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Hurricane Damage to Residential Structures: Risk and Mitigation

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SUMMARY

Property damage and loss from hurricanes have increased with population growth in coastal areas, and climatic factors point to more frequent and intense hurricanes in the future. This paper describes potential hurricane hazards from wind and water. Damage to residential structures from three recent intense hurricanes - Hugo, Andrew, and Iniki - shows that wind is responsible for greater property loss than water. The current state-of-the-art building technology is sufficient to reduce damage from hurricanes when properly applied, and this paper discusses those building techniques that can mitigate hurricane damage and recommends measures for mitigating future hurricane damage to homes.

Note: Because this treatise deals with residential hurricane damage, a guide to the construction terms used is supplied at the end of the paper.

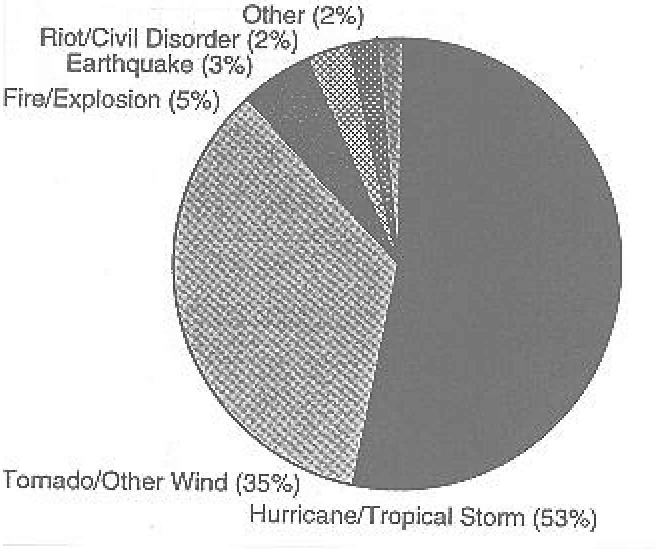
INTRODUCTION

For many years, the risk of significant property loss due to hurricanes seemed small. Many homes along the U.S. East and Gulf coasts were built during the 1970s and 1980s, a period of relatively inactive hurricane formation, and these homes were never exposed to a hurricane. Likewise, many people living in coastal areas during the period grew up never experiencing the effects of an intense hurricane. Florida, the state most at risk from hurricane damage, had not seen a major hurricane since Betsy in 1965.

Hurricanes were seen as infrequent events, and the storms that did occur were low in intensity. Consequently, both homeowners and government agencies regarded the risk of widespread hurricane damage as manageable within the scope of private home insurance and, sometimes, federally subsidized flood insurance. When homes were damaged by hurricanes, they were usually repaired to their pre-storm condition, but not often upgraded to reduce or mitigate damage from the next storm. The hurricane risk during those twenty years may not have seemed sufficient to warrant the increased investment. However, Hurricanes Hugo (1989) and Andrew (1992) redefined the way the public and government regard the risk of hurricane damage to homes.

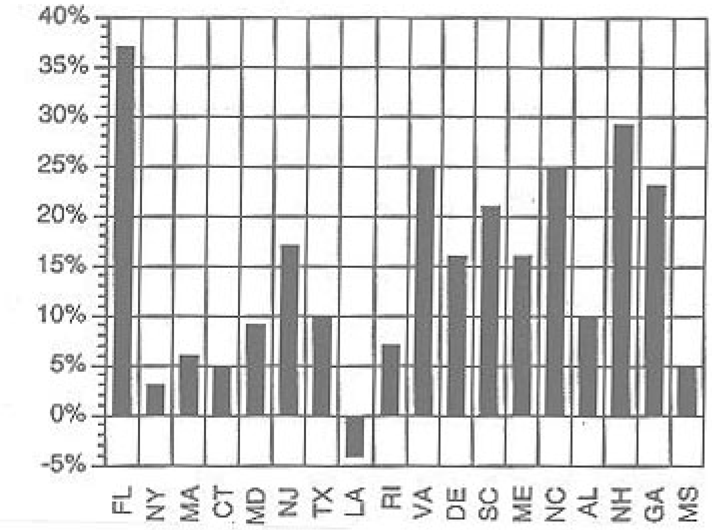
Hugo and Andrew were the strongest hurricanes to strike the U.S. East or Gulf coasts since Hurricane Camille struck Louisiana in 1969. The property insurance industry that, as recently as 1986, had presumed that two $7 billion hurricanes would be the most catastrophic loss that the industry could expect in a given year, was shaken by the $15.5 billion loss from Hurricane Andrew (AIRAC, 1986). The size of the losses from Andrew proved that the damage that a single hurricane could do had been seriously underestimated. In fact, hurricanes and tropical storms accounted for the major share of all property insurance losses during the period from 1986 to 1992.

Figure 1
Percentage dollar loss by type, 1986-1992
(From Mehta et al., 1994)



Along with an increased awareness of the risks to property posed by hurricanes, there came an increased awareness of the likelihood of catastrophic hurricane damage, particularly considering the rising population and development in hurricane-prone areas. In the last two decades, the population along high-risk coastlines has increased significantly. The National Oceanic and Atmospheric Administration predicts that by the year 2010 more than 73 million people will be living in hurricane-prone areas. In Florida alone, population grew by 37% to 10.5 million in the period from 1988 to 1993 (IIPLR, 1995). Figure 2 illustrates the change in coastal population from 1980 to 1993.

Figure 2
Coastal population change, 1980-1993
(From IIPLR, 1995)



Further exacerbating the problem, climatic factors increasingly favor a rise in the frequency of intense hurricanes (Gray, 1990). 1995 was the second most active hurricane season on record. The reason the U.S. was spared by most of 1995's storms was primarily the favorable upper-level winds from the southwest that steered the storms out to sea (Howard, 1996).

Although U.S. fatalities due to natural hazards are currently decreasing because of better warning, property losses are increasing with population shifts to more hazardous areas (Showalter et al., 1993). This paper will examine the risks to residential property posed by hurricanes, and investigate steps that can be taken to mitigate risk to typical wood-frame and masonry-wall homes. Damage from three recent intense hurricanes Hugo (1989), Andrew (1992), and Iniki (1992) will be used as case studies.

THE COST OF THE HURRICANE HAZARD

In 1986, the All-Industry Research Advisory Council (AIRAC), an advisory organization for the insurance industry, released a study of the potential worst-case losses the industry might face from hurricanes. The study concluded that two $7 billion hurricanes could occur in the same year. At the time, this figure might have seemed excessive; the study noted

> Although no hurricane striking the U.S. mainland has ever caused $7 billion in insured losses, AIRAC determined that storms of that dollar magnitude are now possible because of the large concentrations of property located along the Gulf and Atlantic coastlines of the United States. (AIRAC, 1986)

The first significant test of the insurance industry's assumptions regarding hurricane damage occurred when Hurricane Hugo struck South Carolina in 1989. Hugo, a category 4 hurricane at landfall, was the strongest storm to strike the U.S. since 1969, when Camille slammed into the Gulf Coast. Hugo was South Carolina's worst hurricane disaster since 1872 (Rubin and Popkin, 1990). Hugo caused approximately $9 billion in damage, although most of the areas affected (except for the city of Charleston) were lightly developed.

In 1992, Hurricane Andrew again shattered the $7 billion estimated ceiling on damage due to a single hurricane. Andrew, a compact category 4 hurricane that did not strike any major population centers, caused an estimated $15.5 billion in damage to insured property. This figure does not include uninsured losses. Total losses could have been as high as $50 to $75 billion had Andrew struck Miami or Fort Lauderdale (Sheets, 1994; IIPLR, 1995).

Given the relatively small size of Andrew and the fact that, like Hugo, it did not directly hit a major urban area, the main question that Andrew raised was whether the attributable damage was commensurate with the intensity of the storm. The opinion of the the Insurance Institute for Property Loss Reduction (IIPLR) was that it was not:

> A 40-year period of relatively benign weather left southern Florida with a false sense of security regarding its ability to withstand hurricanes. This led to complacency about hurricane risk, leading to "helter-skelter" development, lackluster code enforcement, building code amendments, shortcuts in building practices, and violations that seriously undermined the integrity of the [building] code and the quality of the building stock. Conservative estimates from claim studies reveal that approximately 25 percent of Andrew-caused insurance losses (about $4 billion) were attributable to construction that failed to meet the code due to poor enforcement, as well as shoddy workmanship. At the same time, concentrations of population and of property exposed to hurricane winds in southern Florida grew many-fold. (IIPLR, 1995).

The risk of property damage and loss in hazard-prone areas grows along with population. Hurricane Andrew, the most expensive disaster in U.S. history, has focused awareness on ever-growing populations now at risk due to hurricane damage. According to IIPLR (1995), two states, Florida and New York, account for nearly half of the Gulf and Atlantic coastal property exposure. Florida, the state most at risk from hurricanes, accounts for the largest share of insured coastal property exposure. From 1988 to 1993, the value of insured property in Florida went from $565.8 billion to $871.7 billion and at the current rate of growth will soon surpass $1 trillion. While one does not usually think of New York as a state exposed to hurricanes, Long Island is a highly exposed region. Coastal property exposure for New York has increased from $301.7 billion to $595.6 billion between 1988 and 1993 (IIPLR, 1995). Figure 3 illustrates the increase in coastal property exposure on a state-by-state basis during the period from 1980 until 1993. Figure 4 illustrates the total value of insured coastal property as of 1993.

Figure 3
Percentage increase in the value of insured coastal property exposures by state, 1980-1993 (From IIPLR, 1995)

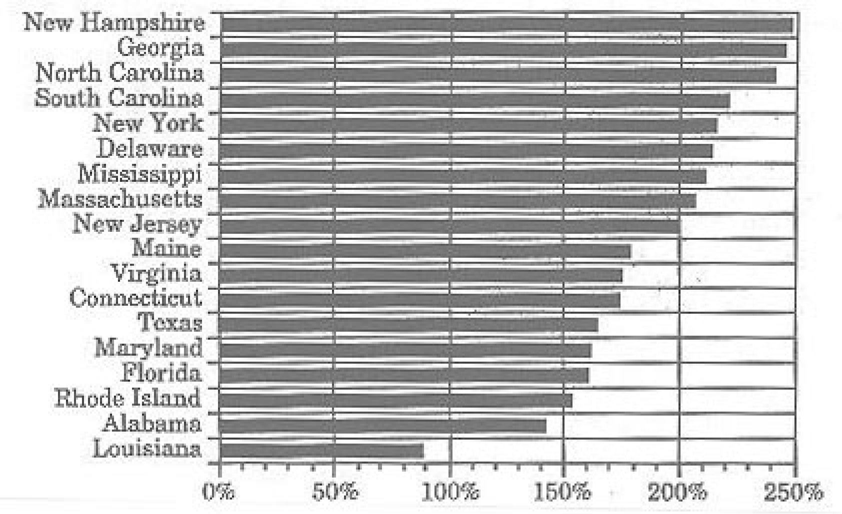
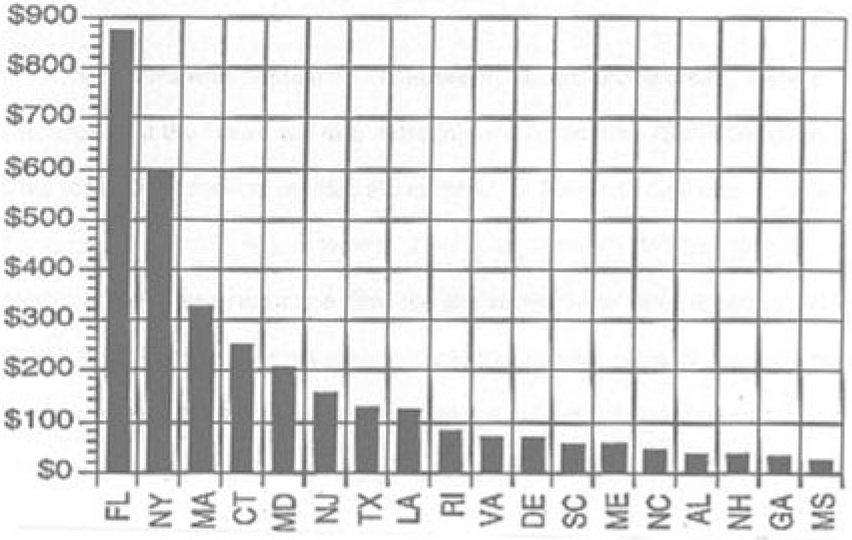


Figure 4
Value of insured coastal property by state - billions of dollars (From IIPLR, 1995)



Gauging property exposure by considering only coastal property underestimates the risk. Hurricane Hugo, for example, was a storm that created severe damage with hurricane-force winds as far as 140 miles inland, severely damaging homes and commercial buildings in Charlotte, North Carolina. Houston, Philadelphia, and New York City are examples of major urban areas that are just beyond the first-tier counties that are usually the only counties considered when in estimates of coastal property exposure.

