brackets or stanchions for active opening protection systems be incorporated into the design of the exterior of the building to reduce installation time. The lack of availability of equipment or staff to move flood protection measures into place in a timely manner can render the flood protection ineffective and leave the building vulnerable.

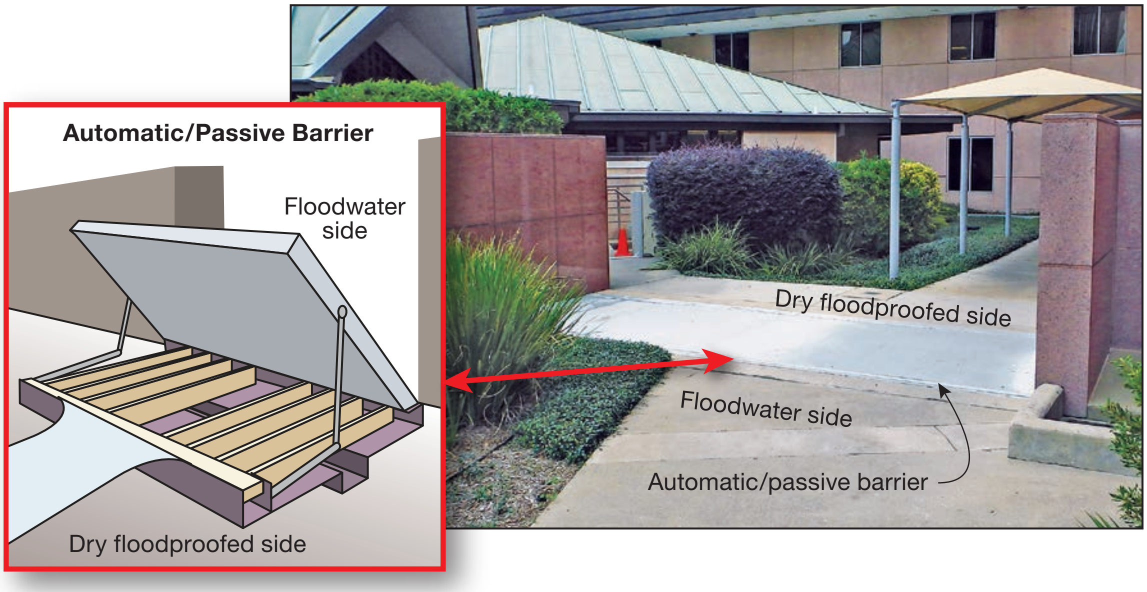


Figure 8: Example of passive opening protection installed to protect openings in the floodwall constructed around an existing building to establish a flood barrier with minimal openings below the DFE

Note: Figure mirrored for clarity

Design Considerations

A successful dry floodproofing systems design should start with a flood vulnerability assessment and should consider building use, maintenance considerations, and operational requirements before, during, and after an event (refer to previous sections of this advisory). The design should take a comprehensive approach that addresses all possible points of water entry and allows the building to maintain flood protection effectiveness for the life of the building.

Dry Floodproofing New Facilities

Installing dry floodproofing in new construction involves considerations and techniques that are similar to those used when installing dry floodproofing in existing buildings. However, with new construction the floors and wall systems can be designed and constructed to resist the hydrostatic and buoyant forces without costly retrofits.

Dry floodproofing design is discussed in detail in FEMA P-936, *Floodproofing Non-Residential Structures* (2013), and Section 6 of the American Society of Civil Engineers (ASCE) 24, *Standard for Flood Resistant Design and Construction* (2014). Design considerations are discussed in Chapter 2 of FEMA P-936. Specific dry floodproofing details are addressed in Chapter 3; the introduction of Chapter 3 provides readers with a list of building retrofitting recommendations.

NFIP Floodproofing Certificate. The requirements of the NFIP Floodproofing Certificate are described in FEMA P-936 and should be understood before starting design. The NFIP Floodproofing Certificate requires compliance with ASCE 24 and is both a design and construction certification. Professional engineers and architects should read the Floodproofing Certificate in its entirety and the applicable sections of ASCE 24, FEMA P-936, and Technical Bulletin 3, *Non-Residential Floodproofing* (FEMA 1993), prior to signing it.

