Performance of Residential Buildings in Hurricane Prone Coastal Regions and Lessons Learned for Damage Mitigation

Mehrshad Amini[1] and Ali M. Memari[2]

[1]Ph.D. Candidate, Department of Civil and Environmental Engineering, Penn State University, e-mail: mxa261@psu.edu

[2]Professor, Department of Architectural Engineering and Department of Civil and Environmental Engineering, Penn State University, e-mail: amm7@psu.edu

1. Abstract

Coastal residential buildings are vulnerable to significant damage due to different hurricane hazards. Recent damage to such residential buildings illustrates poor performance of coastal structures as it relates to hurricane hazards. This could mean that recent standards and building code provisions need to be improved in terms of loading and design requirements. This paper reviews the evidence from actual damage in past hurricanes with respect to direct and indirect damage to different types of residential buildings in coastal areas. The results show that building materials other than wood have better performance during strong hurricanes. Regardless of building materials, residential buildings have mainly suffered extensive wind-induced damage to envelope systems and roofs more than the structural systems. Therefore, selecting adequate connection systems, suitable wind resistant materials, and appropriate installation methods for wall/roof covering can significantly reduce the level of direct and indirect wind-induced damage. Furthermore, many non-elevated or low-elevation buildings sustain severe flood damage in coastal areas. It can be concluded that elevating the structure and its supporting base on deep embedded piles above the BFE is the most effective method to reduce flood damage to residential buildings in coastal areas. However, it might increase the wind damage due to the fact that the house is exposed to higher wind pressures so that further measures should be considered. Last but not least, selecting the appropriate foundation system, enhancing foundation connections, and using flood-resistant materials below the BFE can also reduce flood-induced damage to residential buildings in coastal regions.

Keywords: Hurricane Engineering, Residential Buildings, Wind/Flood-Induced Damage, Damage Mitigation Methods.

2. Introduction

Coastal residential buildings are vulnerable to significant damage due to hurricane related hazards such as high wind pressure/suction, air-borne debris impact, wind-driven rain, as well as potential flood due to surge and floating debris impact (NIST 2014). Almost all states in the United States are susceptible to damage caused by extreme windstorms such as tornadoes and hurricanes. Florida and Texas are the most vulnerable states, such that 85% of Category 4 and 5 hurricanes have directly hit either of these states (FEMA P-55a). From 1996 to 2012, hurricane related hazards have caused over 4,045 fatalities and resulted in property losses on the order of $250 billion (in 2012 dollars) in the U.S. (NIST 2014). Furthermore, the total damage cost of the four recent destructive hurricanes: Maria (2017), Irma (2017), Harvey (2017), and Sandy (2012) is estimated to be $330 billion (NCEI 2018). However, such damage extent illustrates the poor performance of coastal structures under the effects of hurricane related hazards. Over the past several decades, the population in coastal areas in the United States has increased significantly, which will result in larger economic losses during hurricanes in the future. Therefore, identification and quantification of these hurricane associated hazards is the first step in order to understand the behavior of residential buildings and identify common failure mechanisms and subsequent mitigation techniques.

Many studies have contributed to better understanding of the problem and attempts have been made to protect communities and homes against hurricane hazards (White, 1945; Xian et al., 2015; Park et al., 2017). Based on studies conducted on flood-prone areas, e.g., Flood Insurance Studies (FISs) program, FEMA has mapped flood hazards for nearly 20,000 communities in the United States called Digital Flood Insurance Rate Maps (DFIRMs) to show flood hazard areas and risk premium zones. Practically, the BFEs are shown on DFIRMs for riverine flood zones (Zone A, AE, AO, and AH) and coastal flood zones (Zone V and VE). In addition, FEMA developed guidelines and recommendations such as minimum lowest floor elevation, foundation type, suitable retrofit techniques, and other requirements for new and exciting buildings based on specific flood zones and structural characteristics. It should be noted that other factors such as proper planning, siting, design, and construction are subsequent steps in order to mitigate vulnerability of buildings to hurricane hazards in coastal areas (FEMA P-55b).

