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Andrew

U.S. Department of Housing and Urban Development
Office of Policy Development and Research

Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki

Acknowledgements

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Foreword

As the populous coastal regions of the United States continue to expand, the increasing risk of devastation by hurricanes demands our exacting attention. The damage to homes caused by Hurricanes Andrew and Iniki bears painful testimony to this concern. Yet the destruction reaches far beyond physical damage, inflicting emotional and economic changes on the people and communities during a long and continuing reconstruction process.

This report, *Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki*, evaluates the performance of houses damaged by these hurricanes. Extensive data collection, statistical analysis, and observations provide a realistic perspective on the damages that can guide decisions related to housing in hurricane-prone areas. While comprehensive in detail, this report also identifies the major problems in home construction that can lead to productive improvements in hurricane resistant housing.

We hope that the report will provide a useful resource to enhance the durability of homes subject to hurricanes in a manner that rationally balances the important social issues -- the preservation of life, property, and affordability.

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EXECUTIVE SUMMARY

On August 24, 1992, Hurricane Andrew struck South Florida producing an estimated $20 to $25 billion in damage to a heavily populated area of Dade County in the suburbs south of Miami. The cost of this damage is not, in itself, sufficient to describe what is recognized as the most costly natural disaster in the history of the United States. Hurricane Andrew continued across southern Florida, the Gulf of Mexico, and then struck the Louisiana coast causing an additional $1 billion in damage. On September 16, 1992, just 16 days after Andrew, Hurricane Iniki struck a direct blow to the Hawaiian Island of Kauai causing an estimated $1.2 billion in damage.

In one hurricane season these two events provided a revealing test of the strength of building construction in the United States. Many facets of the construction process were tested by the severe winds and storm surge, including structural and architectural design, building codes and enforcement, workmanship, building product approvals, and all other aspects affecting the final building product. Also put to the test was home owner preparedness and public policy on acceptable levels of risk.

In response to the opportunity to learn from these disasters, the U.S. Department of Housing and Urban Development (HUD) initiated this unique damage assessment of single-family homes to better understand how different types of residential construction fare under hurricane conditions. The primary goal of this study is to provide an impartial assessment of the damage to single-family homes caused by Hurricanes Andrew and Iniki. To this end, over 500 homes in Florida and 160 homes in Kauai were subject to detailed assessment of housing characteristics and damages. Many other homes, including those damaged in Louisiana by Hurricane Andrew, were also observed to capture unique aspects of the housing populations and the damages sustained.

The assessed homes were subject to some of the most severe winds of Hurricanes Andrew and Iniki. The winds in these events exceeded the design specifications of all U.S. building codes and standards. Widespread water damage was the most costly factor in the damages for both South Florida and Kauai where 65 percent and 40 percent of the surveyed homes, respectively, suffered severe water damage to their interiors. Significant structural damage (e.g. a collapsed roof) occurred in less than 20 percent of the sampled homes affected by the worst winds of both hurricanes.

The analysis of hurricane damage to single-family homes in this study reveals three characteristics of a typical home, which have the greatest influence on the overall resistance to hurricane damage:

- Opening protection (windows and doors)
- Roof coverings
- Roof sheathing attachment

It is recognized that the hurricane resistance of a home is dependent on all components of the system. However, the three characteristics above were consistently found to be the weakest links in the assessed homes. Improvements in these areas will have the greatest impact on limiting the damage to single-family homes under hurricane conditions.

Window and door damages contribute substantially to increased levels of water damage as well as to a greater potential for structural damage through internal pressurization. Internal pressurization from wind entering a breached opening can effectively double the wind loads on structural components such as roof sheathing. In the Florida survey, 64 percent of the accessible homes experienced damage to at least one window. In most homes surveyed, it was apparent that little regard was given to proper window protection. In most instances of window damage, it is likely that a simple but effectively applied plywood covering would have provided the needed protection.

Damage to roof coverings also contributed heavily to the high levels of water damage experienced. In Florida, 77 percent of the homes were judged to have sustained significant damage to the roof coverings. Roof covering problems were most commonly associated with conventional composition shingles and, in Kauai, corrugated metal roofing as well. These materials were not designed to withstand the conditions experienced in Hurricanes Andrew and Iniki, although composition shingles are the most widely used and affordable roofing materials in most areas of the United States.

Where it occurred, most structural damage in Florida, Louisiana, and Kauai was related to the roof systems. Roof structural problems were most evident in gable-roof homes, which experienced much greater damages than hip-roof homes. Considering only single-story homes in the Florida survey, about 33 percent of the gable roofs were rated in the highest level of roof damage (e.g., one or more severely stressed gables and several missing sheathing panels). Only 6 percent of the hip roofs received this rating. Since gable-roof homes comprise about 80 percent of the houses surveyed in Florida, they provide a focal point for analyzing the detailed structural problems in homes.

While gable roofs are more susceptible to damage, the basic problem in most cases was inadequate attachment of roof sheathing at the gable ends. Roof sheathing is a critical component that locks all other roof members together to form a rigid structural system. The significance of roof sheathing is best illustrated in the Florida survey where almost 25 percent of all assessed homes experienced the loss or damage of one or more panels of roof sheathing, commonly starting at the gable end.