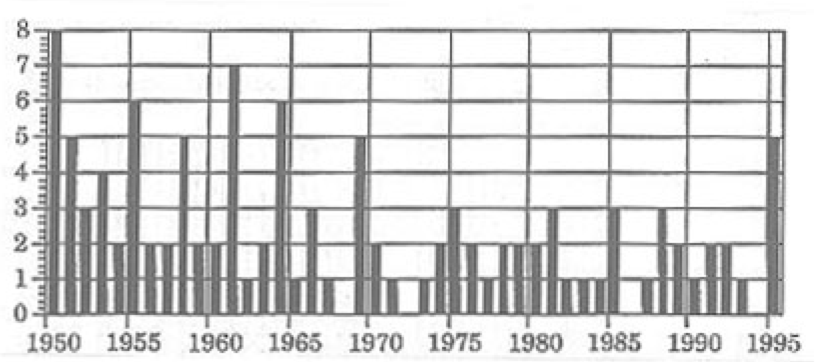
CLIMATE FACTORS AND HURRICANE RISK

Concurrent with population increases in hazard-prone areas, there is evidence that the future will bring more intense hurricanes (Saffir-Simpson Categories 3-5) making landfall along the U. S. East and Gulf coasts. In a September 11, 1995, interview with *Time* magazine, William Gray said, "We're going to see hurricane damage like we've never seen it before" (Nash, 1995). Gray is known for his research into the 20-year cycle of intense Atlantic hurricanes and his increasingly accurate annual predictions, based on climatic factors, of the number and severity of Atlantic hurricanes that will form in a given year.

Indeed, there is strong evidence that intense hurricane formation is cyclic, with a periodicity of approximately twenty years (Gray, 1990). In his paper "Strong Association Between West African Rainfall and U.S. Landfall of Intense Hurricanes," Gray presents evidence that there is a high positive correlation between rainfall in the West African Sahel and the incidence of intense hurricanes making landfall along the U.S. East Eoast. Gray found that during periods of West African Sahel drought there are few intense hurricanes making U.S. East Coast landfalls, while during rainy periods in the Sahel a greater number of intense hurricanes make U.S. East Coast landfall. The increased Sahel rainfall produces slow-moving squall systems called easterly waves that act as triggers for hurricane formation.

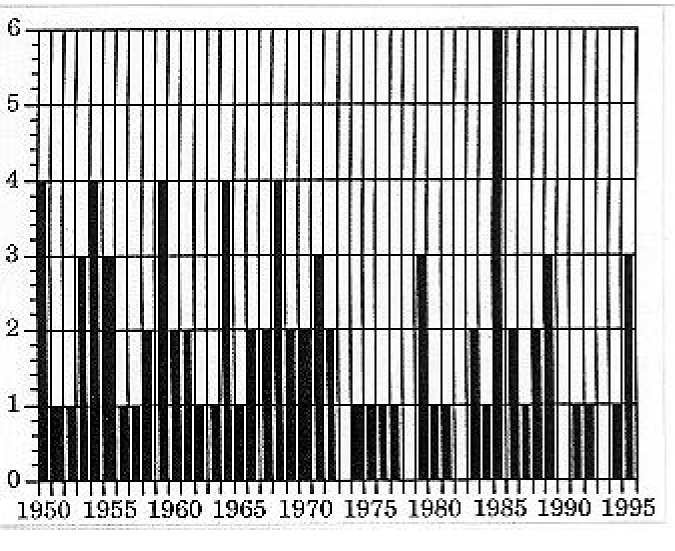
The frequency of intense Atlantic hurricanes doubles during periods of Sahel rainfall. Gray documents that the average number of intense Atlantic hurricanes per year went from approximately 1.5 per year during dry periods to approximately three per year during wet periods. Viewed another way, the number of intense hurricane days increased significantly during wet periods: the number of intense hurricane days was four times greater than during dry periods. This implies that not only are there more intense Atlantic hurricanes during Sahel wet periods, but also that these intense hurricanes are longer-lived. Figure 5 illustrates the decrease in the frequency in intense Atlantic and Gulf hurricanes during the 20 years prior to 1995.

Figure 5
Intense Atlantic and Gulf Hurricanes, 1950-1995
(From National Hurricane Center, 1995)



Climate studies indicate we are returning to a period of greater Sahel rainfall, which may cause a return to the more active hurricane seasons typical of the 1940s and 1950s. This has serious implications for the tremendously increased residential coastal construction during the last 20 years. In the several decades preceding Hurricanes Hugo and Andrew, few hurricanes struck the United States. However, from 1941 through 1950, there were ten major (Saffir-Simpson Scale category 3 or stronger) hurricanes that struck the continental United States. Seven of those struck Florida. From 1951 through 1960, there were eight major hurricanes that struck the United States, seven of which struck the East Coast. For the next 30 years, the only major hurricane to strike the Florida peninsula was Hurricane Betsy in 1965. Similarly, during this period, no major hurricanes made landfall on the East Coast until the mid-1980s (Sheets, 1994). It should be noted that although intense hurricanes were less frequent during the 1970s and 1980s, the U.S. East and Gulf coasts continued to experience hurricanes, albeit of lesser magnitude. Figure 6 shows the frequency of hurricanes making U.S. East and Gulf coast landfall over the past 45 years regardless of magnitude.

Figure 6
Number of hurricanes making U.S. East and Gulf Coast landfall, 1950-1995
(From National Hurricane Center, 1995)



In addition to a greater number of intense Atlantic hurricanes as a result of the Sahel rainfall cycle, there is growing concern that global climate may be changing in ways that could increase hurricane frequency and intensity. Concerns have been raised by IIPLR (1995) that global warming will put coastal areas at increased risk:

1. With further melting of ice sheets on Greenland, Antarctica, and mountain glaciers, sea levels could rise substantially. Beaches and dunes helping to protect communities along the Gulf and Atlantic coasts will further erode.
2. Even a modest 0.9 degree (fahrenheit) increase in average global temperature could produce a 20-day extension of the hurricane season, a 33% jump in U.S. hurricane landfalls, an increase in storm severity fueled by warmer ocean temperatures, and a significant annual rise in catastrophic hurricane losses of about 30% by 2010.
3. Global warming could cause shifts in precipitation and storm activity, and it may cause unpredictable changes in the cycle of hurricane activity. Storm tracks could be shifted further north, allowing for more frequent U.S. landfalls.

HURRICANE HAZARDS

A common image of the damaging effects of hurricanes is that of storm-driven waves crashing against a shoreline, destroying fishing piers and coastal homes. Waves, driven to a speed that is a significant fraction of the hurricane's wind speed, crash against any structure in their path with irresistible force. Storm surge ahead of the hurricane raises sea level and carries damaging waves even farther onshore, which causes flooding in areas normally well above the high tide line.

Although hurricane winds can exert tremendous pressure against homes, a large fraction of hurricane damage is not from the wind itself, but from airborne missiles such as tree limbs and branches, signs and sign posts, roof tiles, metal siding and other pieces of buildings, including entire roofs in major storms. This wind-borne debris penetrates doors and windows, and allows the force of the wind to act against interior walls and ceilings not designed to withstand such forces.

Rain is torrential in the rain bands surrounding the eye of a hurricane. Driven by hurricane-force wind, water can enter homes through usually rain-tight openings and cause significant damage. Hurricane-force rain entering through a wind-destroyed roof can completely devastate a home's interior and contents.

The degree of damage that a hurricane produces varies with the intensity of the storm. Hurricane strength has been categorized in several ways. The accepted scale today for measuring hurricane intensity is the Saffir-Simpson Damage-Potential Scale (Figure 7), which came into general use in 1974. Before that, hurricanes were categorized as Great Hurricanes, or as Minor, Minimal, Major, or Extreme Hurricanes. Great Hurricanes were characterized by winds greater than 125 mph, and diameters of hurricane winds of 10 miles or more (Doehring et al., 1994).

Figure 7
The Saffir-Simpson Damage Potential Scale

Saffir - Simpson	Central Pressure (mb)	Maximum Sustained Wind Speed (mph)	Storm Surge (ft)	Damage Category
1	>980	74 to 95	4 to 5	Minimal
2	965 - 979	96 to 110	6 to 8	Moderate
3	945 - 964	111 to 130	9 to 12	Extensive
4	920 - 944	131 to 155	13 to 18	Extreme

5	<920	>155	>18	Catastrophic

The advantage of the Saffir-Simpson Scale is that it relates hurricane characteristics such as wind speed and storm surge to observed damage. The Saffir-Simpson Scale spans the wide range of damage that hurricanes can produce. Damage from category 1 storms is described as "damage primarily to shrubbery, trees, foliage, and unanchored mobile homes." At the other extreme is damage from a category 5 hurricane:

> Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Very severe and extensive damage to windows and doors. Complete failure of roofs on many residences and industrial buildings; extensive shattering of glass in windows and doors. Some complete building failure. Small buildings overturned or blown away. Complete destruction of mobile homes. . . . (Simpson and Riehl, 1981)

Direct Wind Pressure and Uplift

Of all the hazards posed by hurricanes, hurricane-force wind causes the greatest property loss. Hurricane winds are unique in several ways. Hurricane winds

1. are more turbulent than winds in most other types of wind storms;
2. are sustained for longer periods of time (periods of hours) than in other types of wind storms;
3. change slowly in direction, which allows the wind to seek out the most critical angle of attack and to generate large quantities of debris as the built environment is damaged; and
4. carry large amounts of debris from unsecured items, as well as from the progressive failure of the built environment (Minor and Behr, 1994).

In a hurricane, gusts of wind can be expected to be 25%-50% higher than the sustained wind velocity (Pilkey et al., 1981; Simpson and Riehl, 1981). Thus, a hurricane with sustained winds of 150 mph may produce gusts exceeding 200 mph. Simpson and Reihl describe hurricane gusts as a gradual local wind speed acceleration of five to ten seconds followed by an abrupt decrease in wind speed to values of much less than the mean within one to two seconds. The gust cycle recurs in a period of several minutes.

The effect of a storm's wind is best evaluated in terms of the pressure it exerts. Pressure varies with the square of the velocity, meaning that pressures increases very rapidly with increasing wind velocity. For example, a 100 mph wind exerts a pressure of about 40 pounds per square foot on a flat surface, while a 190 mph wind would exert a force of 122 pounds per square foot. As an example, in a 100 mph wind, a 4x8 sheet of plywood would be thrown by up to 1100 pounds of force. Figure 8 shows how the force of hurricane winds increase with wind speed (ASCE, 1990).

Figure 8
Velocity pressure as a function of wind speed
(From ASCE, 1990)

Wind Speed (mph)	75	95	110	130	155	180	200
Velocity Pressure (psf)	19.0	30.6	41.0	57.2	81.3	109.7	135.0

The external and internal pressures generated on a structure can be greatly increased or decreased based on elevations, shapes of buildings and their components, openings in structures, and surrounding buildings and terrain.

While it is often thought that wind damage is caused by uniform horizontal pressures, it is mostly caused by uplift (vertical), suctional, and torsional (twisting) forces (Pilkey et al., 1981). The effects of wind uplift pressures on a roof vary depending on roof height, roof slope, siting (oceanfront or inland), and style (gable vs. hip) (Cunningham, 1994).

The wind stream generates uplift as it divides and flows around a structure. The wind stream following the longest path, which is usually over the roof, speeds up to rejoin the stream following the shorter distance (usually around the walls). According to Bernoulli's principle, as the wind speeds up across the roof, the pressure drops, generating uplift. The roof, in effect, acts as an airfoil and attempts to "take off" from the remainder of the building.

Uplift forces are greatest at the corners of the roof. The flow mechanism responsible for this phenomenon is called roof vortex (PAWEI, 1993). Roof vortexes can generate extreme suction peaks along each of the two leading edges at each roof corner (Tieleman, 1994). These local suction forces can be 2,5 times those on other parts of the roof (Imbert et al., 1994). Tieleman (1994) compares the phenomenon to the lift of a delta wing aircraft, noting that in aeronautics it has long been recognized that the increased lift from a delta wing is directly associated with a strong vortex that develops downstream of the wing's sharp leading edge.

Internal Wind Pressure

Once the envelope of the building has been breached through loss of windows or doors, or because of roof damage, wind pressure on internal surfaces and structures becomes a factor. Openings may cause pressurization or depressurization of a building. Pressurization pushes wall panels and sheathing out, while depressurization can pull ceilings down. Internal pressure coupled with external suction adds to the withdrawal force on sheathing fasteners. When the openings are on the leeward side of the building, the result is a pressure drop in the interior, which can pull ceiling materials away from the framing. (Wolfe et al., 1994).

An uncontrolled buildup of internal air pressure occurs once the envelope of a building is breached. This can result in a wide range of damage (Oliver and Hanson, 1994; Mitrani et al., 1995). Damage can range from the blowout of windows and doors to total building collapse due to structural failure. Structural failure of exterior wall components because of internal pressure is most common in wood-frame construction, but has also been seen in concrete block/stucco construction (Oliver and Hanson, 1994).

Wind-borne Debris

Wind-borne projectiles are a major factor in home damage and destruction during a hurricane. Penetration of the building envelope by wind-borne debris was directly responsible for many catastrophic failures of roof systems during Andrew because such penetration allowed the uncontrolled buildup of internal air pressure (Minor and Behr, 1994; Mitrani et al., 1995). An opening on the windward wall of a building of only 5% is enough to allow full internal pressurization and effectively doubles the pressures acting to lift the roof and push the side walls outward (Minor and Behr, 1994).