This paper presents a review of damage types to residential buildings under various hurricane hazards, including high wind, storm surge, and associated flood effects. The paper briefly reviews the evidence from actual damage in past hurricanes with respect to direct damage (structural system failure) and indirect damage (water intrusion) to residential buildings with different materials in coastal areas. In addition, common failure mechanisms and subsequent mitigation approaches are discussed based on available resources, which can help to provide a better understanding of the performance of residential buildings in coastal areas. Furthermore, the results can be used to determine the potential wind/flood damage sequences during hurricanes, which can be helpful to insurance companies and homeowners regarding settlement of insurance claims for hurricane related hazards.

3. Literature review on hurricane associated hazards

Hurricane is a tropical cyclone with a maximum wind speed of 74 mph or more, and is one of the most devastating multi-hazard natural catastrophic events. Hurricanes typically are categorized based on Saffir-Simpson Hurricane Wind Scale (SSHWS) updated in 2012 for more accurate outputs (NOAA 2012). The SSHWS consists of five separate categories based on peak wind speed. However, this scale does not consider other potential hurricane-related damages like storm surge, rainfall-induced floods, and tornadoes. This section briefly discusses various hurricane related hazards: high winds, storm surge, and associated flood effects, including hydrostatic forces, hydrodynamic forces, waves, erosion and scour, wind and flood-borne debris.

3.1. High winds

Strong winds are one of the most important hazards associated with hurricanes, which are able to cause serious direct and indirect damages to buildings. During a hurricane event, both positive and negative pressures simultaneously act on the building. ASCE 7-16 specifies 3-second gust speeds as the design wind speed (measured at 33 feet above the ground in Exposure Category C). The magnitude of design pressure is a function of several primary factors, including exposure, basic wind speed, topography, building height and shape, and internal pressure classification. Then, final forces are obtained by applying calculated design pressures to the appropriate tributary area for the main wind resisting system (MWRS) and different components and cladding (C&C). However, design against other damage modes such as water intrusion damage and integrity of the building envelope is still a challenge.

3.2. Storm surge/waves

Storm surge and subsequent waves cause the most destructive damage to residential buildings in coastal areas (Simpson and Riehl, 1981). Strom surge is a sea wave accompanied with combined lower barometric pressure and forward speed of hurricane rising above the normal sea level. Similarly, waves are generated in deep water by strong winds caused by hurricanes blowing across the surface, moving toward shallow water. Waves can damage coastal buildings by four main wave mechanisms, including breaking wave, wave runup, wave reflection/deflection, and wave uplift (FEMA P-55a). Among these mechanism, breaking waves are the most destructive factor for buildings in coastal. Storm surge and subsequent waves is a complex phenomenon, which can be affected by many factors such as hurricane wind speed, angle of approach to the coast, coastal bathymetry characteristics. Therefore, there is no simple method like SSHWS to predict the storm surge height and wave characteristics with respect to each hurricane category.

3.3. Flooding

Flood and subsequent hazards are the main reasons for fatalities during hurricane events, which also cause serious damage to buildings in coastal areas (FEMA P-499). Two types of flooding can occur during hurricanes, namely, rainfall-induced flooding and surge-induced flooding. The former happens due to rainfall in a very small region over a relatively small-time interval, while the latter occurs where the hurricane makes landfall. Moving floodwater generates hydrodynamic forces on submerged foundations and walls, which can cause failure of solid walls and building components due to inappropriate connections or load paths. However, once the water penetrates inside the building, hydrostatic pressures on both sides of walls and floors are equalized. Therefore, all building components are less likely to fail due to pressure equalization.

3.4. Erosion and scour

Erosion (general lowering of the ground surface over a large area) and scour (localized lowering of ground around foundation elements) are two secondary hurricane surge related hazards, which can cause serious problems independently or simultaneously such as partial or complete collapse of residential buildings in coastal areas. Unlike complex dynamic nature of erosion, which is hard to estimate, scour has mostly a predictable behavior and is generally limited to small, cone-shaped depressions less than 2 feet deep and several feet in diameter. Therefore, FEMA 55b recommends that scour depths around individual piles can be estimated as two times the pile diameter for circular piles and two times the diagonal dimension for square or rectangular piles.