Walls and foundations contributed to only a small portion of the overall structural damages. The performance of wood-frame walls depended on the integrity of the roof system to a much greater degree than reinforced concrete and block walls. As a result, wood-framed walls observed in Florida case study homes exhibited more susceptibility to wind damage. Of the limited number of wood-frame walls observed, damage was often related to deficient connections, particularly at the corner top plate joint—even when the roofs were still intact. Use of non-structural siding and tall, steep roofs also contributed to damage of the wood-frame walls observed.

In summary, the damages experienced in Florida, Louisiana, and Kauai were caused by several intertwined factors. The principle factors or causes relevant to the damages discussed in this report are:

- Construction (workmanship, inspection, and building code requirements)
- Design (aesthetic and structural elements)

- Building products and materials (performance standards and building code requirements)
- Preparedness (home owner awareness, preparation, maintenance, and training)
- Acceptable risk policy (with respect to probable extreme wind speeds and storm surge in coastal areas)

While some of these factors may be viewed as more significant than others in influencing the level of damage from hurricanes, they all have the potential to seriously affect the cost of housing as well as the protection of property in hurricane-prone areas. The most beneficial policies for the public at large will require a rational balance between the cost and the degree of protection afforded to homes. Meanwhile, the protection of lives should retain its essential function through distinct measures related to hurricane forecasting, evacuation, and storm shelters.

With the above factors in mind, the following recommendations are suggested in accordance with the observations and analyses conducted in this investigation:

1. Improved compliance to wind resistant construction practices is needed. Multidisciplined efforts to assure compliance to existing wind resistant building code measures should be prioritized above all other corrective alternatives. This effort includes establishing adequate training and accountability for all participants in the building process.
2. Improvements in building code requirements related to hurricane resistance are recommended according to the findings in this report. Careful examination of building codes should focus on major contributors to damage (structural and water) identified in this report, including roofing, roof sheathing attachment, and window protection. Each proposed modification should be carefully considered for its relative cost vs. benefit before implementation. Affordable housing should be maintained through rational amendments to building codes. One possible approach involves a differentiation between houses with higher risk characteristics that may require special engineering, and those with lower risk qualities that can be more effectively administered and constructed through easily understood, cost-effective prescriptive provisions.
3. Programs to inform and train home owners in effective measures to prepare their homes for impending storms should be instituted in hurricane-prone areas. All residents and property owners should be accountable for basic preparatory actions. Evacuation procedures and storm shelters should continue to receive high priority.
4. Research efforts to improve the technical understanding of extreme wind events and near-ground wind effects on buildings should be prioritized. Wind engineering design procedures should include the effects of topography and projectiles.
5. Industry involvement in the investigation and development of cost-effective, wind-resistant construction methods and materials should be encouraged, particularly in the areas of roof coverings, window protection, and structural connections.
6. Standardized procedures for assessing and reporting damage in future hurricanes and other natural disasters should be developed and improved. The objective techniques used in this investigation should be considered in such an effort. Multivariate analysis techniques should be considered to improve the explanatory power within the damage database.

INTRODUCTION

On August 24, 1992, Hurricane Andrew struck South Florida producing an estimated $20 to $25 billion in damage to a heavily populated area of Dade County in the suburbs south of Miami. The cost of this damage is not, in itself, sufficient to describe what is recognized as the most costly natural disaster in the history of the United States. Hurricane Andrew continued across southern Florida, the Gulf of Mexico, and then struck the Louisiana coast causing an additional $1 billion in damage. On September 16, 1992, just 16 days after Andrew, Hurricane Iniki struck a direct blow to the Hawaiian Island of Kauai causing an estimated $1.2 billion in damage.

In one hurricane season these two events provided a revealing test of the strength of building construction in the United States. Many facets of the construction process were tested by the severe winds and storm surge, including structural and architectural design, building codes and enforcement, workmanship, building product approvals, and other aspects affecting the final building product. Also put to the test was home owner preparedness and public policy on acceptable levels of risk.

In response to the opportunity to learn from these disasters, the U.S. Department of Housing and Urban Development (HUD) initiated this unique damage assessment of single-family homes to better understand how different types of residential construction fare under hurricane conditions. The study involved a team of eight people who worked almost two weeks collecting field data and documenting damage in Florida, Louisiana, and Kauai. Tasks required to implement the damage assessment survey are listed in Appendix A.

This report is presented in two parts—Part 1 is devoted to Hurricane Andrew and Part 2 addresses Hurricane Iniki. The objectives of this report are to:

1. Present statistical data and qualitative observations on the overall performance of the housing stock in the South Florida, Louisiana, and Kauai hurricane damage zones;
2. Present case studies on the performance of several construction types, materials, and practices, and on specific failure modes;
3. Evaluate and compare applicable building code and engineering provisions that control single-family residential construction in hurricane-prone areas; and,
4. Provide credible information and recommendations that will improve the understanding of causes and effects of hurricane damage, and will provide a sound basis for decisions related to improving the hurricane resistance of housing.

BACKGROUND

WIND CHARACTERISTICS

This report focuses on the hurricane resistance of low-rise residential structures, specifically single-family homes. This section presents a general review of wind theory as it relates to such structures to provide a basis for understanding the discussions in this report. A glossary of terms used in this report is contained in Appendix B.