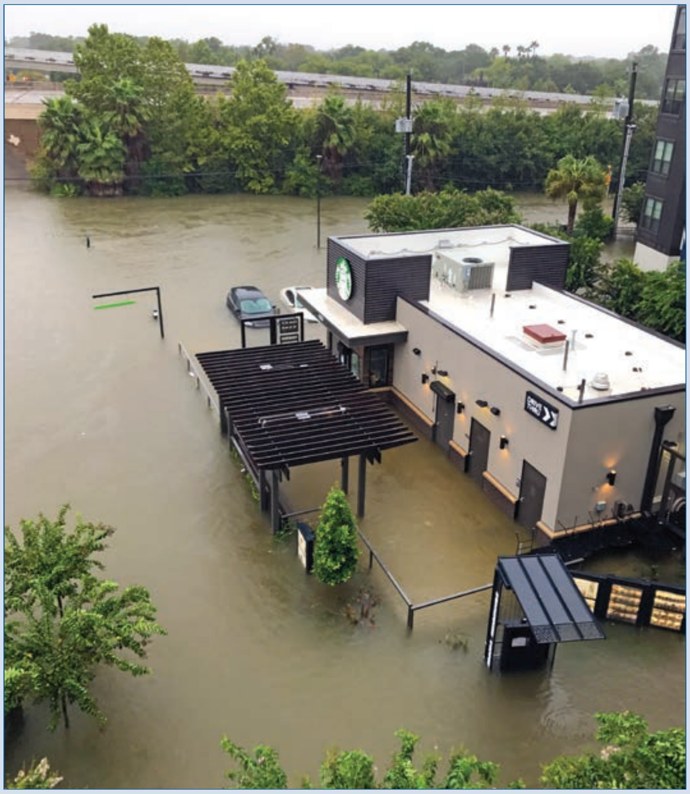
Improving reliability of floodproofing measures. Based on the performance of dry floodproofing retrofit mitigation measures observed by the MATs after Hurricanes Harvey and Irma in Texas and Florida, additional attention must be paid to specific items to improve the reliability of floodproofing measures. The MATs recommend that the measures described in Table 2 be considered to help avoid the types of system failures observed.

Combining Flood Risk Reduction Measures

For new buildings, the design height of dry floodproofing can be reduced by using fill material to raise the building site. The image on the right shows where the designer elevated the building on fill, thereby reducing the height of the dry floodproofing system for the building.

Reducing the height of dry floodproofing measures allows more flexibility in the design, reduces flood loads, reduces the potential for leakage, and can minimize any loss of function.

The image on the right shows a dry floodproofed building that was constructed on approximately 3 feet of fill. The building incorporated 1.5 feet of freeboard into floodproofing design, and the flood level during Hurricane Harvey used up 1.0 of the 1.5 feet.



Photograph courtesy of Kati Southern

Table 2. Dry Floodproofing Design Considerations

Item	Description
Backflow preventers	Install backflow prevention valves for any piping in the building below the flood protection elevation or that connects to other piping networks that extend below the flood protection elevation. Backflow prevention systems can be either passive or active.
Building system locations	Locate building systems (e.g., mechanical, electrical, and plumbing components; communication systems; potable water supply pumps; fire suppression equipment) above the DFE. Consider relocating critical building systems above the flood protection elevation. If relocating is not possible, consider installing redundant protection systems and protecting these systems to a higher-severity flood event than the rest of the dry floodproofed area.
Design forces	Flood load calculations should address both lateral hydrostatic and vertical buoyancy forces, as well as velocity, debris impact, and wave forces, if applicable. Wall and floor systems may need to be modified or sections completely reconstructed to resist flood loads or to ensure that water cannot penetrate the wall or floor. Additional reinforcement may be required in some areas, and connections between floors and walls may need to be improved to resist lateral and uplift loads. In some instances, this modification may require constructing a new wall around the existing exterior wall to achieve the desired strength or waterproofness.