3.5. Wind and flood-borne debris

Wind damage to building envelopes is not limited to direct wind pressure, but is also due to flying debris during the hurricane. Furthermore, building envelope defects and breaches caused by windborne debris result in undesirable problem like high internal pressure, rain penetration, and more debris. On the other hand, flood-borne debris typically consist of trees, breakaway wall panels, pieces of other damaged buildings, vehicles, etc., which are often capable of causing damage to unreinforced masonry walls, light wood-frame constructions, and small diameter posts and piles in two different ways, including impact and water damming (Robertson et al. 2007). There are several factors including characteristics of flood-borne objects, flood velocity, debris velocity, and duration of impact that should be considered in order to simulate the realistic loads (ASCE7-16).

4. Damage due to hurricane wind hazards

Wind-induced damage to coastal residential buildings can be categorized into three main groups, including structural damage, direct envelope damage, and indirect water intrusion damage. The most severe structural damage was recognized as the loss of roof structure and exterior wall collapses, which also resulted in subsequent extensive water intrusion. The structural framing damage is typically initiated by the onset of a breach on the windward side of the building, which results in an increase of internal pressure (pressurization). Figure 1a shows a masonry home with a wood roof structure, which suffered severe damage to roof structural components due to pressurization during Hurricane Charley (2004). It should be noted that installing shutters on windows and doors is known as an effective measure protect the envelope and prevent the subsequent increase in the internal pressure.

The lack of continuous load path from roof to the foundation is another important factor, which cause severe structural framing damage such as partial or even complete collapse of the building (FEMA P-55b). A building can have many continuous load paths, which can play an important role in resistance against various forces from hurricane hazards. It is important to mention that most load path failures occurred at connections such as roof sheathing to framing connection and roof framing to external walls other than failure of an individual structural members such as roof rafter or wall studs. Buildings can also suffer damage caused by pressurization and insufficient load path simultaneously, which is likely to result in a progressive sequence. Figure 1b shows a wood-frame house that experienced partial wall failures and severe damage to the roof and gable end wall due to lack of continuous load path. The partial wall failure can be considered as a trigger to initiate the internal pressurization, which caused additional damage to structural framing members leading to complete collapse of the building.

(a) (b)

Figure 1. Wind-induced damage to structural members (FEMA P-488): (a) severe structural damage due to pressurization during Hurricane Charley, 2004; (b) severe damage to roof, structure, and gable end wall during Hurricane Andrew, 1992.

Although the structural system suffered wind-induced damage, the building envelope system sustained more damage due to localized pressure along the edges and corners in hurricanes. Building components and cladding (C&C) consists of several elements, including roof and wall covering, sheathing, walls, windows, and doors. Additional observed damage was associated with wind-driven rain that entered and damaged building interiors through openings in the building envelope. As a result, significant increase in design loads for C&C has been considered in design standards and provisions over the past 20 years, such as the more recent editions of ASCE 7. Typical damage to residential houses during hurricanes occurred at or above the roof lines in terms of loss of asphalt shingles or tile roof coverings. However, houses with metal roof coverings had better performance during such hurricanes due to higher weight, longer and continuous length, and stronger connections. Figure 2 compares a typical asphalt shingle roof covering loss with an undamaged metal roof panel during Hurricane Charley (2004). The good performance of metal panels was also observed during Hurricanes Irma and Maria (2017). Furthermore, widespread loss of vinyl and aluminum soffit panels were observed, indicating that such panels were either pulled out by suction or pushed up by positive pressures. This type of damage can result in severe indirect damage due to wind driven rain to the interior components like drywall walls or ceilings.

(a) (b)

Figure 2. Typical roof covering loss during Hurricane Charley, 2004 (FEMA P-488): (a) asphalt shingle roof covering loss (Captiva Island); (b) undamaged metal panel roof (Pine Island).

Loss of roof sheathing is another common wind-induced failure in wood-frame houses during strong hurricanes due to lack of or inadequate connections between roof sheathing and roof structural frames. This type of damage has been observed in different building types with wooden roof structures. Figure 3 shows severe sheathing loss in the roof structure during Hurricane Charley (2004) and Katrina (2005). Moreover, extensive loss of roof sheathing resulted in lack of lateral bracing of the gable end wall from the top and subsequent partial or total collapse under high wind loadings. Lack of lateral support at the end gable wall can also be caused by the failure in unsupported rafter outriggers at overhangs, which lifts off by the wind and takes the roof sheathing with it. Therefore, the bottom or top chord can be pulled outward easily, twisting the truss and causing an inward collapse of the gable end wall. Last but not least, the gable end wall can also suffer serious damage when the wall sheathing fails as a result of poor connection to the wall framing system. It can be mentioned that failure of gable end walls during strong wind loads has been observed widely in residential buildings with wooden roof structural systems.