Two key elements are necessary to establish an acceptable level of risk of damage by wind. The first element entails the characteristics of wind and the second is the long-range probability of an extreme wind event or storm. Defining the characteristics of extreme winds and predicting their occurence involves statistical analysis of historical wind records, meteorological modeling, and wind engineering and research, all of which are based on a limited amount of extreme wind data (i.e., hurricane winds).

The ability to determine wind loads on buildings must be viewed with respect to an imperfect understanding of wind and near-ground wind effects. Near-ground wind effects are the most variable of all meteorological elements.[1] This variability, coupled with limited empirical data on near-ground wind effects and problematic weather records pertaining to wind, result in "ballpark" wind information for designing structures of a desired life expectancy (return period) against extreme winds. This is of particular concern in the analysis of wind loads on low-rise residential structures in coastal areas. Associated with near-ground wind effects in some extreme storms are dangerous wind phenomena described in the literature as "down-bursts," "hurricane swirls," and "gustnadoes."[1,2,3,4,5] Fortunately, the understanding and predictability of near-ground wind effects in severe storms is advancing through increased use of new techniques in recording extreme wind speeds.[1]

Variations in the manner of recording wind speed have added confusion to the understanding of reported wind events. As wind is the most variable of meteorological elements, the recording time or averaging time for reporting the wind speed is crucial in understanding the significance of the measurement. The elevation and exposure of the instrument used to make the measure-

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[1] Joseph H. Golden and John T. Snow, "Mitigation Against Extreme Windstorms," *Reviews of Geophysics*, Vol. 29, No. 4 (November 1991): 477-504.

[2] Theodore T. Fujita, *Memoirs of an Effort to Unlock the Mystery of Severe Storms, During the 50 Years, 1942-1992* (Chicago: University of Chicago, 1992).

[3] Theodore T. Fujita, "Wind Fields of Andrew, Omar and Iniki, 1992," 20th Conference on Hurricanes and Tropical Meteorology (Boston: American Meteorological Society, 1993).

[4] Mark D. Powell and Sam Houston, "Surface Wind Field Analysis in Hurricane Andrew," 20th Conference on Hurricanes and Tropical Meteorology (Boston: American Meteorological Society, 1993).

[5] Roger M. Wakimoto and Peter G. Black, "Damage Survey of Hurricane Andrew and Its Relationship to the Radar-Detected Eyewall," 20th Conference on Hurricanes and Tropical Meteorology (Boston: American Meteorological Society, 1993).

ment is also significant. An anemometer is typically used to measure near-ground wind speeds by rotational movement of its wind cups or propeller. During a severe storm event, an anemometer might record data for compilation of a 5-second average, 1-minute average, or fastest-mile maximum wind speeds. Fastest-mile wind speeds are predominant in historical weather records for the United States because of the early mechanical methods used to obtain wind data. Fastest-mile wind speeds are simply the speed calculated by determining the amount of time for a "mile of wind," as registered by the rotation of an anemometer, to pass by a particular point. Today, digital technology is used to record wind speeds for various averaging durations commonly ranging from 2 seconds up to 15 minutes. The 2- to 5-second average wind speeds represent "gusts" and "lulls." The National Hurricane Center (NHC) in Miami, Florida, commonly reports hurricane winds as maximum sustained surface wind (1-minute average) for warnings and advisories.

For a given record of wind data, the reported wind speed values will vary in magnitude based on the duration of measurement. A shorter duration wind measurement will capture higher spikes or gusts in the wind over the time of record, whereas longer duration measurements tend to average out these spikes. For example, an anemometer at the Fowey Rocks C-MAN station (a National Weather Service buoy on the Florida coastal barrier) recorded the magnitude of Hurricane Andrew just before landfall. The maximum gust (2- to 5-second duration) wind speed was recorded as 169 mph and the maximum 2-minute sustained wind speed was recorded as 141 mph.[6] These measurements were the highest recorded just before the measurement station was disabled from wind damage. Both of these wind speeds are correct in describing the wind data. The fact that they are greatly different demonstrates the dynamic nature of extreme winds. It is important to note that these measurements are based on readings taken with an over-water exposure (Category D) at an elevation of 43 meters. Other data for Andrew were taken at different exposures and elevations, representing different aspects of the wind and Hurricane Andrew. By theory, the Fowey Rocks data may be converted to a fastest-mile wind speed of approximately 120 mph for exposure Category C (open terrain, inland) or 142 mph for exposure Category D (over-water, open coastal) at an elevation of 10 meters as used for engineering purposes. However, the theoretical means of converting wind speeds to represent other conditions are based on very limited data, especially in the case of extreme wind conditions.

For design purposes, the complexities of wind can be generalized in terms of several variables that describe wind and its interaction with structures, as follows:

- Basic wind speed (based on a statistical analysis of historical wind data that defines the level of risk)
- Gustiness of wind (dynamic nature of wind speed)
- Importance of a building (modifies the level of risk or design return period relative to occupancy)
- Effects of elevation and exposure on wind speed (wind speeds theoretically drop with decreasing elevation and increased obstruction or surface roughness)

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[6] National Weather Service, "Preliminary Report—Hurricane Andrew, 16-18 August 1992" New Orleans, LA, September 24, 1992.