A notable example of damage from wind-borne debris prior to Andrew resulted from Tropical Cyclone Tracy in 1974. Debris damage was so severe that 90% of the homes in Darwin, Australia, a city of 40,000, were made uninhabitable (Minor and Behr, 1994). Mitrani et al. (1995) reported that window breakage and door failure on the windward side of buildings caused most of the roof failures, which were the most important damage due to Tracy. After examining damage caused by Andrew, the Florida Department of Community Affairs concluded:

> The loss of doors (primarily garage and sliding glass doors) and windows was the second most important and costly aspect of the storm. Wind-borne debris (particularly from roofing materials) contributed to a significant portion of this damage. The loss of windows and doors, along with the loss of roof coverings, caused the large amount of damage to building interiors and contents. (Mehta et al., 1994)

The pool of potential projectiles that can be picked up by hurricane-force winds and turned into wind-borne debris includes roofing materials such as shingles, tiles, and gravel; inadequately attached cladding components such as sheathing and siding; and rocks and tree limbs (HUD, 1993). Smith (1994) reported that wind-borne debris from

Andrew included tree limbs, fences, dislodged rooftop antennas and HVAC equipment, and components from failed buildings. FEMA (1992) observed that the failure of metal-clad buildings and mobile homes generated considerable wind-borne debris during Andrew.

Storm Surge

Storm surge is an increase in ocean level due to a combination of direct wind-driven water and uplift induced by atmospheric pressure drop (Simpson and Riehl, 1981). Along the U.S. East Coast, the storm surge wave can have a height ranging from 4 to 5 feet for a category 1 hurricane up to 18 feet for a category 5 storm. The surge arrives ahead of the full force of the hurricane, and the more intense the storm, the sooner the surge arrives. Water rise can be quite rapid. During Hurricane Hugo, the storm surge rose 2-3 feet per hour at one location (Hogan and Karwoski, 1991). For a category 5 hurricane, the surge arrives up to five hours ahead of the storm, and can be more than 50 miles wide. Storm surge is affected by several factors (Bryant, 1991):

1. wind setup;
2. decrease in the atmospheric weight on a column of water;
3. direction and speed of movement of the pressure system;
4. shallowness of the continental shelf, bay, or lake; and
5. shape of the shoreline.

The first element, wind setup, is determined by a combination of factors, including the depth of the channel, wind speed, and the fetch length of the surge. According to Bryant, a wind speed of 120 mph would produce wind setup of approximately 6 feet. Decreased atmospheric pressure associated with the storm also contributes to sea-level elevation. For every 1 millibar decrease in atmospheric pressure, sea level will rise 1 centimenter.

Other factors can raise the height of the surge even further. As the shoreward moving wave encounters shallower coastal water, its speed decreases and, to conserve energy flux through a decreasing water depth, wave height increases. The faster the wave travels, the more it shoals when it reaches shallow water. Finally, the shape of the coastline can magnify the storm surge. The surge will be highest where land juts out into the path of the storm. Funnel-shaped basins, such as the Bay of Bengal and Bay of Fundy, can significantly increase the size of the surge. In 1869, a cyclone called the "Saxby Gale" moved up the Bay of Fundy, moving a mass of water at about the resonant frequency of the Bay of Fundy-Gulf of Maine system. The resulting storm surge of 48 feet, superimposed on a 42-foot tide, almost overwashed the six mile-wide isthmus joining Nova Scotia to the mainland (Bryant, 1991).

Simpson and Riehl (1981) note that storm surge is an example of a wave that has outrun its generating source, creating a swell. While the amplitude of the wave decreases, the period stays relatively constant. The storm surge is the dominant swell with the longest period, and is always highest in the right-front quadrant in the direction of hurricane movement, because it is generated in the area of longest fetch, the right-rear quadrant. When the surge reaches a coast, its height is always greatest (along the U.S East Coast) to the north of the hurricane eye.

Waves

Hurricane waves travel toward shore until the water becomes shallow enough to initiate wave breaking. The maximum breaker height in shallow water is a function of water depth; bottom slope; and incident wave height and period. Larger waves initially break some distance offshore, then reform and continue shoreward as smaller waves that break and reform several more times before reaching shore (Yamamoto et al., 1994). Waves may move shoreward at speeds of about half the sustained wind velocity of the storm (Doehring et al., 1994).

The force of a wave may be visualized by considering that a cubic yard of water weighs over 3/4 of a ton. A breaking wave moving shoreward at high velocity can be one of the most destructive elements of a hurricane. Waves can cause severe damage not only in forcing water onshore to flood buildings, but also by throwing floating debris against standing structures. Further, wave action can erode the sand that underlies many shore-front buildings and cause their collapse.

The phenomenon of wave setup can compound wave damage. Wave setup is a process that causes still-water surfaces to incline upward locally to elevations above the prevailing sea level as deep water waves move into a rapidly shoaling area. As the waves break, water is thrown forward toward the beach. Subsequent waves add to the increasing water height. In Hurricane Eloise (1975), wave setup was believed to account for over three feet of the 15-foot tidal maximum, with storm surge accounting for nine feet of the increased sea height (Simpson and Riehl, 1981).

Wave setup also creates strong erosional forces during a hurricane as the up-slope in the near-shore water level creates powerful long-shore currents. These currents are major factors in erosion along the shore. Wave setup may be exacerbated by activities such as beach replenishment projects that pump sand from the near offshore area. These projects increase the near-shore sea bottom slope. Commonly, the natural slope of the bottom is more gradual, and deep-water or transitional waves cannot get as close to shore before breaking; therefore packets of shorter, lower waves are generated. In these cases, wave setup is not a large factor in wave height. But wave setup can significantly increase wave height where depths go quickly from deep to shallow over a short distance (45 feet to 9 feet in less than 3/5 mile in the case of Hurricane Eloise in 1975) (Simpson and Riehl, 1981).

In discussing the hazard presented by storm surge and wave action, it is useful to categorize the different locations affected. Rogers (1991) distinguishes four zones on low-elevation shore areas:

1. the wave erosion zone,
2. the zone of wave flooding,
3. the still-water flooding zone, and
4. the high ground zone with no flooding.

The wave erosion zone, the most hazardous location, is the closest to the ocean and is the area that experiences erosion due to storm surge and waves.

The next zone, typically extending across the beach road and one or two blocks inland, is at risk from flooding with waves, but not erosion. Conditions are dissipated from the wave erosion zone, but water levels and wave heights are still significant threats. Rather than eroding, this region is often buried by overwash deposits transported landward from the erosion zone. If the wave heights are high enough to deposit significant amounts of sand, the waves are usually large enough to cause significant damage to buildings.

Farther inland, most wave activity usually dissipates before the still-water flooding zone is reached. Flooding by storm surge can extend far inland over low topography, and is similar to still-water flooding typical of slow velocity riverine floods. Flooding of up to 18 feet occurred 50 miles inland in some areas during hurricane Hugo (Hogan and Karwoski, 1991).

Rain

Heavy rain in a hurricane adds to the danger of the storm by causing floods, flash floods, and interior damage to structures with walls or roofs already breached by the wind. Hurricane Andrew, a fairly "dry" storm because of its high forward speed, still dumped 10 inches of rain on south Florida and left many buildings extensively water-damaged. Water seeping into gaps between the roof sheathing saturated insulation and ceiling drywall and caused some buildings to collapse (Wolfe et al., 1994). Nearly 65% of homes exposed to Andrew, and 40% of homes exposed to Hurricane Iniki, had water damage from rain (HUD, 1993).

HURRICANES HUGO, ANDREW, AND INIKI

For this research, hurricanes Hugo, Andrew, and Iniki were chosen as case studies in hurricane-inflicted damage. While quite a lot has been written regarding damage caused by earlier storms, it was not until the enormous losses from the first of the case-study storms, Hurricane Hugo, that field reports began focusing on the details of damage to residential structures. These three storms provide both similarities and contrasts. All were strong category 3 or 4 hurricanes. All three demonstrated the enormous losses that can be caused by hurricane winds. Both Hugo and Andrew narrowly missed heavily populated areas with their maximum winds and storm surges. Both were fast moving. Andrew, however, was a much more compact storm than Hugo. Damage from Andrew was minimal north of the center of Miami, approximately 35 miles from the eye, while damage from Hugo was extensive as far north as Myrtle Beach, 100 miles north. Storm surge damage from Andrew was minimal, but significant from Hugo. Hurricane Iniki, like Hugo, not only caused significant wind damage, but also created a large storm surge that caused substantial damage from coastal flooding along the Kauai coast.

The three storms also differed in that they struck areas with varied residential construction styles: in the South Carolina area struck by Hugo, wood-frame houses with asphalt shingle roofs predominate; in Dade County, Florida, where Andrew came ashore, masonry block construction is more common than wood-frame, and tile roofing is popular; in Kauai County, Hawaii, corrugated metal roofing is very common. Figure 9 compares the three storms.

Figure 9
Physical characteristics of Hurricanes Hugo, Andrew, and Iniki
(From Murden, 1991; Rojahn, 1993; Wang and Lin, 1994; Chiu, 1994)

	Hugo	Andrew	Iniki
Saffir-Simpson category at landfall	4	4	3
Sustained winds (mph)	134	145	130
Maximum gusts (mph)	160	175	160
Eye-wall diameter (miles)	30	20	10
Hurricane-force winds (miles	140	45	50 from eye)
Tropical storm-force winds	250	140	Not available (miles from eye)
Storm surge (feet)	5 to 20	5 to 17	12 to 24
Rainfall (inches)	5 to 10	2 to 5	Not available
Forward speed at landfall	27	18	20 (mph)

Hurricane Hugo

Hurricane Hugo in 1989 was the strongest storm to strike the United States since 1969 when Camille struck the Gulf Coast. Hugo was catastrophic and caused widespread residential damage, extensive lifeline destruction, and enormous timber destruction in South Carolina. The storm surge from Hurricane Hugo was, at 20 feet, the highest to hit the East Coast this century (Sparks, 1994). Hugo created $1 billion in damage for each of the six hours it moved through South Carolina (Curry, 1991).

Hugo formed as a tropical depression on September 10, 1989, 12 days before crossing the South Carolina coast. With winds of up to 160 mph, Hugo was classified as a category 5 hurricane. Shortly before midnight on September 22, Hugo, now a category 4 storm with sustained winds diminished to 135 mph, crossed the South Carolina coast just north of Charleston. Hugo's strongest winds now were confined to the Bulls Bay area 25 miles northeast of Charleston. Winds there gusted to 144 mph (Powell, 1991). Hurricane winds extended 100 miles northeast, and 50 miles south. A storm tide of nearly 20 feet inundated the coast as far north as Myrtle Beach. The eye of Hugo passed just east of Columbia, South Carolina, 100 miles inland, at 3:00 a.m. with winds of 109 mph. By sunrise Hugo, now a tropical storm, had reached Charlotte, North Carolina, with winds still gusting to 87 mph.

South Carolina suffered severe damage, but little loss of life. Thirteen of the 49 deaths attributed to Hugo were in South Carolina. The low death toll was a result of timely warnings and evacuations (Rubin and Popkin, 1990). One interesting aspect of the damage caused by Hugo was the amount of wind damage to trees. There were many areas where the wind caused significant damage to trees, while wind damage to buildings was minimal. The main reason for this was that the predominant tree in the area is pine; pine trees tower 30-40 feet above the ground, where the wind speeds are higher than at ground level. The trees served as a wind shield that prevented the wind from damaging many structures. On the other hand, homes were damaged by broken trees and branches (Manning and Nichols, 1991). On the whole, more structures appeared to have benefitted rather than suffered from the trees (Murden, 1991).

Hurricane Andrew

Hurricane Andrew was the most destructive natural disaster in U.S. history in terms of property loss. Andrew began as a tropical storm on August 17, 1992. By August 22, Andrew was a minimal category 1 hurricane, 800 miles east of Miami. Andrew intensified quickly, and less than a day later was a strong category 4 storm with winds of 135 mph. That same afternoon, winds increased to 150 mph, Andrew's maximum sustained winds, and near category 5 in strength. Andrew was now 330 miles east of Miami, and hurricane warnings went up from Vero Beach, Florida, south to the Keys. On August 24, Andrew struck Florida with sustained winds of 145 mph.

Damage to Florida agriculture alone was over $1 billion. One hundred seventeen-thousand homes were damaged or destroyed and 90% of all homes in Dade County had major roof damage. Only 41 deaths were attributed to Andrew, thanks to mass evacuations prior to Andrew making landfall (Doehring et al., 1994).

Although the storm produced a high storm surge and high winds, storm surge damage was confined to a small area of the coastal floodplain. Therefore, the flood damage from Andrew, unlike many storms of its size, was minimal. Wind damage was common, however. Andrew caused substantial damage to both residential and commercial structures in southern Dade County, Florida.

Andrew was an intense but compact storm. Major damage to structures was limited to an area bounded by Homestead to the south, Coral Gables on the north, the Everglades on the west, and Biscayne Bay on the east. Again, storm surge damage from Andrew was minimal when compared to Hugo. Storm surge higher than 10 feet extended about 10 miles north of Andrew's landfall, while the same surge elevation extended 100 miles north of landfall for Hurricane Hugo (Cook, 1994). Although Andrew produced high winds and a high storm surge, the effects of the storm surge and wave action were confined to a small area of the coastal floodplain.

Flood damage was minimal for a storm as large as Andrew, although landfall occurred at high tide. The maximum storm surge reported was 16.9 feet at Cutler Ridge, about 20 miles south of Miami. The surge tapered off rapidly, and was only five feet at the north end of Miami Beach. Coastal flooding was limited to a few spots in Key Biscayne, and a few canal-front communities along the coast off Cutler Ridge. No significant beach erosion was attributed to Hurricane Andrew. This may have been the result of the compactness of the storm and the speed at which it moved inland (Wang and Lin, 1994).