(a) (b)

Figure 3. Sheathing loss and subsequent gable end wall and roof truss failure due to lack of lateral bracing during (FEMA P-488): (a) roof decking loss on one-story house, Hurricane Charley, 2004 (Punta Gorda); (b) wind damage to roof structure and gable end wall, Hurricane Katrina, 2005 (Pass Christian, MS).

Figure 4 shows elevated houses sustained severe wind-induced damage in terms of loss of roof coverings, roof sheathings, and roof structural members during Hurricane Ike (2008). As shown in Figure 4a, roof envelope damage occurred at the roof edge and roof corners, where the wind flow separation is quite significant. This flow separation can cause small vortices that can cause much higher pressures in small localized areas. Inadequate connection between roof cover and roof sheathing, and between sheathing and roof framing such as truss members or rafters caused extensive roof damage and subsequent indirect damage. It should be noted that nonstructural (e.g., shingles) and structural (e.g., wood studs) components, which fail under direct wind pressure can potentially act as windborne or flood-borne debris to cause severe damage to other surrounding buildings. As shown in Figure 4b, the whole roof structure was blown out due to insufficient connections to resist high uplift wind loads. In addition, severe loss of roofing covering, and sheathing was also observed at roof edges and roof corners.

(a) (b)

Figure 4. Wind-induced damage to the roof structure of elevated houses during Hurricane Ike, 2008 (FEMA P-55a): (a) roof covering and sheathing damage at roof edge and roof corners (Galveston, TX); (b) total collapse of the roof structure (Galveston, TX).

Windborne debris is another important and widespread source that has caused serious damage to buildings during past hurricanes. The extent of damage is affected by several factors, including wind speed, debris source, debris elevation, and angle of impact. Windborne debris typically consists of several types, including roof coverings (tiles, shingles, metal panels, aggregate, etc.), damaged building components, trees, etc. It should be noted that windborne debris such as roof coverings that are detached from higher elevation can travel further with higher speed (one mile in some cases) than others from the ground, which can cause more severe damage to surrounding building envelopes (Figure 5a). As it was observed, use of appropriate laminated glass or shutter systems were the most effective ways to reduce such damage. However, protected building envelopes were still vulnerable to damage caused by windborne debris, which could initiate the pressurization and subsequent serious structural damage to the house (Figure 5b). Last but not least, buildings were observed to suffer severe damage by several types of falling objects such as trees, communications towers, rooftop equipment, etc. Therefore, corresponding measures, including bracing surrounding trees and anchoring outdoor equipment need to be considered in order to mitigate these types of damage to residual buildings.

(a) (b)

Figure 5. Damage due to windborne debris to building envelopes during Hurricane Charley, 2004 (FEMA P-488): (a) impact of structural wood members in the gable end, Pine Island; (b) a roof title punctured the shutter, Punta Gorda.

5. Damage due to hurricane flood hazards

Flood-induced damage to coastal residential buildings results from several hazards, including hydrostatic forces, hydrodynamic forces, waves, erosion, scour, and flood-borne debris. Hydrostatic pressures due to the weight of standing or slowly moving water, saturated soil, and water in the ground underneath a flooded building impose horizontal and vertical forces (buoyancy or floatation) on building components, which can also cause it to float off its foundation (Figure 6a). Moving floodwater generates hydrodynamic forces on submerged foundations, solid walls and building components, which can cause serious damage due to insufficient connections and lack of load path continuity (FEMA P-550). It should be noted that basement walls are more prone to failure due to the additional pressure from the saturated soil. Figure 6b shows typical damage to exterior walls due to hydrostatic and hydrodynamic forces during Hurricane Harvey (2017). It is important to mention that breaking waves are able to cause more severe damage to residential building in terms of damaging exterior walls or completely washing off houses elevated on piles or piers but with insufficient elevation, and also weak connections between the piers supporting floor beam and foundation.


(a) (b)

Figure 6. Typical damage to residential buildings due to hydrostatic and hydrodynamic forces: (a) building floating off its foundation during Hurricane Katrina, 2005 (FEMA P-550); (b) extensive damage to exterior walls due to 3 to 4 feet surge inundation during Hurricane Harvey, 2017 (FEMA P-2022).