Design of a substantially impermeable system	Design and construction criteria for dry floodproofing require both walls and floors to be “substantially impermeable.” Some things to consider for wall systems are:
	• Deciding whether to build a new floodwall or modify the building envelope.
	• Sealing existing construction joints and injecting cracks in concrete walls.
	• For new construction:
	  • The construction joint in and between the foundation slab and walls should contain a waterstop.
	  • Design concrete walls below the flood protection elevation in accordance with American Concrete Institute (ACI) 350, *Code Requirements for Environmental Engineering Concrete Structures*, instead of ACI 318, *Building Code Requirements for Structural Concrete.* ACI 350 has additional requirements that minimize the possibility of water seeping through a concrete slab or wall.
	  • Use a concrete admixture that will limit the porosity of the concrete or a silica admixture.
	Refer to FEMA P-936 (2013) for additional information.

Ejector system	Incorporate ejector systems to prevent the accumulation or backflow of sanitary (wastewater) or stormwater into protected buildings. • Install ejector systems for stormwater with back-flow prevention • Drain fixtures below the maximum surcharge level into a sump, and pump effluent out to a municipal line • Design and size pipelines for the maximum anticipated surcharge pressure conditions associated with ejector pumps For buildings that must be occupied when municipal lines are surcharged, collect sanitary sewage from all fixtures below the surcharge level (not just those below the level of the sanitary sewer lateral) into a sanitary sewage sump equipped with an ejector pump and check valve. Ensure the ejector pump has adequate capacity to discharge with anticipated sewage flow rates against the maximum anticipated head of the surcharged lines.

Table 2. Dry Floodproofing Design Considerations (concluded)

Item	Description
Flood barrier penetrations	Do not penetrate the flood barrier unless no other options exist and do so only when absolutely required. All penetrations below the DFE should be sealed to resist flood forces and render the flood barrier substantially impermeable. For chill water lines and steam lines, consider removing a small section of insulation and casing around the insulation, since some of those materials can prevent a watertight seal from being made.
Flood damage-resistant materials	Consider wet floodproofing behind dry floodproofed barriers. In the event of seepage through walls or shield systems, the incorporation of flood damage-resistant materials will reduce the amount of damage to the building. The MATs found that damaged drywall behind the flood barrier still had to be replaced in numerous dry floodproofed buildings, which resulted in sections of the building being unusable while repairs were made.
Labeling of the flood barrier	The location of the flood barrier and DFE should be indicated on the building drawings, similar to how fire walls are labeled. Additionally, the walls and slabs that create a dry floodproofed area should be labeled with “Flood Barrier: No Penetrations Below This Level” with a demarcation of the DFE.
Peer review	Perform a peer review on plans and specifications for dry floodproofed systems to help ensure that failure points have been properly identified and addressed.
Pump control panel locations	Relocate pump control panels above the DFE and away from perimeter walls. The MAT observed buildings where water seeping through cracks in the perimeter wall entered pump control panels, resulting in their malfunction.
Sealing inside flood barrier penetrations	Seal the inside of electrical conduits, as the interior of electrical conduits can convey water even if the wall penetration is properly waterproofed.
Seepage	Regardless of the type of dry floodproofing incorporated into the system, the approach should plan for seepage. All dry floodproofing systems required to comply with ASCE 24 or the NFIP must have a sump pump system sufficient to adequately drain seepage in the dry floodproofed area. It is recommended that the sump pumps be connected to a standby power source. Redundancy in the system should be considered and leak detection alarms incorporated into the design. Internal drainage systems should have a discharge point above the flood protection elevation.
Standby power	Provide standby power for critical building systems, which includes sump pump systems, building mechanical systems, and electrical systems. Standby power systems should be sized to meet the start-up power loading requirements of equipment. Design should consider the possible loss of power for extended times when critical building systems may need to function for days or weeks until power is restored. Fuel sources and how to replenish supplies should be considered, as well as how many redundant generators should be installed.
Stormwater	Rainfall behind the flood barrier should be considered. Sump pumps should be sized to handle the additional water, and the use of redundant or additional pumps should be considered when designing systems that remove rainfall from behind the flood barrier. When designing for rainfall events behind the flood barrier, the design rainfall should be consistent with the design level of protection, so protection for a 0.2-percent-annual-chance (500-year) flood event should accommodate a 0.2-percent-annual-chance (500-year) rainstorm or rainfall of record.
System redundancy	Consider providing redundancy in the overall flood protection system, compartmentalization, or a series of gates or shields. This redundancy is especially important in tunnels and below-grade areas, where the potential for a single point of failure can be reduced by such measures. Over the years, MATs have observed many single points of failure that have resulted in excessive damage that could have been reduced had redundant systems been in place.