Hurricane Iniki

Hurricane Iniki was one of the most powerful and destructive storms to hit Hawaii in recent memory. Iniki's central barometric pressure of 938 mb was the lowest ever recorded in a central Pacific hurricane (Fletcher et al., 1994). A small and compact storm like Andrew, Iniki formed as a tropical storm on September 7, 1992, and became a hurricane a day later. Iniki followed a track that historically had carried hurricanes south of the Hawaiian Islands, but a low pressure trough turned the storm northward and into the island of Kauai on September 11. By the time Iniki passed over the north shore of the island and back out to sea two hours later, over 90% of all buildings on the island had been damaged, ranging from minor damage to complete destruction (Chiu, 1994). Iniki caused $3 billion in damage in two hours (Schroeder, 1994). Over 14,000 homes were damaged or destroyed. Damage was most severe on the north, south, and east ends of the island. Despite the widespread damage, only three deaths were attributed to the storm, thanks to ample warning and evacuation.

Hawaii is a mountainous state, unlike Florida and coastal South Carolina. This complex topology created extremely complex wind-flow patterns that resulted in high localized wind speeds, which exacerbated the destruction in certain areas. According to Chiu (1994), one 227 mph gust was reported over one of the higher ridges. Topological wind amplification caused heavy damage to buildings built along the island's cliffs in areas such as Princeville on the north shore of the island.

Iniki produced a significant storm surge and corresponding damage. The geology of the Hawaiian Islands contributed to one unusual effect, damage to structures from wave-borne floating volcanic rock.

Coastal flooding was significant along the southern shoreline from Kekaha to Poipu Beach. Still-water flood elevations ranged from 10.5 to 12.5 feet above mean lower low water (mllw) at Kekaha to 12.5 to over 20 feet above mllw along Poipu Beach (FEMA, 1993).

HURRICANE DAMAGE TO HOMES

Catastrophic failure of one- and two-story wood-frame buildings in residential areas during Andrew was observed more frequently than the catastrophic failures of other types of buildings. Because less engineering oversight is applied to design and construction, residential construction is especially vulnerable to damage during hurricanes. As opposed to hospitals and public buildings, which are called "fully engineered," and offices and light industrial buildings, which are considered "marginally engineered," residential construction is categorized as "non-engineered." Historically, the bulk of the wind damage in the United States has occured to residential construction. Fully engineered construction, on the other hand, performs well in high winds, because of the attention given to connections and load paths (Perry, 1991).

When houses are exposed to hurricane forces, roofs are most susceptible to damage, followed by walls and openings, and then foundations. After Hurricanes Andrew and Iniki, the Department of Housing and Urban Development (HUD, 1993) surveyed damaged homes from both storms. HUD used a scale that identified not only the number of homes damaged, but the degree of damage (ranging from one-third or less, to two-thirds or more) to each home. Figure 10 summarizes home elements suffering damage levels of one-third or more from Hurricanes Andrew and Iniki. The chart shows clearly that roofs are damaged more often, followed by walls and foundations. It is worth noting that water damage was a significant factor in both storms.

Figure 10
Percent of damaged homes surveyed with damage levels greater than one-third (From HUD, 1993)

Damage Type	Andrew	Iniki
Roof	51	34
Wall	15	12
Foundation	0	3
Projectile Damage	20	24
Water Damage	66	54

Florida, South Carolina, and Hawaii together offer a representative sample of residential building styles and methods common in hurricane hazard areas. In Florida, the most common type of home construction is slab-on-grade foundation with concrete block walls and wood-truss roofs, although wood framing is becoming more popular as an alternative to concrete block wall construction. In Hawaii and South Carolina, wood is the most popular building material. Wood-truss roofs are common in all the sample areas.

Roof Damage

Roof covering failure was the most widespread type of damage observed after Hugo, according to Manning and Nichols (1991). Roof coverings which were not adequately attached, and corner and eaves regions of roofs were frequently damaged. Smith and McDonald (1991) note that in the Charleston area probably more than 75% of all roofs had at least minimal damage. Once roofs were breached, house interiors were exposed to further damage from water. Roof failures were also the most frequently observed structural failures from Andrew. Cook (1991) estimates that over 80% of losses were related to roof failures and associated water damages. In Dade County, Florida, the most common building failure observed was loss of roof cladding (shingles, tiles, etc.). Ninety percent of all homes in Dade County had some degree of roof damage (Doehring et al., 1994).

Roof failures occurred because of lack of proper connection between the roof and the exterior walls (Cook, 1991). Often, rafters were attached by toenails to the top plate, and in other cases hurricane clips attached the rafter to only the top plate (rather than to the wall studs). With the roof gone, walls lost the support provided by the roof system and were subject to collapse even when exposed to lesser winds (Manning and Nichols, 1991). Miehe (1991) observed that nearly all wall failures were a result of other failed components, such as roofs and doors or windows.

In Florida, roofs are constructed using plywood sheathing over wood roof trusses and are covered with tar paper and either extruded concrete tile or asphalt composition shingles. Both roof tile and conventional shingles are common. Examination of conventional composition shingle roofs showed evidence of substandard workmanship, such as insufficient staples or incorrectly located or oriented staples (FEMA, 1992). Smith and McDonald (1991) also observed misaligned fasteners while examining roof damage from Hurricane Hugo. Further, Reardon and Meecham (1994) noted that the use of staples also provided an inadequate connection in attaching sheathing.

In addition, it appeared that many shingles and attachment adhesives used were not adequate for the wind speeds that occurred. The most common failure mode was lifting of the tabs due to failure of the self-seal adhesive, and subsequent tearing of the shingles at the fasteners (Smith, 1994). Smith went on to note that nearly all the shingles examined were attached with only four fasteners, the minimum required by the 1988 SFBC, although most manufacturers recommended six fasteners in high wind areas. Examination of damage from Hurricane Hugo showed that mis-located fasteners were also a common cause of cladding failure (Smith and McDonald, 1991).

Tile roofs, composed of either extruded concrete or clay, showed failures in both nailing and mortar connections. The most common failure was the lack of a bond between the mortar and the tile. Many mortar pads appeared to have been applied nonuniformly. Clay tiles seemed more susceptible to damage from flying debris than concrete tiles, but they seemed to have better adhesion to mortar than the extruded concrete tiles (FEMA, 1992).

During Iniki, over 90% of all one- and two-family dwellings lost substantial portions of their roof covering (Sheffield, 1993). On Kauai, where corrugated roofs were common, large portions of the metal sheathing were removed from most roofs due to inadequate fastenings. Failure of roofing material not only exposed the buildings to water penetration, but also provided a major source of wind-borne debris. Water penetration was a major problem whenever roofing material was removed by wind action. For steep roof systems, many roofing failures occurred at the ridge or gable ends where wind-induced forces were the highest. For low-slope roof systems, damage occurred primarily at roof corners (Chiu et al., 1994). Figure 11 summarizes roof damage greater than one-third from Andrew and Iniki.

Figure 11
Percent of damaged homes surveyed with damage to roofs greater than one-third (From HUD, 1993)

	Andrew	Iniki
Cladding	59	63
Sheathing	54	33
Rafters/Trusses	21	18
Soffit/Facia	27	22

Roof-Wall Connection	12	5
Gable End	30	5

Building failure during Andrew was primarily a result of negative pressure and/or induced internal pressure overloading the building envelope. The wood-frame gable ends of roofs were especially failure-prone. In addition, many houses had been built with the plywood roof sheathing acting as the sole stiffener of the roof diaphragm and lateral support for the trusses. Once sheathing was blown away from the roof, nothing prevented the roof trusses from collapsing. Failure to properly attach the roof sheathing to the top chord of the roof truss and omission of gable end and roof truss bracing left roofs highly susceptible to loss of structural integrity (Oliver and Hanson, 1994). Because the roof sheathing provided the only stiffening of the roof diaphragm, the attachment to the sheathing became critical to the successful performance of the building envelope. No truss failures were cited as a primary cause of general roof or building failure, and no trusses failed because of the loads imposed. In fact, when properly anchored, trusses transmitted wind loads to the rest of the structure satisfactorily (Riba et al., 1994).

HUD (1993) identified roof sheathing as a critical component that locks all other roof members together to form a structural system. Loss of roof sheathing led to instability and subsequent failure of the wood-frame gable ends and trusses. Oliver and Hanson (1994) did find instances where debris punctured roofs, but this did not seem to be a significant or direct cause of roof failure.

Where roof failure did not lead to total structural failure, roof failure allowed rain, often heavy, to penetrate to the interior of the home. This not only resulted in damage to furnishings, but also further weakened the structure when rain-soaked ceilings collapsed, reducing reinforcement of the ceiling joists.

One of the most damaging classes of failure in economic terms was the loss of gypsum wallboard ceilings (Keith, 1994). This form of damage affected most houses in the path of Andrew to some degree. The rain accompanying and following the passage of Andrew was driven in through gable-end vents and roof turbines, through the joints between roof sheathing panels after roofing was blown off, and directly into the attic space of failed roof systems. Rain quickly saturated the insulation and the ceiling. The loss of ceiling strength due to water saturation, and the increased weight of the wet insulation, caused widespread collapse of ceilings. The loss of the ceiling also contributed to gable-end wall failures due to the diminished lateral support at the base of the gable-end walls.

Keith (1994) observed that the most common type of structural damage from Hurricane Andrew in Florida, where over 80% of houses have gable roofs (Crandell et al., 1994), was loss of gable-end walls. Keith (1994) further observed that loss of the gable-ends was usually accompanied by loss of between four and 12 feet of roof sheathing immediately next to the gable-end wall. Once the roof sheathing was blown off, the gable-end truss and adjacent trusses collapsed in domino fashion.

Riba et al. (1994) describe the following progression during gable-end collapse: typically, the gable-end popped out due to suction on the leeward side of the building and the loss of sheathing, or to a combination of suction and increased pressure resulting from breached openings in the shell. When the gable-end was on the windward side of the building, collapse was caused by the withdrawal of the fasteners connecting the sheathing to the gable end top chord. This caused the gable-end overhang to peel up, causing a cascading loss of additional sheathing downwind. This led to more sheathing loss and the eventual toppling of the adjoining trusses.

Diagonal cross-bracing of end trusses was rarely present in roofs that failed in this manner. Keith (1994) observed that gable-end trusses were often only attached to the top plate of the end walls by infrequent toenailing, only four to six feet on center, and inadequate to transfer shear forces from the gables to the walls.

Sanders (1994) concurs that gable-ends were especially problematic. Sanders observed that one of two failure modes accounted for almost all gable-end failures:

> Either the connection of the top chord to the roof diaphragm was not able to resist the combination of

horizontal reaction from the truss combined with the uplift on the sheathing at the roof edge (i.e., nailing patterns used on roof sheathing were not designed for both shear and uplift acting simultaneously), or the bottom chord was not supported adequately to resist lateral loads.

Manning and Nichols (1991) examined damage from Hurricane Hugo and concluded that roofs had been tied to walls with hurricane clips that were inadequately sized to support the design wind load. Hoover (1993) examined gable-end collapses from Hurricane Andrew and concluded that, in every case, the collapse was due to lack of proper connections, either between the gable-end and the roof, or the gable-end and the end-wall. Hoover noted the following problems:

1. Nail Spacing did not meet the code minimum of 6 inches o.c. [on center] in the roof panel edges, and 12 inches o.c. in the interior of the panels.
2. Staples were not installed at the correct spacing and orientation. Staples must be spaced closer than nails, and installed parallel to the truss rafter chord.
3. Fastener spacing over the gable probably had been incorrectly considered as interior spacing rather than edge spacing.
4. In general, there seemed to be a reliance on the code minimum nail spacing as opposed to the specific connections being designed.

It was the opinion of the FEMA assessment team that reliance on sheathing for truss-roof bracing, coupled with the corresponding loss of sheathing, was a major cause of the total damage of the building systems. Cook (1994) regards this as the most costly aspect of the damage and notes that loss of sheathing was usually the result of inadequate nailing; either nails were spaced too far apart according to building code, or nails missed the underlying rafter altogether.

Damage to Walls

Walls are not as vulnerable to hurricane damage as roofs, windows and door openings, but failures did occur during Hugo, Andrew, and Iniki. Damage from flying debris was not a significant factor, although there were cases where debris penetrated walls. Wall failures were caused mainly by to poor connections (Sanders, 1994).

The most common residential building methods are concrete block and stucco (CBS) and wood-frame. CBS construction is popular in Florida, while wood-frame is common in Hawaii. In any region, elevated homes in flood or erosion zones are typically wood-frame. In both Florida and Hawaii, wall damage was not as common as damage to roofs as a significant cause of building failure, but it did occur.

Sanders (1994) notes that in South Florida reinforced hollow concrete block masonry is by far the most common building material used in wall construction in both residential and commercial structures. The South Florida Building Code prescribes a method of reinforcing block walls called in Florida "tie beam-tie column." In this building method, unreinforced block walls are first erected. Reinforcing bars are then inserted through the blocks at intervals of no more that 20 feet, and the reinforced column of blocks then filled with mortar. The top ends of the reinforcing bars are then attached to a cast-in-place tie beam at the top of the wall. When properly constructed, the result is a hollow block wall laced with a strengthening network of steel bars and poured concrete columns and cross-members.

Improperly reinforced masonry walls failed because of a combination of uplift and pressure forces. These forces combined to lift up the edge of the roof and bond beam, separating the bond beam from the rest of the roof system. Curry (1991) believes that good inspection practices could have prevented this type of failure.