Erosion and localized scour can threaten the overall performance of coastal residential buildings in many different ways. Erosion and scour effects are usually likely due to combination of waves and high velocity flow, which can easily undermine shallow foundations, and reducing penetration depth of pile foundations resulting in partial or total collapse of buildings. It has been observed that buildings with deep pile foundations performed better than buildings with shallow foundations. In addition, failures of erosion control structures can result in severe unpredictable damage to residential buildings particularly the ones with shallow foundation systems. Figure 7 compares the performance of two residential buildings against erosion and localized scour during Hurricane Irma (2017). Study of damaged homes in such events has also shown that houses sustaining severe damage due to erosion and scour in terms of loss of soil supports are more vulnerable to lateral wind and flood loads acting on the structures during the time of hurricane.

(a) (b)

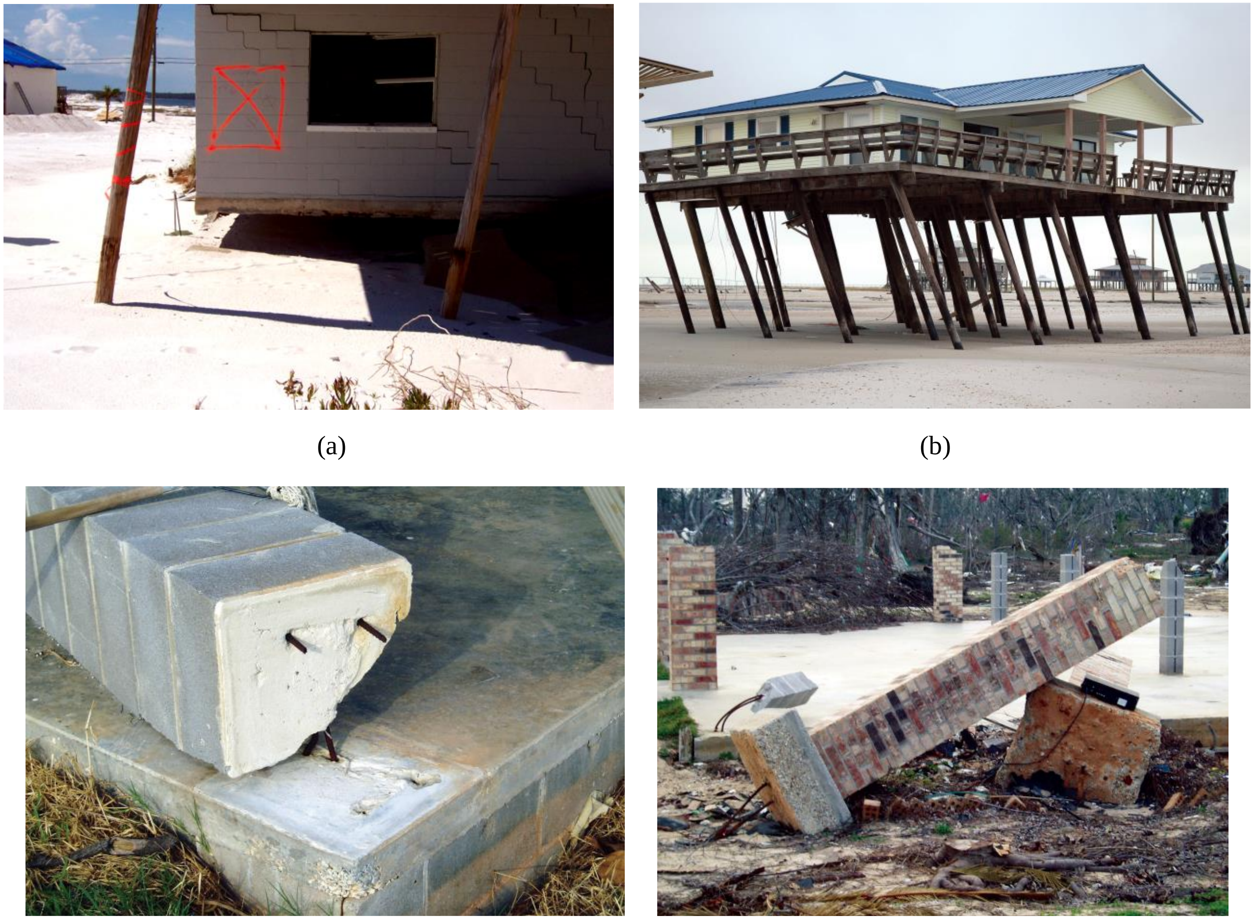
Figure 7. Performance of residential houses against erosion and scour effects during Hurricane Irma, 2017 (FEMA P-2023): (a) total collapse of the house with shallow foundation due to erosion in Vilano Beach, FL; (b) elevated house with deep pile foundation survived erosion in Vilano Beach, FL.