References and Resources

References

ASCE (American Society of Civil Engineers). 2016. *Minimum Design Loads of Buildings and Other Structures.* ASCE Standard ASCE 7-16.

ASCE. 2014. *Standard for Flood Resistant Design and Construction.* ASCE Standard ASCE 24-14.

FEMA (Federal Emergency Management Agency). 1993. *Non-Residential Floodproofing - Requirements and Certification.* Technical Bulletin 3-93. https://www.fema.gov/media-library/assets/documents/3473.

FEMA. 2012. *Engineering Principles and Practices of Retrofitting Floodprone Residential Structures,* Third Edition. FEMA P-259. https://www.fema.gov/media-library/assets/documents/3001.

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FEMA. 2014. *Homeowner's Guide to Retrofitting,* 3rd Edition. FEMA P-312. https://www.fema.gov/media-library/assets/documents/480.

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FEMA. 2018. *Public Assistance Program and Policy Guide (PAPPG).* FP 104-009-2. January 2018 (V.3). https://www.fema.gov/media-library/assets/documents/111781.

American National Standards Institute and FM Approvals. 2014. *Approval Standard for Flood Abatement Equipment.* ANSI/FM 2510. http://www.fmapprovals.com/products-we-certify/products-we-certify/flood-mitigation-products.

Oak Ridge National Laboratory. 2011. *Floodproof Construction: Working for Coastal Communities.* Southeast Region Research Initiative (SERRI) Report 80024-01. Part of SERRI Project: Floodproof Commercial Construction and Fortified Residential Construction for Neighborhood-scale Mixed-use Buildings. https://static1.squarespace.com/static/54500d67e4b0fe2b86e37264/t/549343a1e4b0d5186e34f6e6/1418937249160/SERRI+Report+80024-01_Floodproof+Construction+%28Sept+2011%29.pdf].

USACE (U.S. Army Corps of Engineers). 1995. *Flood Proofing Regulations.* EP 1165-2-314. http://www.publications.usace.army.mil/Portals/76/Publications/EngineerPamphlets/EP_1165-2-314.pdf.

Resources

Risk Management Series publications listed below are available at https://www.fema.gov/security-risk-management-series-publications.

- FEMA. 2007. *Design Guide for Improving Critical Facility Safety from Flooding and High Winds.* FEMA P-543.
- FEMA. 2007. *Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds.* FEMA P-577.
- FEMA. 2010. *Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds.* FEMA P-424.

Technical Bulletins listed below are available at https://www.fema.gov/media-library/collections/4.

- FEMA. 1993. *Non-Residential Floodproofing - Requirements and Certification.* Technical Bulletin 3-93.
- FEMA. 1993. *Wet Floodproofing Requirements.* Technical Bulletin 7-93.

- FEMA. 2008. *Flood Damage-Resistant Materials Requirements.* Technical Bulletin 2.

Recovery Advisories for Hurricane Sandy listed below are available at https://www.fema.gov/media-library/assets/documents/30966.

- FEMA. 2013. *Reducing Flood Effects in Critical Facilities.* Hurricane Sandy RA2.
- FEMA. 2013. *Reducing Interruptions to Mid- and High-Rise Buildings During Floods.* Hurricane Sandy RA4.
- FEMA. 2013. *Designing for Flood Levels Above the BFE After Hurricane Sandy.* Hurricane Sandy RA5.