Failures in this type of wall construction were observed when the reinforcing bars were omitted at wall intersections or corners. These intersections provided continuity of tie beam reinforcing. When this deficiency existed in combination with the failure of the tie beam to roof connection, the wall collapsed. In general, when the tie beam to roof connection failed, or was not present, the tie beam was then subjected to lateral stresses for which it was not designed (Sanders, 1994). Many total failures of CBS houses were the result of lack of tie down for the tie beam. Once uplift forces on the roof overcame the mass of the roof and tie beam, there was only the tension strength of the mortar to prevent total building collapse (Reardon and Meecham, 1994). Curry (1991), and Cook (1991) observed that most wall and roof system failures from Hugo began at the roof corners and eaves of buildings regardless of wall type.

The FEMA team observed that masonry-wall buildings tended to fair better than wood-frame homes. Where failures did occur, the primary reason was lack of vertical wall reinforcing. The lower rate of masonry wall failure was attributed to the heavier mass of the masonry wall, and the tendency of a continuously constructed system to be less prone to failure from lack of attention to design and construction details. Where failures did occur, the team observed the following conditions: poor mortar joints between walls and slab; lack of tie beams, horizontal reinforcing, tie columns, and tie anchors; and misplaced or missing hurricane straps between walls and roof. Khan and Suaris (1994) observed some cases of failure where block walls collapsed completely because of inadequate anchorage to resist uplift and lateral forces. In these cases, the deficiencies (and code violations) were common and included lack of tie downs, tie downs in unfilled cells, missing hooks from tie downs to the tie beams and foundation, and lack of corner bars.

Woodframe walls suffered few component failures, except damage from missile impact. When failures did occur, connectors were usually the cause. Although nearly all wood structures had hurricane straps to transfer tensile forces across framing joints, shear connections were nonexistent or inadequate. This was especially problematic with multistory buildings (Sanders, 1994).

In wood-frame construction, the SFBC requires that either board or plywood storm sheathing cover all exterior walls. Kahn and Suaris (1994) and Cook (1994) report that sometimes, however, the only sheathing was hardboard siding applied directly over the studs of some homes, leading to their collapse. In other cases, products such as Masonite and Thermax were used. Although approved by the SFBC, Masonite had a raking shear strength of only 120-125 pounds per square foot, compared to 430 pounds per square foot for 15/32 inch plywood sheathing with a wider stud spacing. The actual raking shear strength was often even less, since contractors did not usually follow the recommended nailing and stud spacing requirements. Kahn and Suaris observed other cases where the SFBC had been violated:

1. Corner studs constructed with less than three studs or improperly constructed,
2. no overlapping of plates at intersections,
3. inadequately nailed connections,
4. improper splicing of members
5. improper notching of members,
6. missing hurricane straps in stud-plate connections, and
7. missing sill plate anchors.

Two-story homes offered additional problems. In some cases with composite houses (first floor, masonry; second floor, wood-frame) the second-story stud walls were erected off the second floor framing with no direct anchorage to the lower story. In some two-story wood-frame homes, no direct connection existed between first story and second-story stud walls. The vertical framing on both floors was connected to the floor joists using metal straps, but the vertical framing for the two floors was not connected to the framing of the other floor. Sometimes, the metal straps were merely bent under the floor joists, providing no anchorage at all. This lack of attention to detail, in the opinion of Kahn and Suaris, led to the collapse of many wood-framed houses.

Damage to Windows and Doors

When window and door loss occurs, interior damage from wind and rain intrusion can be substantial. Many homes were uninhabitable for long periods after Hugo, although the main structural system was intact and damage appeared minimal from the outside (Murden, 1991). Windows, especially sliding glass doors, were very susceptible to failure from wind pressure and debris impact. Frame systems were usually found intact after Hugo, but only because the glazing had already failed.

The breaching of the building envelope by failure of openings (doors, windows) due to debris impact was a significant factor in much of the damage from Andrew. Smith (1994) notes that roof damage from flying debris was a major problem during Andrew because of the quantity of missiles in the air stream. Missiles included tree limbs, fences, dislodged rooftop HVAC equipment, and components from failed buildings.

Window protection such as shutters and precut plywood performed well. Structures with adequate roof ventilation were observed to have performed better due to the ability of the ventilation to relieve induced internal pressure.

Garage door failure was a significant cause of damage during Andrew. The most common failure was deflection of the garage door from wind pressure until the tracks rotated and the door rollers separated from the tracks. Loss of doors resulted in envelope breach and a sudden increase in internal pressure. Single-car garage doors were observed to have performed better than two-car garage doors (Cook, 1994). Cook regards the loss of doors (primarily garage and sliding glass) and windows to be the second most costly and important cost aspect of the storm after roof damage. Sometimes, loss of windows and doors caused roof loss. Murden (1991) noted that during Hugo many anchored roofs failed because of loss of windows and sliding glass doors.

Entry doors, especially french doors, and wood and metal double doors, were prone to failure. Observed failures included either pullout of the center pins, or shattering of the door leafs at the location of the center pin. Metal doors tended to deflect until the center pin pulled out, while wooden doors resisted the deflection but shattered at the pin instead.

Chiu et al. (1994) report that windows and garage doors were weak points in the performance of residential buildings during Iniki as well.

Foundation Damage

In Florida, slab-on-grade foundations performed well, and in Kauai, post-and-pier foundations presented only a few wind-related failures (Crandell et al., 1994). However, foundations exposed to storm-driven water in South Carolina during Hugo sustained substantial damage.

Foundations are subject to damage from water and wind. Foundations are especially at risk from hurricane-driven water. Wave action can scour support from beneath a foundation or batter a foundation with the lateral force of the waves. Elevated seas can float a poorly-attached house from its foundation. This was especially problematic during Hugo where, for example, in the Bull's Bay, South Carolina, area storm surge exceeded the flood insurance elevation requirements by several feet.

A frequent failure during Hugo was flotation of a home from its foundation due to flood waters (Manning and Nichols, 1991). A survey of damage showed inadequate, or lack of, connections between house superstructures and foundations. Houses that were raised often lacked pier reinforcement, and exhibited inadequate pier foundations and pile embedment.

The piers were also susceptible to failure from water forces. Rogers (1991) observed that the greatest weakness of the columns proved to be the shallow embedment. Several hundred oceanfront buildings in South Carolina received major structural damage when the footings were undermined by as little as two feet of erosion under the buildings. The vast majority of these foundations were in non-engineered buildings (i.e., residential structures).

Under-house cross-bracing also proved to be unreliable, according to Rogers (1991). Wooden cross-bracing frequently broke, particularly when parallel with the shoreline. Even steel rods were ineffective. Rods with diameters up to 1/2 inch were bent and loosened by waves and debris. The bracings stiffen the foundation only when under tension. Once loosened, they have no beneficial effect.

Non-elevated structures fared even worse. Slab-on-grade foundations and other low foundations were extensively damaged or destroyed. Single family homes occasionally floated off the foundation, but were more often demolished into small pieces and carried away by the waves. Often, no remnant of the building or foundation remained. Among oceanfront buildings in the wave erosion zone, major structural damage was caused by either inadequate elevation, an erosion-sensitive foundation, or both (Rogers, 1991). Rogers observed that non-engineered buildings experienced the greatest damage. Some small oceanfront buildings designed by architects and engineers showed much better quality control, but an equal disregard for the possibility of erosion. Rogers (1991) summarized wave and water damage from Hugo:

> Most of the buildings that received severe structural damage were clearly incapable of surviving either Hugo's conditions or design conditions reasonably predictable before the storm. Most damage occurred not because Hugo substantially exceeded reasonable design conditions, but because most buildings were not constructed to tolerate any storm conditions. Buildings can withstand Hugo's conditions as proven by the well-built structures that remained in some of the most hazardous locations. The keys to preventing damage are:
>
> 1. a minimal understanding of the hazards likely for the zone where the building is to be sited,
> 2. sufficient floor elevation to avoid getting wet or hit by a wave, and
> 3. where appropriate, a piling foundation to resist waves, and
> 4. adequately embedded piles to avoid undermining by erosion.
>
> The biggest surprise from Hugo was that for every building destroyed, there were five or ten equally damage-prone buildings nearby that remained standing. If the storm had made landfall farther north or south, or if slightly worse conditions had occurred, damage would have been far beyond its already record-setting costs.

Wind forces are also hazards to foundations. Wind pressure against the walls of an elevated house produce enormous strain on the superstructure-to-foundation connection. Further, poorly embedded pile-and-pier foundations are subject to racking (horizontal sheer force); lateral wind and water forces horizontally displace the superstructure from the foundation to a point at which the foundation "folds" beneath the superstructure.

According to Murden (1991), wind-induced foundation failures were more common during Hugo than in other recent storms. Many homes on the South Carolina coast are elevated on masonry piers. These piers are often unreinforced and frequently exceed eight feet in height. Piers are usually on small individual spread footings. The net results of this design is piers that are unable to provide lateral support. As the supported structure moved from wind forces from Hugo, the piers underneath simply toppled.

DAMAGE MITIGATION DURING CONSTRUCTION

Pilkey et al. (1981) summarize safe coastal construction in one sentence: "Put the building or dwelling at a high enough elevation where the highest water will not reach it, and make it sturdy enough so the fastest winds will not destroy it." This recommendation should be applied to all residential construction in all hurricane hazards areas.

Analysis of damage from Hurricane Andrew identified three factors that have the greatest effect on the hurricane resistance of a home: roof coverings, opening protection (windows and doors), and roof sheathing attachment. These three factors were consistently the weakest links in the homes examined (HUD, 1993). Hurricane-resistant building must focus on these weak links, but other potential failure areas such as walls and foundations should be addressed as well.

Residential structures are best able to survive exposure to hurricane forces when the envelope of the structure consisting of exterior walls, roofs, and exterior opening closures remains intact as a unit. Pilkey et al. (1981) observed that buildings designed for inland areas are primarily designed to resist vertical (gravity) loads, and only insignificant wind forces. Homes in hurricane-prone areas, however, must be constructed to resist forces from many directions. Once any one building element fails, the other elements of the structure are at an increased risk. Further, not only must the individual structural elements remain intact, they must also provide unbreached load paths from one to the other. Roofs must not only be well constructed, but also adequately connected to walls. Walls in turn, must not only contain suitably strong windows and doors, but must also provide a load path from the roof to the foundation. Foundations must be capable not only of supporting the gravity load of the structure above them, but they must also be connected to the structure in a way that addresses flotation and horizontal loads, as well as transmission of those loads to the earth.

Roofs

When homes fail under exposure to hurricane-force winds, the order of failure is usually roofs, openings, and foundation (Perry, 1995). Roof systems are exposed to higher loading than any other building element (Smith and McDonald, 1991). Field observations of damage from hurricanes Hugo, Andrew, and Iniki confirmed that once the roof of a home was breached, failure of other building elements usually followed. Roof failure followed the following scenario. First, cladding was lost at a roof corner due to the greater uplift there, followed by loss of sheathing. Once sheathing was lost, the building envelope was effectively breached. Wind pressure was now exerted against the inside of the gable end-wall, leading to its possible failure, and against the underside of the remaining sections of the roof, increasing the likelihood that the reminder of the roof would be lost. If the roof became detached, gables collapsed, and the remainder of the structure, now much weakened, often failed.

Roofs are subjected to wind forces from many directions. Direct wind pressure can loosen shingles and tiles. Suction forces on the surface of the roof and vortices on the roof corners can lift both roof cladding and sheathing. Internal pressure generated when windows, doors, or sections of the roof itself are breached can lift and separate the roof from the rest of the structure. A properly designed and constructed hurricane-resistant roof must be able to withstand all these forces.

Hip vs. gable roofs

Hip roofs, which slope in four directions, are less prone to breaching than gable roofs, which slope in two directions. HUD (1993) examined damage from Andrew and found that only 6% of houses with hip roofs were rated at the highest level of roof damage, while 33% of houses with gable roofs received this rating. This represents a significant amount of damage, since about 80% of the houses surveyed had gable roofs.

Hip roofs do not present any flat surfaces to the wind despite wind direction, and the sloping faces of hip roofs enhance the performance of the roofing material (FEMA, 1986). Amirkhanian et al. (1993, Oliver and Hanson (1994), Pilkey et al. (1981), Riba et al. (1994), Sheffield (1993), and Keith (1994) all point to the superior performance of hip roofs. The hip roof generates much less uplift and is structurally better braced than a gable system (Sparks, 1994). Hip roof framing is effective structurally because it laterally braces the primary roof trusses, or rafters, and supports the top of the end walls of the home against lateral wind forces (Keith, 1994). Further, hip roofs eliminate the "hinge" formed between a gable end and gable-end wall. It was noted as early as Hurricane Camille in 1969 that hip roofs outperformed gable roofs (Pilkey et al., 1981). In 1986, FEMA noted that hip roofs appeared to perform best in high-wind areas.

Amirkhanian et al. (1993) note that during Hugo, no hip roof building suffered more than 20% normalized direct wind damage, while among the gable-roofed homes, about 5% suffered direct wind damage of more than 25% of the insured structural value. Hip roofs were common in Hawaii and were found to have performed well during Iniki (Keith, 1994). Hip roofs performed well in South Florida as well. Unfortunately, in South Florida 80% of homes were constructed with gable roofs (Crandell et al., 1994).

Cladding selection and attachment

In hurricane-prone areas, both asphalt composition shingle and clay, and concrete tile, are common roofing materials, and both have proven problematic when exposed to hurricane-force winds. Asphalt shingle is warranted for wind gusts of 60 mph, although performance can be improved by sealing the edges at the roof eaves and rakes with roofing cement, and by using six nails per shingle rather than four nails or staples (Wolfe et al., 1994).