Floodborne debris produced by costal flood events is often capable of destroying a wide variety of building types such as unreinforced masonry walls, light wood-frame construction, and small diameter posts and piles. In addition, debris trapped by structural components such as cross-bracing or closely spaced piles are capable of transferring flood and wave loads to the foundation of an elevated structure. Figure 8 shows damaged residential buildings in coastal areas due to flood-borne debris during different hurricanes. The impact loads resulting from floodborne debris can be estimated and applied based on the procedure in ASCE 7-16. There are some uncertainties which must be determined before estimating impact loadings, including physical characteristics of floating objects, flood velocity, most vulnerable portion of building, and duration of the impact. Therefore, the more reliable estimation will result in more accurate load calculation results.

(a) (b)

Figure 8. Damage to the coastal building due to floodborne derbies (FEMA P-55a; FEMA P-2023): (a) pile supported house washed into another house at Dauphin Island, AL. during Hurricane Georges, 1998; (b) boat and small debris washed into a house in Big Pine Key, FL, during Hurricane Irma, 2017.

Foundations in coastal areas must be able to perform several functions in order to ensure that buildings are able to resist various hurricane loads. The foundation system not only needs to provide a continuous path for vertical and lateral loads transferred from the building to the ground, it should also be able to directly resist different types of flood loads, including storm surge, wave, foodborne debris impact, erosion, and scour effects. For example, deeply embedded piles or other open foundation systems are required for V zones because of high waves and floodwaters. However, closed foundations are not recommended in coastal A zones and are not allowed in V zones due to the fact that these foundations provide a large surface area exposed to waves and flood forces. The performance of open/closed foundations rely on various factors, including sufficient load capacity of continuous foundation walls, piles, or piers against lateral loads (wind and flood), adequate connections between piles or piers with foundation and floor beams, and sufficient embedment length of piles. Figure 9 shows typical damage to different foundation systems of residential buildings in coastal areas in past hurricanes, including damage due to the erosion, scour, insufficient pile embedment, and lack of sufficient connections between piers and the foundation.



(a) (b)

(c) (d)

Figure 9. Typical damage to foundation systems of residential buildings in coastal areas (FEMA P-550): (a) slab-on-grade foundation failure due to erosion and scour from Hurricane Dennis, 2005 (Navarre Beach, FL); (b) partial collapse due to insufficient pile embedment during Hurricane Katrina, 2005 (Dauphin Island, AL); (c) column connection failure during Hurricane Katrina, 2005 (Jackson County, MS); (d) failure of pier on discrete footing due to overturning moment during Hurricane Katrina, 2005 (Pass Christian, MS).

6. Observation from buildings with material other than wood

Residential buildings in coastal areas can be mostly classified into four categories based on materials of the structural system, including wooden frame buildings, concrete masonry units (CMUs), reinforced concrete frames, and steel frames. Wooden frame buildings are widely adopted in residential building due to economic aspects, feasibility, and light weight. Reinforced concrete and concrete masonry units (CMUs) are also common building types in coastal areas, with wood/steel framings or trusses used as their primary roof structure. It has been observed that buildings with other than wooden frame systems have generally performed better against strong wind and flood loads. However, the nature and extent of flood damage to residential buildings regardless of material are more complicated and depends on several factors, including location, foundation type, and lowest floor elevation.

The CMU buildings compared to wooden frame buildings have a better performance during strong hurricanes against wind and flood loadings in terms of lateral and uplift resistance due to its larger self-weight and more effective continuous load path. However, widespread vulnerability in connections has been observed if CMU buildings have wooden roof trusses. For example, many CMU buildings with wood truss roofs that only had toe-nailed connections between rafters and beams and no additional strapping, plates, or bolts experienced severe failure during Hurricanes Irma and Maria (2017). Similarly, CMU buildings combined with steel joist roof system and metal deck suffered severe failure in welds at the plate connectors used to secure the steel joist to the wall system. Figure 10a shows the common wind-induced damage to typical CMU building with wooden roof structure in Hurricane Charley (2004).