Recovery Advisories from the 2016 Fall Flooding in Iowa listed below are available at https://www.fema.gov/media-library/assets/documents/130555.

- FEMA. 2017. *Flood Protection for Critical and Essential Facilities.* 2016 Fall Flooding in Iowa RA3.
- FEMA. 2017. *Flood Protection and Elevation of Building Utilities.* 2016 Fall Flooding in Iowa RA4.
- FEMA. 2017. *Flood Protection for Backup and Emergency Power Fuel Systems.* 2016 Fall Flooding in Iowa RA5.

For more information, see the FEMA Building Science Frequently Asked Questions Web site at http://www.fema.gov/frequently-asked-questions-building-science.

If you have any additional questions on FEMA Building Science Publications, contact the helpline at FEMA-Buildingsciencehelp@fema.dhs.gov or 866-927-2104.

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Asphalt Shingle Roofing for High-Wind Regions

FEMA

HURRICANE HARVEY IN TEXAS *Recovery Advisory 2, April 2018*

Purpose and Intended Audience

The purpose of this Recovery Advisory is to recommend practices for installing asphalt roof shingles that will enhance wind resistance in high-wind regions. For the purpose of this advisory, a high-wind region is considered to be an area where the basic (design) wind speed for Risk Category II buildings (as defined in American Society of Civil Engineers [ASCE] 7, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures)* is greater than 115 miles per hour. The primary audience for this advisory includes contractors and design professionals, but the practices presented here may also be helpful for homeowners and other building owners.

> This Recovery Advisory supersedes Technical Fact Sheet No. 7.3 in FEMA P-499. The primary change is the inclusion of ASTM D7158, which was published after FEMA P-499 was published.

Key Issues

- Various types of asphalt shingle wind performance problems are discussed and shown in FEMA P-55, *Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas*, 4th Edition (2011).
- The FEMA Hurricane Harvey Mitigation Assessment Team (MAT) observed many asphalt shingle wind performance problems, similar to those shown in FEMA P-55.
- The damaged shingle roof coverings included shingles that had recently been installed.
- In instances where the MAT made detailed observations, the installations did not incorporate the best practices described in Technical Fact Sheet No. 7.3 in FEMA P-499, *Home Builder's Guide to Coastal Construction* (2010).