- Aerodynamic shape effects (defines changes in wind pressure as a result of basic geometric influences on wind flow around a building)
- Building integrity (whether or not the building envelope is breached, allowing internal pressures to build up)
- Topographical wind effects (Bernoulli fluid flow effects near land or structural formations—not developed in current U.S. design standards)

These variables are used to analyze wind pressures (loadings) on a building. Most are found in the wind engineering procedures of design standards and building codes. Errors or omissions in the characterization of basic (design) wind speed or any of these variables can substantially affect the accuracy of estimated wind loads. Characterizing the design wind speed is the first and most important step in the design process. Determination of an acceptable basic wind speed is critical to the analysis of structures because wind loads (pressures) on a building vary as the square of wind speed. Thus, a twofold increase in wind speed quadruples the wind load on a structure.

When implementing such an engineering procedure to determine design wind loads, the design wind speed establishes the basis for the level of risk or permanence of a structure against potential wind events. Commonly, the design wind speed is based on an estimated annual probability of occurence of 0.02, which represents a 50-year return period. In other words, there is a 2 percent chance that these winds would be experienced or exceeded in any given year at that particular site. Over a 50-year life expectancy, the cumulative probability would result in a 64 percent chance that the site would experience at least one wind event that exceeds the design wind speed. A reasonable assumption is that normal safety factors in design applications will accommodate most winds in excess of a design event. A 50-year return period design does not guarantee a 50-year life expectancy nor does it suggest survival during a given hurricane. It is merely an expression of an acceptable level of risk over time. Wind storms such as Hurricanes Andrew and Iniki should not be viewed as unexpected meteorological events but rather as anticipated events, although they may be viewed as rare events when such storms happen to have a landfall in a densely populated area.

Because of the statistical methods applied to hurricane wind prediction and risk analysis, there is a strong likelihood that the winds will exceed the design wind speed at a given site over the life of a structure. This is so because part of the risk analysis process depends on the probability of that site being struck by a hurricane, regardless of the strength of the hurricane. The probability of a "site" being struck by a hurricane depends of the size of the site, whether it is defined as a point or a region along the coast. For example, according to one method for predicting coastal (hurricane) wind speed,[7] Hurricane Andrew is ranked as more than a 2,000-year return period event based on a "point" occurrence using a fastest-mile wind speed of 145 mph at an elevation of 10 meters and exposure Category C (open terrain, inland). In other words, the area (point) of Dade County, Florida affected by Andrew's maximum winds could expect to experience an event of this magnitude or greater once every 2,000 years on average by this method.

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[7] Martin E. Batts, et al., *Hurricane Wind Speeds in the United States*, NBS Building Science Series 124 (Washington, DC: GPO, May 1980).

The method currently used by the NHC[8] results in a vastly different prediction. With the NHC method, Hurricane Andrew is viewed as approximately a 25-year return period event for a region defined by a 75 nautical mile radius around Miami. In this scenario, the area of exposure to a potential or statistically modeled hurricane landfall is significantly larger than a "point." However, not all "points" within that area will be hit by the maximum hurricane winds during one such event. The NHC uses this method of describing the return period estimates of hurricane winds because any event occurring in this region is considered a "hit" by the public, even to those at the majority of "points" in the region not directly affected by a hurricane's maximum winds. The NHC method also provides a return period estimate based on the chance that a point or specific site will experience a certain wind speed. In this case, Hurricane Andrew is viewed as having approximately a 250-year return period. Obviously, the value of the design wind speed at a particular return period is very dependent on the area or length of coast used in the predictive model, as well as the operating assumptions within the predictive model and the quality of the historic wind data.

WIND LOADS ON BUILDINGS

Once the design wind speed is defined, the previously mentioned wind engineering variables are used to convert the wind speed into a loading, based on the current understanding of wind characteristics and effects on buildings at the near-ground level. Generally, the windward wall (directly facing the wind) of a building experiences a positive or inward acting pressure, and all other walls, often including the entire roof, experience negative or outward acting pressures (suction). Steeper roofs may experience positive pressures on the windward (upwind) slope and negative pressures on the leeward (downwind) slope. Abrupt changes in the geometry of the building create localized increases or decreases in wind pressure due to turbulent wind flow. Localized areas of increased wind pressure include overhanging eaves, perimeter of the roof, and corners of the building. These basic wind effects are illustrated in Figure 1.

A crucial variable affecting the wind resistance of buildings is the integrity of the building's envelope or "shell." The components comprising the building envelope include siding, sheathing, roofing, windows, and doors. Damage to these components is likely to result in water damage to interior parts of the home.

Of equal concern are the effects of internal pressure when wind forces its way through an opening into a building envelope (see Figure 1). When the building is not completely enclosed or is penetrated by high winds or wind-driven debris (projectiles), the building experiences some degree of internal pressurization. The larger the opening the greater the effect. However, openings as small as 1 to 5 percent of the windward facing wall area can create full internal pressurization effects that can double the wind load on some components of a house according to actual field measurements.[9] However, it is common practice to design residential buildings

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[8] Charles J. Neumann, *The National Hurricane Center Risk Analysis Program (HURISK)*, NOAA Technical Memo NWS NHC 38 (Washington, DC: GPO, August 1991).

[9] Byron B. Yeatts and Kishor C. Mehta, "Field Study of Internal Pressures" (Presented at the 7th U.S. National Conference on Wind Engineering, Los Angeles, CA, June 27-30, 1993).