Steel frame buildings are more vulnerable compared to reinforced concrete buildings and have experienced more damage to the structure and envelope system during strong hurricanes mainly due to poor and corroded connections. Several types of failure were observed, including loss of roof and wall panels, partial/complete collapse of structural frames, and damage to gable end walls due to inadequate lateral bracing. Steel frame buildings are more vulnerable to windborne debris so that subsequent pressurization due to possible breach to envelope system can also cause severe damage to the structure. Figure 10b shows partial and complete structural damage due to failures in connections between roof members and base plate for the gable end wall column.

(a) (b)

Figure 10. Wind-induced damage to concrete and steel frame buildings during Hurricane Charley, 2004 (FEMA P-488): (a) damage to a multi-family building roof deck with inadequately supported and braced overhang; (b) roof framing failure and gable end wall collapse due to insufficient lateral supports.

Buildings with heavy concrete frames or prefabricated concrete wall and roof have shown to be less vulnerable to serious wind-induced structural and envelope damage during hurricanes. These types of buildings and their concrete roofs have performed well due to high load resistance of concrete and reinforcements. However, they are still vulnerable to flood-induced damage in terms of chloride penetration into the concrete, corrosion of reinforcements, and spalling of the concrete cover. In addition, metal R-panel roofs, corrugated metal roofs, and liquid-applied membrane roofs (applied over plywood roof covers) have generally performed well and for the most part did not sustain visible damage for example during Hurricane Irma and Maria (2017). However, it was observed that strict design details for the ridge are required in order to prevent water infiltration due to the wind-driven rain and subsequent damage to the interior (FEMA P-2021).

Regardless of the material used for the structural system, even fully engineered residential buildings but with elevated floors below the BFE with deep foundation systems (Zone V or A) have also sustained flood and erosion damage. Figure 11a shows a 5-story concrete building with shallow foundation system, which sustained severe damage due to surge, debris, and erosion effects during Hurricane Ivan (2004). In addition, exterior walls below the BFE regardless of material mostly suffered severe flood-induced damage particularly in V and A coastal zones. Figure 11b shows a concrete building elevated on deep piles, but with low elevation living unit that was destroyed due to surge, high waves, and subsequent flood debris. Based on observations during Hurricane Ivan (2004), regardless of material, almost 80 percent of lowest floor living units were destroyed by flood and erosion effects, despite the fact that most of buildings were constructed on pile foundation above the estimated BFEs selected from available DFIRMs.

(a) (b)

Figure 11. Several flood-induced damage to concrete buildings during Hurricane Ivan, 2004 (FEMA P-550): (a) severe structural damage to the building with shallow foundation due to surge, wave, and floodborne debris; (b) partial/complete collapse of exterior walls below the BFE for a concrete building elevated on deep piles.

7. Lessons and mitigation methods

Actual observations show that building materials other than wood have better performance during strong hurricanes. However, they are still vulnerable to other types of damage, including widespread vulnerability in connections for CMU buildings and steel frame buildings, chloride penetration into the concrete, corrosion of reinforcements, and spalling of the concrete cover for buildings with heavy or prefabricated concrete frames. Regardless of building material, load path failures due to wind or flood mostly occur at connections either for structural members or envelope systems. Besides, residential buildings have suffered extensive wind-induced damage to envelope systems more than structural systems. It should be noted that selecting denser connection and bracing designs particularly at roof corners, edges, and wall corners, shallow roof slope, appropriate shutter systems or laminated glasses, absence of overhangs, suitable wind-load resisting material, and appropriate installation methods for wall/roof sheathing and covering can significantly reduce direct wind damage to envelop systems, which also results in the elimination of potential pressurization and subsequent progressive failures to structural members. Furthermore, using adequate connection system between structural members, sufficient lateral bracing for gable end walls, using wood structural panel as wall sheathing, and bracing surrounding tress and anchoring outdoor equipment can significantly reduce the level of direct and indirect wind-induced damage to the structural system for residential buildings. Similarly, past hurricanes show that many non-elevated or low-elevation buildings have sustained severe flood damage in coastal areas, where damage is almost inevitable once flood reaches first floor level. Failures typically occur in connections between piles/piers to the superstructure and foundation system due to high lateral flood loadings. The use of flood-resistant materials under the BFE can significantly reduce the potential flood-induce damage. Furthermore, use of open foundation systems reduce surge risk while slab-on-grade foundations suffer the most in flood, particularly against erosion and scour effects.