This Recovery Advisory Addresses

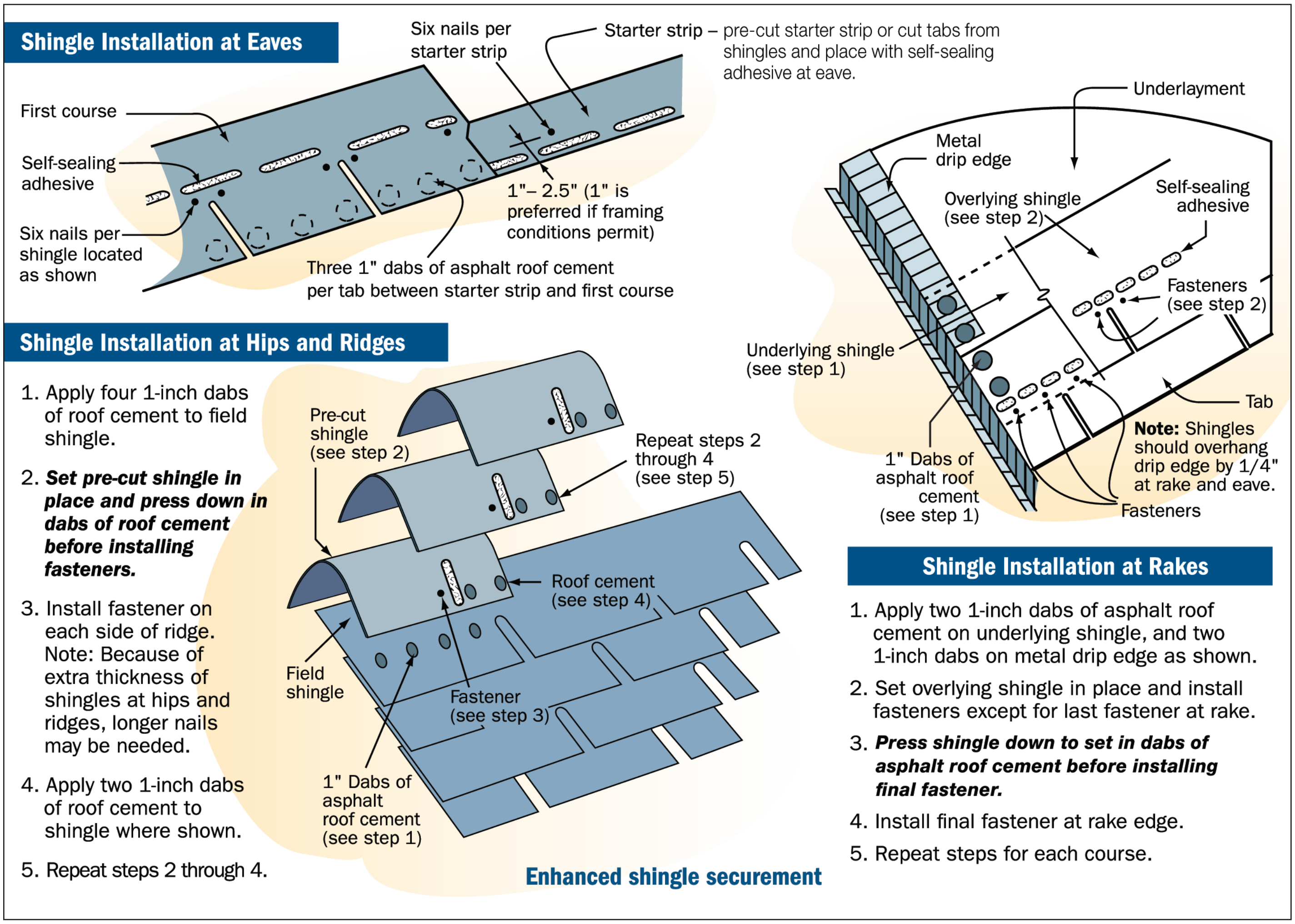
- Construction Guidance
- Fastener Guidelines
- Weathering and Durability
- Wind-Resistance Ratings

Key Actions for Achieving Good Wind Performance

- Use special installation methods described in this advisory for asphalt roof shingles used in high-wind regions.
- Use wind-resistance ratings to choose among shingles, but do not rely on ratings for performance.
- Consult the local building code for specific installation requirements. Requirements may vary locally.
- Always use underlayment (see Technical Fact Sheet No. 7.2 in FEMA P-499 [2010] for installation techniques in coastal areas).
- Pay close attention to roof-to-wall flashing and use enhanced flashing techniques (see Technical Fact Sheet No. 5.2 in FEMA P-499).

Construction Guidance

1. Follow shingle installation procedures for enhanced wind resistance, including the asphalt roof cement and nailing guidance shown in Figure 1.
2. Consider shingle characteristics and physical properties (Tables 1 and 2). Note that higher pull-through resistance may need to be specified.
3. Ensure that the fastening equipment and method results in properly driven roofing nails for maximum blow-off resistance (Figure 2).



Shingle Installation at Eaves

Shingle Installation at Hips and Ridges

1. Apply four 1-inch dabs of roof cement to field shingle.
2. ***Set pre-cut shingle in place and press down in dabs of roof cement before installing fasteners.***
3. Install fastener on each side of ridge. Note: Because of extra thickness of shingles at hips and ridges, longer nails may be needed.
4. Apply two 1-inch dabs of roof cement to shingle where shown.
5. Repeat steps 2 through 4.

Shingle Installation at Rakes

1. Apply two 1-inch dabs of asphalt roof cement on underlying shingle, and two 1-inch dabs on metal drip edge as shown.
2. Set overlying shingle in place and install fasteners except for last fastener at rake.
3. ***Press shingle down to set in dabs of asphalt roof cement before installing final fastener.***
4. Install final fastener at rake edge.
5. Repeat steps for each course.