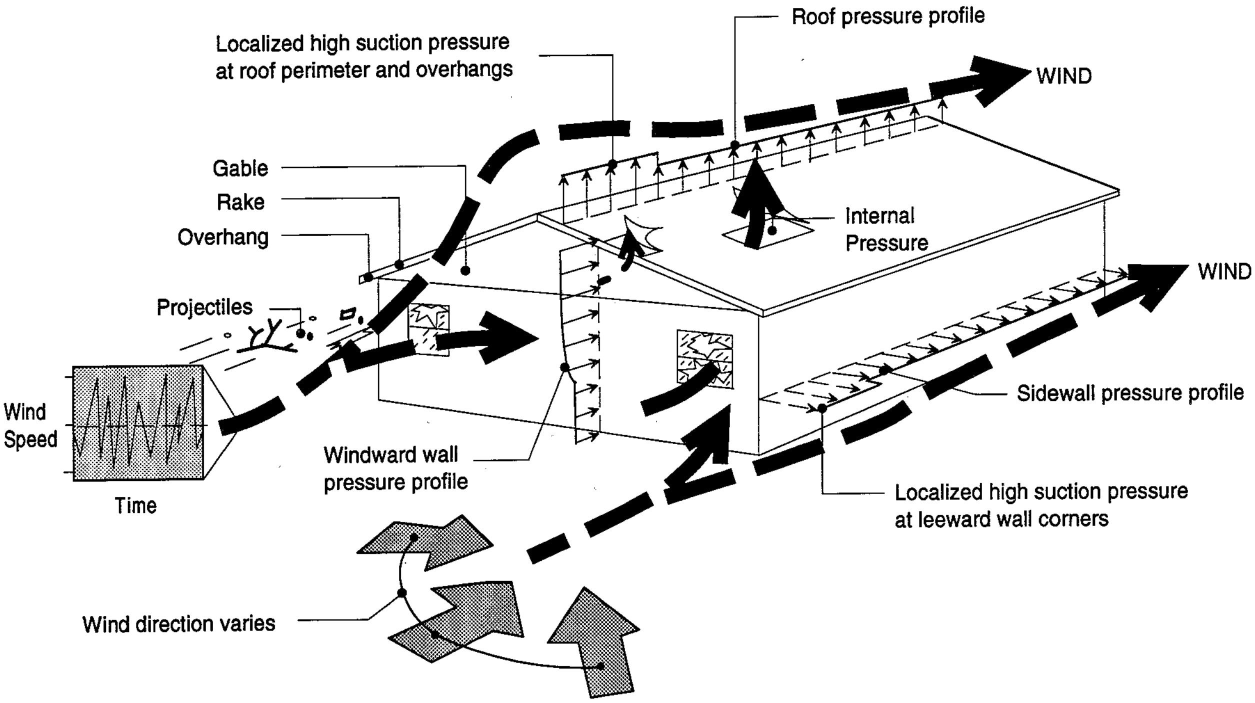

Figure 1. Illustration of basic wind effects on low-rise buildings.

based on the absence of significant internal pressures. In such cases, the integrity and protection of the building envelope against penetrating winds and projectiles is presumed to be adequate.

Because of the lack of comprehensive data on the complex and dynamic nature of extreme wind and its interaction with the natural and manmade environment at this point in time, it is not yet possible to address structural performance in abstract engineering terms. However, comparative or relative inferences on general structural performance can be made with some level of confidence if proper methods of gathering and analyzing relevant data are followed. Weak links in building systems may be identified by competent observation and analysis. This report employs this approach to develop some practical recommendations for construction of single-family homes in hurricane-prone areas.

WIND DESIGN REQUIREMENTS

Wind loads on residential buildings are generally accounted for by either performance or prescriptive requirements found in building codes. For most residential construction, prescriptive requirements provide for the necessary wind resistance. Original applications of engineering design procedures based on performance requirements (e.g., minimum wind speed) are seldom used in single-family home construction. Engineering procedures and performance requirements do serve as a guide to many prescriptive measures in building codes. Research, testing, and historical experience also influence prescriptive requirements.

The building codes influencing construction in South Florida and Kauai at the time of the hurricanes were the South Florida Building Code (SFBC) 1991 Edition and the Uniform Building Code (UBC) 1988 Edition, respectively. Although the Standard Building Code is used in Louisiana, much of the south central coastal area of Louisiana did not systematically control building construction with respect to wind loads. The following discussion of engineering procedures and prescriptive requirements reflects the building code system in place in South Florida and Kauai during the 1992 hurricane season.

Engineering Procedures

Engineering procedures are employed to meet performance requirements in building codes. Wind engineering involves analytical assessment of probable wind loads based on historical wind data and wind research. The most advanced technical understanding of wind engineering in the United States is represented by American Society of Civil Engineers (ASCE) Standard 7-88: "Minimum Design Loads for Buildings and Other Structures." This standard provides minimum guidelines for all types of loads, including wind, based on the most reputable research available.