8. Conclusions

This paper briefly reviews the evidence from actual damage in past hurricanes with respect to direct damage and indirect damage to residential buildings with different materials in coastal areas. The results show that although building materials other than wood have better performance during strong hurricanes, they are still vulnerable to other types of damage such as connection failures. The concept of load path is an important factor, which affects the performance of residential buildings in coastal areas. The actual damage shows that residential buildings that are correctly designed in accordance to building code (e.g., IRC or IBC) requirements for wind and flood loads (e.g., 100-year flood level) have sustained less damage during strong hurricanes. However, additional guidance developed by FEMA needs to be considered by designers and homeowners. It should be noted that selecting adequate connection system, optimizing roof plan, suitable wind-load resisting material for the structural wall and roof systems, and appropriate installation methods can significantly reduce the level of direct and indirect wind-induced damage. It should be noted that elevating the foundation on deep embedded pile above the DFE (BFE+ freeboard) is the most effective method to reduce the flood damage to residential buildings in coastal areas. However, it might increase the wind damage due to the fact that the house is exposed to higher wind forces so that further measures should be considered. Furthermore, selecting the appropriate foundation system, enhancing foundation connections, and using flood-resistant materials below the BFE not only reduce direct flood-induced damage but also provide the overall strength and integrity for the building.

9. References

ASCE/SEI (ASCE/Structural Engineering Institute), 2016. Minimum Design Loads for Buildings and Other Structures. ASCE/SEI 7-16, Reston, VA.

IBC, (2012). International Building Code.

IRC, (2012). International Residential Code for One- and Two-Family Dwellings.

FEMA, (2005). Hurricane Charley in Florida. Observations, recommendations, and technical guidance. FEMA P-488.

FEMA, (2009). Recommended residential construction for coastal areas, FEMA P-550.

FEMA, (2010). Home builder's guide to coastal construction. Technical fact sheet series. FEMA P-499.

FEMA, (2011). Principles and practices of planning, siting, designing, constructing, and maintaining residential buildings in coastal areas, FEMA P-55a, Volume I.

FEMA, (2011). Principles and practices of planning, siting, designing, constructing, and maintaining residential buildings in coastal areas, FEMA P-55b, Volume II.

FEMA, (2018). Hurricanes Irma and Maria in the U.S. Virgin Islands. Building performance observations, recommendations, and technical guidance. FEMA P-2021.

FEMA, (2018). Hurricane Irma in Florida. Building performance observations, recommendations, and technical guidance. FEMA P-2023.

White, G. F. (1945). Human adjustment to floods: A geographical approach to the flood problem in the United States. Res. Paper No. 29, Dept. of Geography, University of Chicago, Chicago, 225.

National Centers for Environmental Information (NCEI) (2018) U.S. billion-dollar weather and climate disasters.

NIST, (2014). Measure. Sci. R&D Rdamp Windstorm & Coastal Inun. Impact Red., NIST GCR 14-973-13.

NOAA (National Oceanic and Atmospheric Administration). (2012). The Saffir-Simpson Hurricane Wind Scale.

Park, H., Tomiczek, T., Cox, D.T., Van de Lindt, J.W., Lomonaco, P. (2017). Experimental modeling of horizontal and vertical wave forces on an elevated coastal structure. Journal of Coastal Engineering, 128 (2017) 58–74.

Robertson, Ian, Riggs, H., Yim, Solomon and Young, Yin. (2007). Lessons from Hurricane Katrina storm surge on bridges and buildings. Journal of Waterway, Port, Coastal and Ocean Engineering, ASCE, Vol. (133), No. 6, 463-479.

Simpson, R.H. and Riehl, H. (1981). The Hurricane and Its Impact, Louisiana State University Press.

Xian, S., Lin, N., Hatzikyriakou, A. (2015). Storm surge damage to residential areas: a quantitative analysis for Hurricane Sandy in comparison with FEMA flood map. Journal of Natural Hazards.