Enhanced shingle securement

Figure 1: Enhanced shingle securement
Source: modified from FEMA P-499, 2010

Table 1. Shingle Types and Characteristics

Shingle Type	Product Standard	Characteristics
Fiberglass-Reinforced	ASTM D3462	Considerable variation in fastener pull-through resistance offered by different products.
Styrene-Butadiene-Styrene (SBS) Modified Bitumen	A standard does not exist for this product. It is recommended that SBS modified bitumen shingles meet the physical properties specified in ASTM D3462.	Because of the flexibility imparted by the SBS polymers, this type of shingle is less likely to tear if the tabs are lifted in a windstorm.

Table 2. Shingle Physical Properties

	Minimum Recommended: 25 lb at 73 degrees Fahrenheit (°F)	Minimum Recommended: 30 lb

1 Design wind speed is an ultimate speed (as defined in ASCE 7), based on 3-second peak gust at 33 feet above grade in Exposure C (as defined in ASCE 7).

2 ASTM D3462 specifies a minimum fastener pull-through resistance of 20 lb at 73°F for single-layer specimens. If a higher resistance is desired, it must be specified.

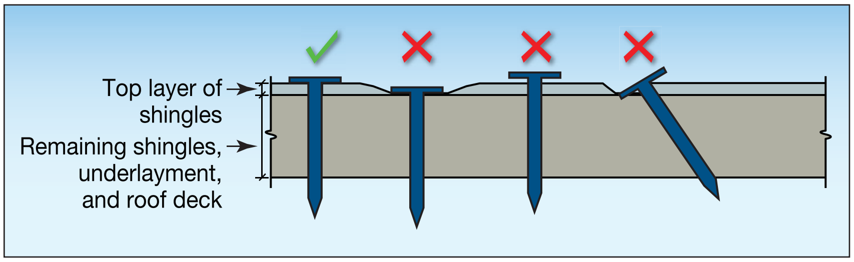


Figure 2: Examples of properly and improperly driven roofing nails

Fastener Guidelines

- Use roofing nails that extend through the underside of the roof sheathing, or a minimum of 3/4 inch into planking.
- Use roofing nails instead of staples.
- Use stainless steel nails for buildings within 3,000 feet of saltwater.

Weathering and Durability

Durability ratings are relative and are not standardized among manufacturers. However, a shingle with a longer warranty (e.g., 30-year instead of 20-year) should provide greater durability.

Modified bitumen shingles generally offer improved tear-off resistance of tabs.

Hail Resistance

Many high-wind regions also experience hail storms. Underwriter's Laboratories (UL) Standard 2218 is used to evaluate the impact resistance of coverings. Products passing this test are classified as Class 1, 2, 3, or 4. Class 4 has the highest impact resistance.

Wind-Resistance Ratings

It is recommended that shingle wind resistance be determined by test method ASTM D7158. Shingles that have been evaluated in accordance with D7158 have a Class D (115 mph), G (150 mph), or H (190 mph) ultimate wind speed rating. Select shingles that have a class rating equal to or greater than the basic wind speed specified in the building code. If the building is sited in Exposure D, is more than 60 feet tall, or is sited on an abrupt change in topography (such as an isolated hill, ridge, or escarpment), consult the shingle manufacturer. (Note: for definitions of Exposure D and abrupt change in topography, refer to ASCE 7.)

References

ASCE (American Society of Civil Engineers). 2016. *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE 7.

FEMA (Federal Emergency Management Agency). 2010. *Home Builder's Guide to Coastal Construction*. FEMA P-499. http://www.fema.gov/library/viewRecord.do?fromSearch=fromsearch&id=2138.

FEMA. 2011. *Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas*, 4th Edition. FEMA P-55. https://www.fema.gov/media-library/assets/documents/3293.

For more information, see the FEMA Building Science Frequently Asked Questions Web site at https://www.fema.gov/frequently-asked-questions-building-science.

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