Wind design provisions in all of the model building codes are based on the current edition of ASCE 7-88 or earlier standards on building loads (e.g., ANSI A58-1). In turn, the basic wind speed map in ASCE 7-88 is founded on the work by Batts, et al., discussed earlier. Local jurisdictions occasionally make amendments to the minimum design standards to account for local conditions, technical uncertainties, or to simplify procedures. For example, SFBC officials increased the basic fastest-mile wind speeds from 110 to 120 mph for South Florida. The design wind speed may have been increased because of acknowledgements of potential underestimates in the wind speed analysis by Batts, et al. However, this increase does not necessarily equate to higher design wind loads than provided by ASCE 7-88 because of other differences in the engineering procedures. For example, the procedure in the SFBC does not apply a gust factor as found in ASCE 7-88. Thus, the SFBC modification effectively makes 120 mph the gust speed for SFBC, but the corresponding fastest-mile wind speed is approximately 100 mph—less than the 110 mph minimum value originally suggested in ASCE 7-88. Differences also occur with other aspects of wind design including the treatment of the main wind force resisting system (MWFRS), and components and cladding, in addition to variables such as basic wind speed, exposure, shape, elevation, and internal pressure influences.

For analysis purposes, a building is divided into two functional categories: components and cladding, and the MWFRS. The components and cladding category consists of the building elements that are directly loaded by the wind including roof sheathing, trusses and rafters; wall sheathing, siding, and studs; and windows and doors. Most elements of a home are represented in the design category of components and cladding. These items bear the brunt of the wind load, including projectiles and localized high pressure effects. They are also crucial to the water resistance of a building. Because of the potentially small tributary areas involved, larger wind pressure coefficients are considered when analyzing components and cladding. The MWFRS consists of major building elements that provide the overall resistance or rigidity against wind loads. The roof diaphragm, shear walls, post and beam or steel frames, and concrete tie-beams are examples of MWFRS elements. Because localized wind effects are distributed over the MWFRS, the wind load coefficients are generally lower than those used for components and cladding.

For two residential applications, the relative differences in wind loads from the design procedures of the SFBC (1991 edition), UBC (1988 edition), and ASCE 7-88 are shown in Figures 2 through 5. These examples represent a specific set of conditions; therefore, the comparison is not exhaustive. Other comparisons of the SFBC and ASCE have shown that much smaller or larger differences can occur under different conditions such as at roof overhangs and corners, or steeper roof slopes, or with other building dimensions or exposures to the wind.[10,11,12,13] In some cases, the calculated wind pressure by ASCE 7-88 can approach twice that calculated by SFBC.

For this report, the comparisons are based on an approximation of the most common home characteristics found in South Florida (SFBC vs. ASCE 7-88) and in Kauai (UBC vs. ASCE 7-88). The basic conditions, assumptions, and wind load calculation formulas for the comparisons are given in Appendix C. For SFBC values, a 120 mph basic wind speed is used in the procedure, as specified by SFBC. A 110 mph basic wind speed is used with the ASCE 7-88 calculations in South Florida, as recommended by ASCE 7-88. The comparison of UBC and ASCE 7-88 in Kauai uses an 80 mph basic wind speed for both procedures.

In this comparison of wind engineering procedures in place at the time of Hurricanes Andrew and Iniki, the following can be concluded:

- ASCE 7-88 generally produces wind loads significantly greater than SFBC, even though a higher basic wind speed is used in the SFBC method;
- ASCE 7-88 and UBC procedures generally produce similar design wind loads; and
- Assumptions regarding a particular wind exposure or internal pressure condition (enclosed vs. breached openings) can have a dramatic impact on calculated wind loads.[11,14]

The calculation of design wind loads by these methods and the means of meeting them (e.g., structural detailing) is limited to those who have a proper technical background and related experience. Critical judgments are necessary in such decisions as determining whether or not to treat a structure as an enclosed building (without significant internal wind pressures) or partially enclosed (with much higher design pressures), among others. As noted previously, small breaches in the building envelope (e.g., a broken window) can increase the loads on structural components by a factor of two.

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[10] NAHB Research Center, *Comparison of South Florida Building Code and Dade County Ordinance 93-14, Including ASCE 7-88 and Other Special Wind Loading Requirements* (Upper Marlboro, MD: NAHB Research Center, 1993).

[11] Ronald F. Zollo, P.E., *Hurricane Andrew: August 14, 1992—Structural Performance of Buildings in Dade County, Florida*, Technical Report No. CEN 93-1 (Coral Gables, FL: University of Miami, March 11, 1993).

[12] Bradford K. Douglas, P.E., *Hurricane Andrew, Part 1—Wood Building Performance and Analysis* and *Hurricane Andrew, Part 2—Wood Building Analysis and Recommendations* (Washington, DC: American Forest and Paper Association, November 1992).

[13] Richard D. Marshall, *Wind Load Provisions of the Manufactured Home Construction and Safety Standards—A Review and Recommendations for Improvement* (Washington, DC: GPO, 1993).

[14] Yeatts and Mehta.