The primary key to good shingle performance is the use of self-seal adhesive, coupled with correct application of fasteners (Smith, 1994). With an adequate number of fasteners, the pull-through resistance of the shingle will determine whether the loss of adhesive seal leads to the shingle being lost. Shingles were attached to roofs using pneumatic staple guns in many cases. Once the wind managed to lift one layer of shingle tabs, the shingles acted as a sail, bending at the attachment and tearing it away. Often the staple remained in place once the shingle was blown away. This would argue for using only nails for shingle attachment. Vognild et al. (1993) observed after Andrew that many fasteners failed to engage the roof structure, or were randomly placed; these observations caused the authors to question the use of staples as fasteners.

The lack of a high-wind-rated composition shingle is a serious problem. FEMA recommends that until such a product is available, a water-resistant membrane - e.g., a hot-mopped underlayment - be installed to protect against water infiltration that could result from loss of cladding (FEMA, 1992).

Although popular for their appearance and their longevity in high-humidity tropical areas, clay and concrete tile roofs did not perform well in hurricanes Andrew and Iniki. The primary and most serious problem was failure of the bond between the mortar and tile. Because of the bonding problem, Smith (1994) questions whether mortar-set tile can safely be used at all in hurricane areas.

A secondary problem was the low ductility of roofing tile. An extensive amount of clay and concrete tile damage during Andrew was caused by flying debris, which included roof tiles among other types of debris. As a tile broke or became dislodged and injected into the wind stream, it was free to impact other tiles, which were also injected into the wind stream, causing a cascading failure. It was not uncommon during Andrew for flying tiles not only to damage roofs, but also to break windows and cause personal injury (Smith, 1994). Because roof tiles (and attaching mortar) are so brittle and easily damaged, Smith suggests that one option is not to use roof tiles in hurricane areas. Instead, metal panels that simulate tile could be used, or tiles could be developed with higher ductility for use in hurricane areas.

Roof sheathing and attachment

HUD (1993) identified roof sheathing as a critical component that locks all other roof members together to form a structural system. Roof sheathing failure was a common problem during hurricanes Andrew and Iniki. During Andrew, almost 25% of houses assessed by HUD had loss or damage to one or more panels of roof sheathing, commonly starting in the gable end (HUD, 1993). Keith (1994) also observed that roof sheathing commonly failed in the region of the gable-end walls, and in all cases he reported failure was due to improper fastenings.

The SFBC requires nail spacing of between 6 inches o.c. and 12 inches o.c., depending on the location of the sheathing panel. But, in sheathing found blown off, nails were spaced much farther apart, and fastening patterns were often erratic, ranging from 10 inches to 48 inches o.c. Further, it was not uncommon to find that staples and nails had been positioned to miss the underlying framing member completely.

Two types of roof sheathing material were common in South Florida: plywood and oriented strand board (OSB) sheathing. Keith (1994) notes that both performed equally well during Andrew. However, Kahn and Suaris disagree, saying that OSB performance was inferior to that of plywood, tending to disintegrate and/or curl at the edges under cyclic wind loading and/or moisture penetration. In Hawaii, OSB is not commonly used, since pressure-treated wood is normally specified.

When sheathing failure did occur during the case-study hurricanes, the usual reason was inadequate or improper fastening (Cunningham, 1994; Keith, 1994). Roof sheathing stayed attached during Andrew and Iniki when properly attached. Cunningham (1994) recommends that a "high-wind" fastener schedule be used. This would consist of 45 nails, spaced 6 inches o.c., except 4 inches o.c. over the gable end, per each 4 x 8 sheet of plywood or OSB sheathing. This is a more rigorous attachment than the South Florida Build Code allowed: 6d common nails 12 inches o.c. along the interior of the panel, and 6 inches along the gable end edge. Cunningham (1994) also recommends that 8d nails be used instead of 6d. Use of the larger nail doubles the withdrawal resistance of the connection, according to tests conducted by Cunningham.

Attachment methods can have an effect on the uplift resistance of sheathing. Riba, et al. (1994), noted after Andrew that some panels appeared to have pulled loose after fastener heads pulled through the panel. They hypothesized that this may have been due to pneumatically driven nails that have only a partial nail head to accomodate the nail collating system on power-driven nail guns. When staples were used, cases were observed in which one leg of the staple missed the underlying truss or rafter. This reduced the strength of the connection by at least 50%. Some staples showed evidence that the staple was driven through the sheathing with excessive force, leaving only a partial thickness of the sheathing to resist the wind. Power nail and staple drivers must be properly adjusted to avoid this problem.

Preventing gable end failure

If a gable roof is chosen for home-building, special care must be taken to strengthen the gable ends. Again, gable roofs are especially prone to damage from gable-end collapse, except when properly braced (Keith, 1994). Gable-end failure seems attributable primarily to poor or nonexistent bracing between gable-ends and the rest of the structure. Gable-end failure was less common in Hawaii during Iniki than in south Florida during Andrew. One reason for this was that Iniki's wind speeds were generally less than Andrew. But another reason, according to Keith (1994), is that in Hawaii gable-ends are braced at the top edge by diagonal and/or lateral bracing from the gable-end to the adjacent roof trusses.

Another factor that mitigated the number of gable-end collapses during Iniki was the use of structural "outlookers" rather than the "ladder-type" framing used in south Florida. Structural outlookers use cantilevered 2x4s oriented flat-wise at roof sheathing joints. These outlookers extend outward from the first interior truss or rafter over "dropped" gable-end wall framing. According to Keith (1994), such framing provides several advantages:

1. Provides bracing of the roof framing at the plane of the roof deck during construction and supplemental distribution of inward and outward forces into the roof "diaphragm" when gable-end walls are subjected to high winds.
2. Provides additional support of roof sheathing at overhanging rake ends. Increases stiffness and strength of cantilevered roof systems to provide added resistance to wind uplift forces, concentrated loads from fascia framing, and foot traffic on the roof deck during construction and maintenance.
3. Increases roof diaphragm shear capacity at the ends of roof decking by creating a "blocked" roof diaphragm in these areas. These blocked areas have greater stiffness and shear load capacity, and the blocking provides improved shear load transfer from gable-end wall framing.
4. Provides additional hold-down attachment points for roof sheathing panels at gable ends where uplift forces are the greatest.

Preventing truss collapse

Roofing systems commonly rely on roof sheathing and bottom chords to provide lateral support for the roof trusses. Oliver and Hanson (1994) and Riba et al. (1994), agree that roofing systems could be considerably improved if simple secondary bracing were installed between trusses. This would reduce the roof's reliance on diaphragm sheathing action alone to provide lateral support. This is especially important when roof sheathing is lost, because nothing remains to prevent truss collapse. Riba et al. (1994) observed that when properly anchored and braced, wood trusses transmitted wind loads to the rest of the building satisfactorily. FEMA (1992) makes the following recommendations regarding roofing systems:

1. Manufacturers of roof tile products should provide testing and verification of tile performance under realistic conditions.

2. Quality control of roof tile installation should be improved by ensuring both consistent mortar pad placements and installation are in accordance with manufacturers' requirements, as specified by the Code. Though this would improve the survivability of roof tile systems, continued debris impact will result in damage occurring from future wind storms.

   The roof should be marked off vertically and horizontally. Interlocking lugged or unlugged tile should be laid with minimum headlaps in accordance with manufacturers' recommendations (2 1/2 - 3 1/2 inches minimum).

   Prefabricated eave closure strips should be used to elevate the butt end of the first, or eave, tile to attain the proper slope.

> A full 10-inch mason's trowel of mortar should be placed under each tile (under the pan section of "S" or barrel tile), beginning at the head of the tile in the preceding course. Each tile should be pressed down tightly in the interlocking position so that the cover rests firmly against the lock of the adjacent tile.
>
> After the roof is laid up completely, traffic should not be allowed on the roof, and no work should be done on the structure that will create vibration in the framing or roof sheathing. At least a 24-hour period is necessary to ensure proper set. Roof traffic should be prohibited for a minimum of 72 hours.
>
> All flashing should be sealed to the subroof for water tightness; otherwise, installation and flashing procedures are the same as those for mechanically fastened tile.

3. The design of more aerodynamic building shapes should be encouraged and promoted. More aerodynamic building systems reduce direct wind forces experienced perpendicular to windward planes of buildings and also the consequent effect of whirling air flows, called vortices, that accumulate at the corners and edges of the planes. The accumulation of both the direct and negative pressures resulting from these wind flows is particularly prevalent in the more abrupt or orthogonal planes of gabled roof systems.

4. The use of braced truss roof systems that will sufficiently resist lateral forces independent of roof sheathing should be required. Roofing systems could be considerably improved if simple secondary bracing of blocking were to be applied within the truss network (thus relieving the roof's reliance on diaphragm sheathing alone).

5. Substituting hip roofs for gable-end is a particularly advantageous solution and should be encouraged. The construction of a hip roof results in an inherently braced roof system.

6. Venting with adequate openings to relieve induced internal pressures on roof structures is recommended. However, venting must be installed in such a manner that the entry of uncontrolled air flow is not allowed. Such uncontrolled air flow could result in a buildup of induced internal air pressure.

Doors and Windows

Modern homes are constructed with more and larger openings than older homes. Entry doors are often double, sliding glass doors replace regular doors, and attached garages often have double-width garage doors to hold two cars. The greater number and size of openings place homes at increased risk from hurricane forces. Sanders (1994) reports that

> Nearly every residential house or apartment [in south Florida] has at least one sliding glass door and frequently more, sometimes placed in adjacent walls. Sliding glass doors are at least 6 feet wide. Typical single family homes have attached garages many with double wide garage doors. Storm shutters for glass openings and doors are very uncommon.

Failure of windows and doors exposes the entire structure to increased force and loads. Issa et al. (1994) estimate that an opening of only 5% in the windward side of a building will allow full pressurization of the interior, exerting uplift pressure on the roof, and horizontal pressure against the interior walls. Because storm shutters for glass openings and doors are very uncommon in south Florida, thousands of houses required interiors and furnishings to be completely removed and replaced because just one sliding glass door failed during Andrew (Sanders, 1994).

Entry Doors

During Andrew, double entry doors often blew out as a result of uncontrolled buildup of internal pressure (Oliver and

Hanson, 1994). As described earlier, French and double doors were especially prone to failure. The most common failure modes were pullout of centerpins, and door leaf shattering near the pin. Pullout was more common with metal doors, while shattering was more common with wooden doors.

Garage Doors

Oliver and Hanson (1994) noted that garage doors tended to be blown in by hurricane-force winds. They recommended that doors be installed with stiffer vertical and horizontal members for reinforcement. Manufacturers should strengthen both the security locking system and door pin to glider track connections to reduce door rotation along the door edges. Individual single-car garage doors should be installed instead of double-car doors.

Windows and Patio Doors

During Andrew, 64% of the homes evaluated by Crandell et al. (1994) had significant window damage. Usually, simple plywood shutters would have provided adequate protection. Whether made of plywood or another material, storm shutters offer the best protection against building envelopes being punctured at windows and at patio doors.

Besides being breached by flying debris, glass patio doors often leak excessively in wind-driven rain (FEMA, 1986). For both debris and rain protection, FEMA recommends that multiple-panel sliding glass doors and windows be avoided, and that individual panel widths be no more than three feet. Further, FEMA recommends that total window and door openings be no more than 30% of a wall's total area.

Patio doors must be properly installed. Wolfe et al. (1994) note that a 40 square-foot patio door is subject to a force of 2,000 pounds when exposed to a 117 mph wind. To adequately resist this pressure, 16d casing nails with a spacing of 20 inches o.c. would be needed.

To reduce window damage from flying debris, laminated window glass may be used. Research by the glass industry has shown that in residential-size windows, 3/8 inch laminated glass anchored to the window frame with a silicone anchor bead can survive both small and large missile impact. Small missiles were represented in testing by steel balls weighing two grams with a velocity of 74 mph. Large missiles were represented by a 9 pound 2x4 traveling at 28 mph (Minor and Behr, 1994).

Storm Shutters

There was no controlled scientific study on the effectiveness of shutters until the work by Mitrani et al. in 1995. This study compared damage to houses that had shutters with damage to houses that did not have shutters; houses were located in the same neighborhood. In one set of compared homes, the shuttered houses sustained from 30.8% to 54.8% less damage than the unshuttered houses in the sample - a significant difference.

Shutter systems can range from simple removable plywood sheets to permanently installed automatic electric systems. Removable shutters are the most common type used in south Florida. These shutters are manufactured from various gauges of either aluminum or steel. For best effect, removable shutters must be well anchored; otherwise hurricane-force winds can remove them easily (Issa et al., 1994). Lag bolts are recommended over nails for installation. Less expensive technology may be adequate, however. Miehe (1991) believes that the use of old fashioned one-inch-thick solid wood shutters and/or the use of temporary 1/2-inch-thick plywood shutters may be the most cost-effective way to protect windows. Permanently installed electrically-driven shutters systems should include some form of manual override in case of power failure.

Shutters are not guaranteed to completely protect windows and other openings. During Andrew, metal gratings and shutters were found that were severely bent or even penetrated by flying debris (HUD, 1993). However, even when damaged, shutters continue to provide protection to openings that would not otherwise be shielded.

FEMA (1992, 1993) makes the following recommendations regarding construction or installation of doors and windows.