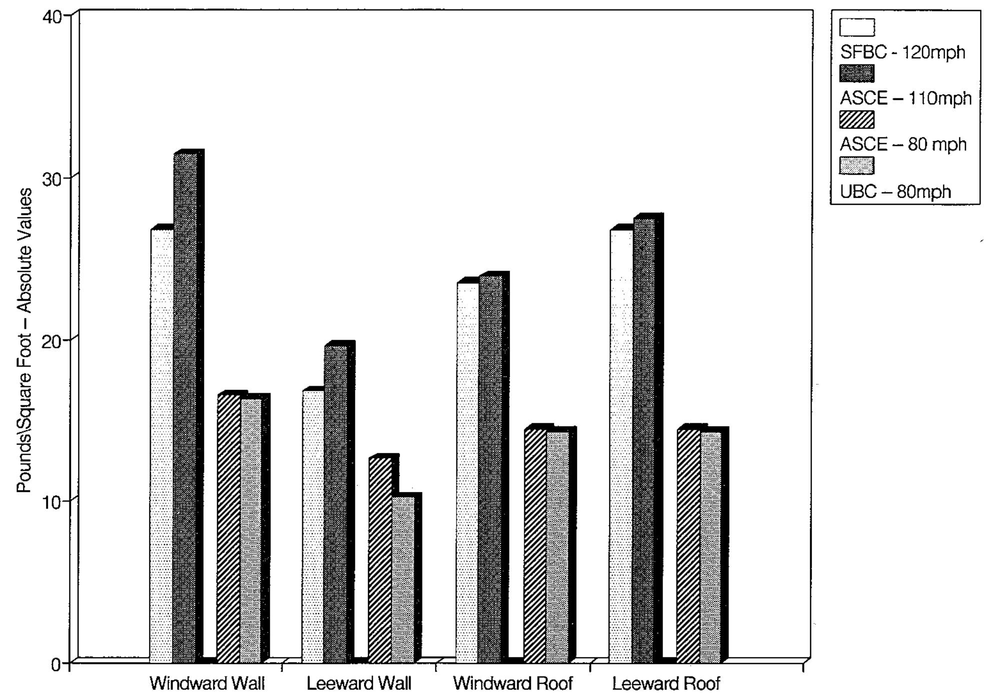

Figure 2. Design loads for the MWFRS of a representative two-story home (enclosed).

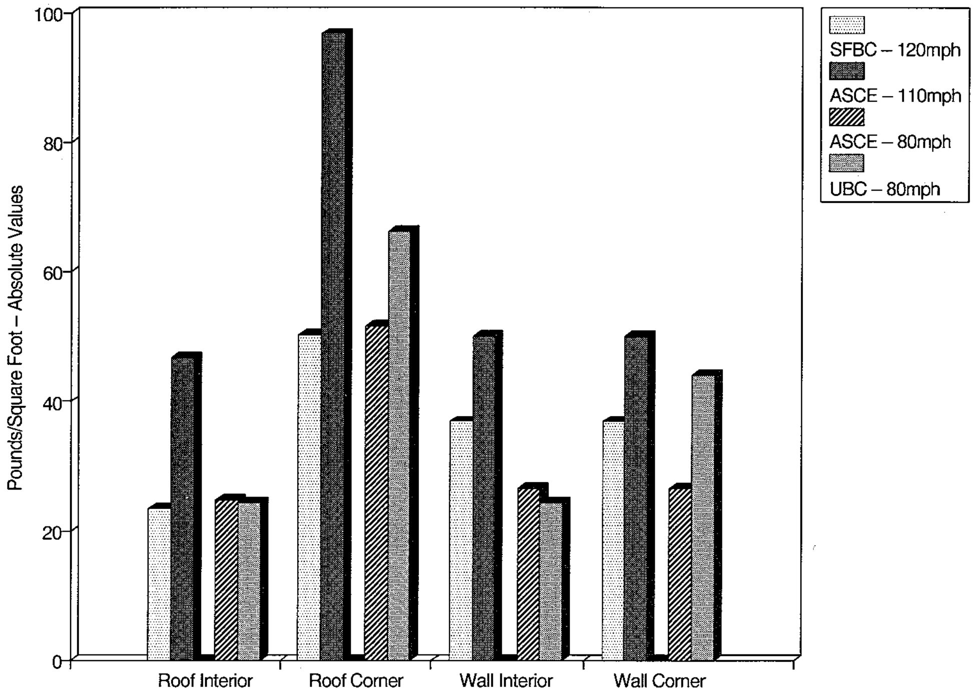

Figure 3. Design wind load for components and cladding of a representative two-story home (enclosed).

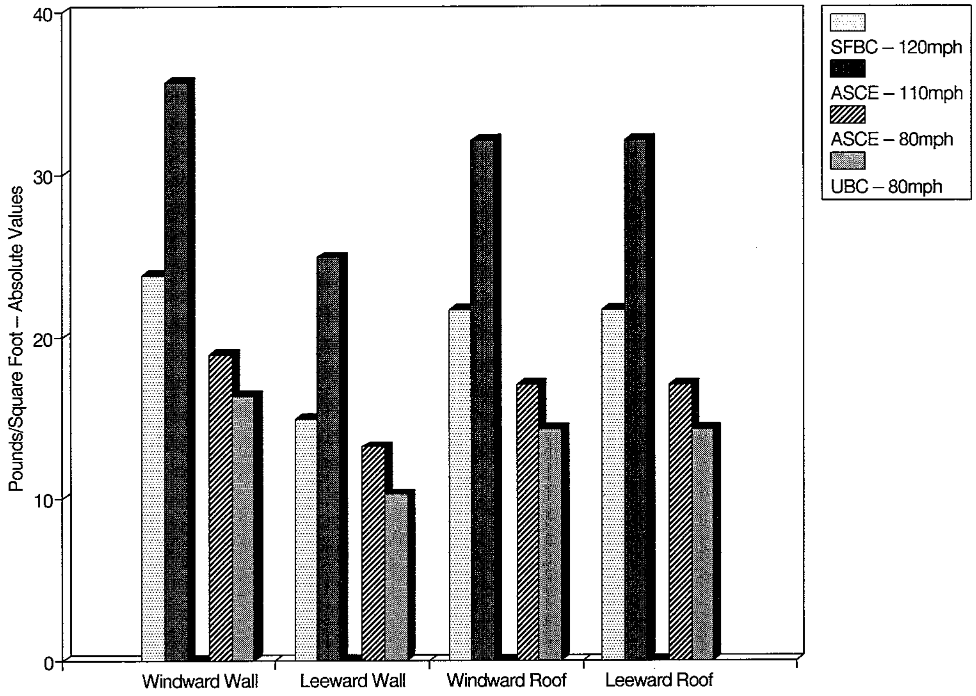

Figure 4. Design wind load for the MWFRS of a representative one-story home (partially enclosed).