1. The specifications for garage doors should be increased to meet a safety factor of at least 2.5.

   Manufacturers' certificates should be required on all garage doors.

2. Window design and protection standards should be developed that require a standard system of design and protection for windows in new buildings. These should include, but not be limited to, consideration of using shutters and precut plywood.

   In areas of greatest exposure to wind-borne projectiles, consideration should be given to the use of in-place shutters or emergency protection devices, increased use of shatter-resistant transparent material, a reduction in the use of glazing, and improved adherence to adequate attachment procedures.

   The specifications for windows and glass doors should be stated such that the design criteria for wind loading are the same as those for the structure itself.

   The adequacy of the engineering design and method of attachment of windows and sliding transparent doors of all types should be reviewed by manufacturers for applications in areas subject to wind exposure. Wind loads should be adequately transferred to the supporting structure.

3. The installation of entire garage door assemblies should be reevaluated for strengthening to resist wind and flood loads.

   In order to reduce the effects of the wide spans of two-car garage doors, the doors should be manufactured to include mullions and girts. Also manufacturers should reinforce both the security locking system, to provide a wind-force resistant latch, and the chain of the door pin to glider track connections, to reduce rotation of the door along its edges.

   Glider tracks and track supports should be strengthened to prevent failure caused by door deflection under wind loads.

   Window design and protection standards should be developed that require a standard system of design and protection for windows in new buildings. These should include, but not be limited to, consideration of using shutters and precut plywood. The protection of windows in existing buildings should be encouraged.

Walls

Miehe (1991) concluded from examining damage from Hurricane Hugo that, in almost all cases, wall failure was the result of other failed components: roofs, windows, or doors. Nevertheless, walls must be constructed to perform the critical function of transferring stress from the roof to the foundation.

Wood-frame walls

Two methods exist for bracing wood-frame walls: diagonal bracing, and sheer-wall bracing. Diagonal bracing usually consists of strips of lumber or metal straps applied at a 45-degree angle across the studs. Cross diagonals, consisting of crossing strips or metal straps, can further increase strength. Sheer-wall bracing consists of a continuous cover of plywood paneling over the studs. Sheer-wall bracing is the most effective method, and when properly applied, can also provide an effective load path from the roof to the sill plate (Pilkey et al., 1981).

FEMA (1992) makes the following recommendations for construction of wood-frame buildings:

1. Designers and plan reviewers should pay greater attention to lateral load transfer mechanisms because of high lateral loads generated by hurricane winds.

2. At the construction stage, greater attention must be paid to the proper installation of all lateral load transfer mechanisms inherent in conventional building framing, especially hurricane straps and clips.

Concrete block walls

Concrete block construction has structural advantages over wood-frame construction in that there are fewer joints, and elements are more robust. Wall construction is not reliant on nailed joints, and the bond beam is more in line with structurally engineered buildings than wood framing typically is (Reardon and Meecham, 1994).

Concrete block walls must be reinforced. Pilkey et al. (1981) say that "there is no excuse for building an unreinforced concrete block or brick masonry house near the coast." Of all house construction materials, unreinforced masonry is the most vulnerable to forces other than gravity. Masonry walls simply cannot withstand the lateral forces of a hurricane.

The SFBC requires that reinforced tie beams be placed around the perimeter walls of each floor and at the roof. The tie beams must be a minimum of 8 inches wide and 12 inches deep, with four 5/8-inch reinforcing bars and two to four bars per tie beam, depending on whether U-block or poured-in-place construction is used. Tie columns, containing four 5/8-inch bars each, are required at all corners, next to any opening higher than 8 feet, and no more than 20 feet o.c. otherwise. The North Carolina State Building Code differs, specifying that rafters and joists be anchored to the footing with 5/8-inch reinforcing bars not more that 8 feet apart, and no more that 2 feet from each corner (Pilkey et al. 1981).

These requirements are much less stringent than building codes in some other hurricane-prone areas. In Australia, for example, normal practice would be to use 12 mm (1/2 inch) rod and fill every sixth block core and every core next to an opening. Reinforcing rods lap a starter rod set in the floor slab and are tied into the tie beam at the top of the wall (Reardon and Meecham, 1994)

FEMA (1992) makes the following recommendations for masonry wall construction:

1. A tie-beam of reinforced concrete should be placed in all walls for unit masonry, at each floor or roof level, and at such intermediate levels as may be required to limit the vertical heights of the masonry units to 16 feet.
2. The use of concrete tie-columns at all corners, and at intervals not to exceed 20 feet on center of columns, should be reviewed as a Code improvement. The maximum area of wall panels of 8-inch-thick unit masonry as measured between concrete members which frame the panel, such as the tie-beams and tie-columns, should not exceed 256 square feet.
3. Masonry walls with continuous tie-beams should be engineered and constructed to support the specific architecture of the building. This includes consideration of freestanding cantilevered wall systems for elements such as fire walls that have discontinuous tie-beams.
4. Bracing with struts or pilaster columns in walls perpendicular to the freestanding walls, or adequate reinforcing on the walls sufficiently anchored in the foundation or story below, must be engineered and installed.
5. Greater emphasis should be given to the transfer of loads to concrete slabs and masonry walls from wood framing. For example, the use of cut nails in lieu of bolted masonry-to-wood connections must be eliminated. Also masonry-to-wood straps must be properly located.

Foundations

Foundations are at relatively low risk from wind forces, but are at higher risks from water forces in wave erosion zones and flood zones. In flooding and wave erosion zones, homes are typically elevated above base flood elevation (BFE), defined as the elevation having a 1% chance of being reached in any given year. The primary methods that can be used to elevate homes in hurricane hazard areas are piers, posts and columns, and pilings. FEMA (1986a, 1995) makes several recommendations for their use.

Piers, which are the most common elevation support structures, are shallow supports installed in pre-dug holes. Piers are vertical support members supported entirely by reinforced concrete footings and designed primarily for vertical loads. Piers generally have shallow embedment, with footings extending only slightly below the frost line.

Piers can be used in areas with little velocity flow and shallow depth flooding. Because of shallow embedment, piers should not be used in areas where scour is a factor. The minimum standard for masonry block piers is 12 inches by 12 inches, with footings that are no smaller than 24 inches by 24 inches, and no less than 8 inches deep. Whether block or poured-in-place concrete, piers should have steel reinforcing in both the pier and the footing. Piers offer the least lateral strength of the three elevation methods. Pier height should not exceed the shortest horizontal dimension of the pier by more than 10 times (Pilkey et al., 1981).

Posts and columns can be used in areas of moderate velocity flow and depth. Posts and columns differ only in size and application. Posts are smaller and can be made of wood, steel, or precast reinforced concrete. They are installed in pre-dug holes that are then backfilled with earth, crushed stone, or gravel. Posts are usually square, making attachment to the house superstructure easier. While piers act as individual support members, posts must normally be braced. There are several techniques that can be used: wood knee and cross bracing, steel rods, and guy wires.

Piles provide the most protection against flooding. Unlike posts, columns, and piers, piles are driven, or water-jetted, deeper into the ground, making piles less susceptible to high-velocity flood waters, scouring, and debris impact. Piles are more slender than posts and usually made of wood, but steel and concrete piles are used in some areas. Wood is the most common material for residential piles, however.

The most common piling sizes acceptable for coastal areas are 8-inch and 10-inch diameters. Eight-inch is the minimum size generally approved for high-wind areas. In areas where the design wind speed is greater than 100 mph, 10-inch piles should be used (FEMA, 1986).

Driven piles offer superior pullout resistance to piles that are water-jetted in. When piles are driven, the driving process forces soil outward. This compresses the soil and increases friction between the soil and the pile. Jetting, on the other hand, loosens the surrounding soil, and the soil by the tip of the piling. This reduces the load capacity of the pile, and produces a void around the pile that must be filled (FEMA, 1986).

Because piles must resist the greatest storm forces and resulting loads, proper installation is essential. Piles must resist downward loads from the weight of the building, upward loads due to wind or flooding uplift, and lateral forces from both wind and water. Piles must either rest on bedrock or be driven deeply enough so that friction transfers the vertical load to the surrounding soil. The following factors must be considered when deciding proper embedment depth (FEMA, 1986):

1. pile depth necessary to resist vertical, uplift, and horizontal loads;
2. anticipated scour depth or elevation at the site;
3. existing ground elevation;
4. base flood elevation.

Proper embedment is the most critical factor in pile installation. Standard construction practice for determining pile embedment is inadequate in many areas. Rules of thumb such as "piles should be embedded as much below ground as above ground" generally underestimate the required embedment depth and have not taken scour into effect (FEMA, 1986).

Soil load bearing is a key factor in determining proper embedment depth. In poor soil, longer piles must be used. Pilkey et al. (1981) roughly categorize soils into three types:

1. Below average soil - soft clay, poorly compacted sand, and clays containing a large amount of silt. Vertical bearing capacity is 1,500 psf, and lateral bearing capacity is 100 psf per linear foot of embedment.
2. Average soil - loose gravel, medium clay, or any more compact composition. Vertical bearing capacity is 3,000 psf, and lateral bearing capacity is 200 psf per linear foot of embedment.
3. Good soil - compact, well-graded sand and gravel, hard clay, and graded fine and coarse sand. Vertical bearing capacity is 6,000 psf, and lateral bearing capacity is 400 psf per linear foot of embedment.

As a guideline, FEMA recommends that piles in wave and erosion zones penetrate sand to a depth of 5 feet below mean sea level, if the base flood elevation is less than 10 feet above mean sea level. Mean sea level is the expected height of water plus waves. If the home is elevated more than 10 feet above mean sea level, then piles should extend to at least 10 feet below mean sea level. FEMA's *Coastal Construction Manual* contains more detailed design tables for determining pile size selection and embedment depths.

To withstand horizontal forces, piles must be cross-braced with knee braces, trusses, or grade beams. Bracing members are as important to the structural resistance of the foundation as the piles themselves. For homes elevated about 8 to 10 feet, FEMA recommends diagonal or knee braces, sized according to construction tables in the *Coastal Construction Manual*. Truss bracing is recommended when a home is elevated more than 10 feet above grade, or when the design wind speed is greater than 100 mph.

Grade beams are a third method of pile reinforcement. Grade beams are horizontal supports such as 8x8's connecting the piles around the perimeter of the home at ground level. FEMA notes some disagreement regarding the use of grade beams. One view is that the use of grade beams increases wave forces on the piles, and scour around the foundation. FEMA recommends their use, however, noting that the stiffer foundation system more than offsets the risk of additional scouring. It is important to note that all bracing must be installed with bolts and not nails (FEMA, 1986).

Connections

The most critical aspect of building in hurricane hazard areas is the method of connecting the structural members. Pilkey et al. (1981) note that wood is one of the best materials for absorbing short-duration loads such as those caused by wind, but the strength of wood cannot be used to advantage if the members are not adequately attached to one another.

Construction in hurricane hazard areas must differ from construction in less hazardous areas. In conventional construction, buildings are designed to support primarily vertical loads: the weight of the building, its contents, and inhabitants. Under normal conditions, these gravity loads comprise the primary stress applied to the structure.

Significant horizontal forces may be applied to structures in hurricane hazard areas. Pilkey et al. (1981) recommend that structures in hurricane hazard zones be built with the assumption that a horizontal or uplift force of at least 25% of the vertical load on a structural member may be applied to the structure during a hurricane.

The key for enabling the structure to resist these loads is to adequately connect, or anchor, each element of the structure to the adjacent element. FEMA (1986) notes that an anchorage system should adhere to the following criteria:

1. withstands all anticipated forces without structural failure;
2. continues to perform satisfactorily when materials are wet, as well as under wetting and drying conditions;
3. is protected to withstand corrosive conditions without loss of strength for many years, preferably for the lifetime of the building;
4. is readily available and requires only normal carpentry for installation.

Connectors must be properly selected according to application, adequate in size and number, and properly attached. Wolfe et al. (1994) conclude that the extent of the damage resulting from Hurricane Andrew was not due to any inherent weakness in wood-frame buildings, but was due in part to misapplied connections. Manning and Nichols (1991) concluded after examining damage from Hurricane Hugo that most of the roof damage was due to the failure of connectors that were inadequately sized. Improper connections were the cause of most roof failures during Hurricane Alicia (1983) as well. Wall failures during Alicia were attributed to inadequate connections between roofs and walls, and between walls and floor plate, deck, and floor joists (AIRAC, 1989).

Simple nailing, especially toenailing, is not adequate in hurricane hazard areas. Bolts, lag bolts, or nails at right angles to the direction of force provide the greatest factor of safety. Lag bolts offer a significant advantage over nails. According to Issa et al. (1994) the smallest lag bolt has more that four times the withdrawal resistance of the largest nail. Toenailing provides an especially weak connection because of the tendency of the nail to split the wood in the toenailed member (Pilkey et al., 1981).

Roof-to-wall connections are the most important. This is not only because of the large uplift forces that may be at work on the roof, but also because the number of connections is limited to the number of roof rafters or trusses in the system. At lower levels in the structure, the number of possible connections is greater. For example, in wall construction, nailed plywood sheathing can be used to supplement strap connections between roof and wall, and wall and sill plate.

Galvanized connectors, also called "hurricane straps," are the most common connectors used in hurricane hazard areas. The straps come in a variety of shapes, but typically connect the rafter or truss to the top plate or wall stud. The strength of hurricane straps lies in the fact that the nails used to hold the strap in place are always at right angles to the wood members to which they are attached.

Wall-to-foundation connections transfer uplift forces on the roof downward to the foundation. Plywood sheathing can act as an effective connector. It is important that the sheathing be nailed into the top plate of the wall, and to the floor joists at the bottom. If the sheathing is only nailed to the bottom plate, the connection will be inadequate because the nails that hold the bottom plate to the floor joists lie in the same plane as the uplift forces that must be resisted; the bottom plate may simply pull off. This connection's strength depends on the number of nails used (FEMA, 1986).

North Carolina coastal building standards, designed for building survival in 120 mph winds, provide a good example to follow for connecting roofs to foundations. According to AIRAC (1989), the standards require that

1. every other rafter be tied to the ceiling joist and studs with a metal tie;
2. rafters be braced with collar beams and horizontal braces to ceiling joist; and
3. secure connections using a combination of wind anchors, plywood or steel rods be provided from the rafters down through the floor joists or beams.

Considerations when selecting fasteners

Connectors made of metal are the most commonly used. However, in coastal areas this presents a problem. Coastal areas have a highly corrosive atmospheric environment, because of inland transport of salt spray by the wind, combined with generally higher moisture levels in the air. All metal connectors are subject to corrosion over the life of the structure. In this environment, the typical life of fabricated metal connectors is five to 10 years (FEMA, 1986). While pre-galvanized connectors work well in protected areas of the structure, galvanized connectors are preferred in exposed parts of the building. Recently, stainless steel connectors have become available, and offer the greatest protection against corrosion. Detailed information on connector selection and application can be found in *Standard for Hurricane Resistant Residential Construction (SSTD-10)*.

POST-CONSTRUCTION RETROFITTING

Preparing a home to withstand hurricane forces is best begun before construction, when mitigation techniques can be incorporated most economically and effectively . However, this does nothing to protect the enormous inventory of existing homes in hurricane hazard areas.The options for improving the storm-worthiness of homes are limited once homes are constructed; nonetheless, some steps can be taken.

According to FEMA (1986), additional rigidity and stability of a gable roof framing system can be provided by installing 2x4's on 2-foot centers between the roof rafters or trusses, for about 8 feet at each end of the house. These will not only strengthen the roof, but will provide additional nailing surface for roof sheathing materials. Using construction adhesives in addition to nails when installing roof sheathing will also improve uplift resistance.

Pilkey et al. (1981) offer several recommendations for strengthening existing homes. Steps can be taken in flood and erosion zones to improve anchoring the house to the ground. Piles can be driven in at the corners of the house and anchored to the structure if the configuration of the house allows it. Taking a technique from mobile home anchoring, screw anchors can be inserted into the ground and connected to the house. If a vertical anchor is used, Pilkey et al. (1981) recommend encasing the top 18 inches in a 12-inch diameter concrete cylinder to prevent the top of the anchor rod from bending or slicing through wet soil from the horizontal component of the pull.

Pilkey et al. (1981) recommend anchoring accessible roof rafters and trusses to the wall system. Except where they meet the walls, roof trusses and braced rafters are usually sufficiently exposed to make it possible to strengthen the joints, particularly at the peak of the roof, with collar beams or gussets.

Pilkey et al. (1981) also recommend bracing or strengthening interior walls if possible, even if this means removing the surface covering. Plywood sheathing or strap bracing should be installed to the extent possible once the wall studs are accessible. Because straps are only good for resisting tension loads, 1x6 lumber with three 8d or 10d nails per stud and wall plate can be used at points where compression loads may be a factor. Bracing should also be provided at right angles to the loaded surface at about 12-foot centers.

Cook et al. (1994) suggest that the highest priority for retrofitting is the protection of openings with shutters or impact resistant glazing. In high wind areas, better attachment of roof sheathing is also important. This retrofit is easily accomplished when re-roofing a building. Once old roofing is removed, sheathing can be renailed to a more rigorous schedule, and a wind-resistant roof covering can be installed. Calfee (1995) goes a step further and recommends removing sheathing at the time a house is re-roofed, and installing hurricane clips. Cook et al. (1994) recommend requiring that roof sheathing be renailed as part of the permit process for re-roofing buildings. The following are potential ways to retrofit:

1. add shutters for glazed openings
2. renail sheathing
3. create a secondary water barrier
4. provide support for sliding glass doors and double doors opening to the outside
5. improve anchorage of windows to openings
6. add ridge ventilators to reduce uplift of roof sheathing
7. strengthen garage doors and particularly double-wide garage doors
8. improve connections of porch roofs and overhangs
9. anchor adjacent structures, including privacy fences, pool enclosures, and patio roofs

Gaus et al. (1993) offer several examples of steps that could be taken by a homeowner to reduce the risk of hurricane damage to the home. It is not possible simply to renail a roof with suspect sheathing to joist or truss connections. However, a bead of construction adhesive could be applied from within the attic with a caulking gun to each side of the roof rafters or trusses to form a connection with the sheathing. This connection, in the opinions of Gaus et al. (1993) would be at least as strong as that provided by common forms of nailing.

The homeowner could also brace gables and rafters. Tension straps could be directly fastened to roof members in readily accessible areas. Adhesives could be used where there is insufficient access.

CONCLUSION AND RECOMMENDATIONS

Trends in population growth and relocation, increase in the rate of hurricane formation as the multi-decade hurricane cycle moves upward, and long-term climate change all point to increased residential damage from hurricanes in the future. With large-scale population shifts to sunbelt states, Florida in particular, and the increased popularity of coastal areas of other states, an increasing housing inventory is now at risk from hurricane damage. The observed 20-year hurricane cycle seems to be moving into its more active phase, increasing the likelihood of more intense hurricanes forming over at least the next decade, and possibly beyond. Studies on global warming suggest an increase in the frequency, intensity, and range of intense hurricanes as the oceans warm, and the pool of warm ocean water that fuels hurricanes spreads farther from the equator.

Recent hurricanes have proved that inland areas, as well as coastal areas, are at risk from hurricane damage. Hugo, a large fast-moving storm, carried hurricane-force winds inland as far as Charlotte, North Carolina. Storms such as Hugo, Andrew, and Iniki have also shown that wind, by a large margin, is responsible for most of the damage and property loss experienced from hurricanes.

Recent hurricanes have exposed the vulnerability of many existing homes located in hurricane hazard areas. Roofs are especially vulnerable to damage. Once roof damage begins, the rest of the structure often succumbs to progressive stages of failure. Wind-borne debris has proved to be a significant cause of damage, and windows and doors have been shown to be vulnerable and usually unprotected.

Current state-of-the-art home construction is adequate, with the exception of wind-resistant roof cladding, to produce homes that can withstand presumable hurricane forces. Unfortunately, homes in hurricane hazard areas have not been designed or constructed with hurricane survivability as a key requirement. Much of the damage inflicted by hurricanes Hugo, Andrew, and Iniki could have been avoided by the application of affordable, straightforward, construction techniques.

There are three areas which, if addressed, will significantly increase the survivability of homes in hurricane hazard areas.

First, roofs must be designed and constructed to remain intact and attached to the rest of the structure during storms. Progressive failure of homes began only after the roofs were damaged or lost in almost all cases observed. Currently technology in roof cladding does not guarantee that roof shingles and tiles will remain attached. But proper roof design and the proper use of fasteners to attach sheathing to roof, and roof to walls, can ensure that in most scenarios the roof will remain structurally intact and attached.

Second, properly connected load paths must be recognized as a key requirement during home design and construction. Homes must be regarded by builders not only as affordable, aesthetically pleasing dwellings, but also as engineered structures that must transfer often enormous external forces from the structure to the underlying earth. In other words, architects and builders must design and build beyond the requirements of only gravity loads. Powerful dynamic forces assault a residential structure during a hurricane. Homes must be designed and constructed to transmit these forces away from the structure.

Last, wind-borne debris must be recognized as a significant factor in home damage, and even structural failure. Once the envelope of a home is punctured by debris, the interior of the home is exposed to the same forces of wind and water as the exterior. On the one hand, steps should be taken to reduce or control potential sources of debris. At the same time, homes should be constructed or retrofitted to strengthen doors and protect windows against debris penetration.

Steps must be taken to protect the current inventory of constructed homes in hurricane hazard areas. Building codes in many hurricane hazard areas have not ensured hurricane survivability, even when storm forces have been within the design requirements of the codes. In short, building codes, even when adequate, have failed to protect homes due to poor adherence by builders and inadequate enforcement by government agencies. The existing homes in risk areas must be regarded as suspect in construction because of this. Inspection techniques should be developed to enable identification of construction faults in existing homes.

Many of the steps that can be taken to increase the survivability of homes are most effectively taken during the construction phase. Some post-construction steps can be taken that will strengthen residential structures. However, there are currently no agreed-upon standards for effective retrofitting. Research should be undertaken to identify and validate effective retrofitting techniques, and efforts should be made to communicate that information to homeowners and building contractors.

Specific Recommendations

1. During construction, a waterproof barrier coat should be applied to roof sheathing before the attachment of

cladding because no current roof cladding, either tile or asphalt composition shingle, can be relied upon to provide a barrier against the incursion of rain in high-wind environments. The waterproof barrier coat should be regarded as the sole waterproofing element of the roof membrane and applied accordingly. As a retrofit, a waterproof membrane should be applied to roof sheathing when re-roofing is done.

2. Re-roofing should be regarded as an opportunity to significantly strengthen a roof against wind loads. As necessary, roof sheathing should be removed so that underlying rafters, trusses, and gable ends can be reinforced with hurricane clips. When roof sheathing is reattached, it should be re-nailed using a wind-resistant nailing schedule.

3. Use of staples should be prohibited in hurricane hazard areas. Staples have been shown to be unreliable as fasteners for roof cladding and roof sheathing.

4. Homes must be made more resistant to damage from wind-borne debris. Storm shutters should be required for all new residential construction. To encourage manufacture of affordable storm shutters, standardized window sizes should be required for all new construction. Efforts should be made to encourage owners of existing homes to install shutters.

5. The amount of wind-borne debris must be reduced. A significant step in this direction would be to prohibit the use of roofing tile in any new construction in hurricane hazard areas until bonding technology is available that can ensure adequate adherence during high-wind events.

6. The building of more aerodynamic homes should be encouraged. Hip roof construction should be encouraged over gable roofs. Cantilevered elements such as balconies and large overhanging eaves should be discouraged.

7. Self-help information should be made available to homeowners. While retrofitting is necessarily less comprehensive than steps taken during initial construction, significant improvements can be made by the homeowner. These include strengthening roof bracing and connections from within attics, shuttering windows, and strengthening foundation connections on elevated housing in wave erosion and flood zones.

8. Homeowners in hurricane hazard areas should be provided with the information necessary to understand the nature of the hurricane hazard and to assess the degree to which their homes are at risk. Homeowners cannot be expected to address the risk of property loss if not first educated to understand it. This is an area in which governmental agencies and the insurance industry could be especially effective.

9. Governmental agencies, especially local governments, must accept their responsibility to the public to rigorously enforce building codes. Building codes are only effective when followed. Too much of the damage from recent hurricanes is attributable to substandard construction.

GUIDE TO TERMINOLOGY

Bottom Plate (Sole Plate)
: The lowest horizontal member of a wall or partition that rests on the subflooring. The horizontal member under wall studs.

Cantilever
: A projecting structure, such as a beam, that is supported at only one end.

Chord
: The horizontal member of a truss connecting corners.

Cladding
: Materials that form the external covering over the structural elements and are directly loaded by the wind;

includes roofing, roof sheathing, siding, wall sheathing, and window glazing.

Collar Beam
A horizontal tie beam in a gable roof, connecting two opposite rafters at a point considerably above the wall plate.

Concrete Block and Stucco (CBS)
A wall construction system common to the southern United States comprising a stucco finish over block or concrete masonry units.

Continuous Load Path
Structural elements and connections that transmit vertical and horizontal loads from the roof to the foundation.

End Wall
Exterior wall oriented perpendicular to the roof ridge or long axis of a building.

Footing
The concrete (usually) base for foundation walls, posts, chimneys, etc. The footing is wider than the member it supports, and it distributes the weight to the ground over a larger area to prevent settling.

Gable End
The triangular portion of the end wall of a house with a pitched roof.

Hip Roof
A roof framing method that provides a sloped roof down to the supporting walls along all sides of the building.

Joist
One of a series of parallel framing members used to support floor or ceiling loads, and supported in turn by larger beams, girders or bearing walls, or foundation.

Lateral Bracing
Bracing that resists lateral or sideways displacement of a structural assembly; may be achieved by diaphragm action or secondary bracing such as diagonal braces.

Rafter
One of a series of structural members of a roof, designed to support roof loads.

Rake Overhang
Sloped edge of a roof that extends beyond the gable end.

Ridge Board
Central framing member at a the peak, or ridge, of a roof. The roof rafters frame into it from each side.

Roof Cladding
The overall system of underlayment material (e.g., building felt) and the topmost roof covering (e.g., tiles and shingles) that are installed in sequential stages.

Sheathing
Plywood, boards, sheet steel, or similar materials that cover the outside of a building frame and tie individual structural members together to provide diaphragm action when properly connected to structural members.

Sill (Mudsill, Sill Plate)
The lowest framing member of a structure, resting on the foundation and supporting the floor system and the uprights of the frame.

Soffit
: Underside of a roof overhang.

Studs (Wall)
: Vertical members (usually 2x4's) making up the main framing of a wall.

Subflooring
: Bottom layer of plywood in a two-layer floor.

Top Plate
: The uppermost horizontal member nailed to the wall or partition studs. The top plate is usually doubled with end joints offset.

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