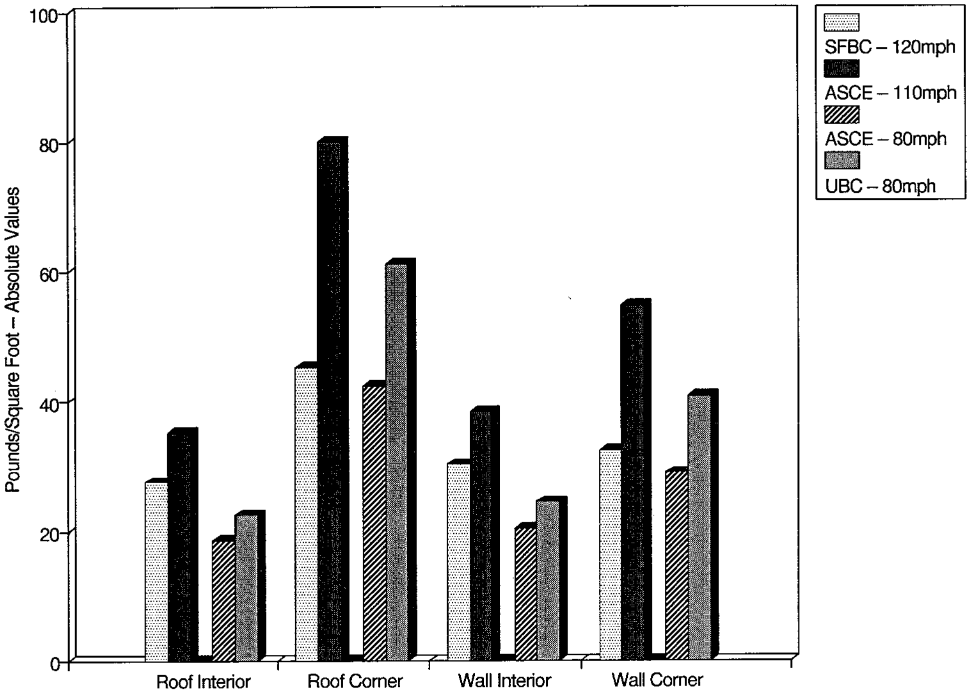

Figure 5. Design wind loads for the components and cladding of a representative one-story home (enclosed).

Few homes are custom designed according to wind engineering procedures. The preceding comparisons illustrate the technical differences in applied engineering procedures for calculating wind loads. They do not reflect actual loads in any particular case, nor do they serve as a benchmark for performance of the wind damaged housing in Florida, Louisiana, or Kauai. A more valid benchmark for housing construction is the prescriptive requirements of each building code, more specifically, the performance of houses properly built to these requirements.

Prescriptive Requirements

Carefully worded, detailed, illustrated, and organized prescriptive requirements are more easily interpreted by the non-engineering community and provide a measurable basis for training, inspection, and quality control in construction. The building codes of a jurisdiction are the final standard for quality on which a home should be built. For most residential construction, numerous prescriptive requirements collectively define the performance intent of the building code. However, it is only realistic to recognize that some substandard construction will result from faults in the building code, ignorance, misinterpretation, careless inspection, poor workmanship, or other problems that reach into both technical and social issues. This reality does not excuse faulty construction when it occurs, for whatever the reason.

While many prescriptive requirements are based on engineering or research, others are the result of experience and accepted standards of practice in the construction industry. Most are generic in nature to meet a variety of applications, sometimes requiring judgments in the field as to the intent. In both the SFBC and UBC codes, prescriptive requirements address fastener sizes, fastener spacings, fastener types, connections for continuous load paths (e.g., hurricane straps), fastening of roofing materials, bracing, and numerous other strength requirements related to wind resistance.

Like engineering design procedures, prescriptive requirements undergo serious scrutiny before they are accepted into a building code and, once accepted, are subject to amendment and revision. Therefore, homes will be built under different and changing requirements over time. New or revised prescriptive requirements are often disseminated to the field through the plan review and inspection process. Since prescriptive requirements change over time, it is beyond the scope of this report to present a detailed evaluation of the construction of homes with respect to age in the hurricane damaged areas.

The adequacy of a building code, like that of a building, can only be measured by its weakest link. Therefore, this report focuses on identifying the weakest links in the house construction affected by Hurricanes Andrew and Iniki, and attempts to identify the essential reasons for damages.

Hurricane Aftermath: Building Codes

Deep concern over the damages inflicted by Hurricanes Andrew and Iniki are driving many changes in the requirements and enforcement of building codes. For the SFBC the changes have already been substantial, including: the ban of OSB sheathing; engineered plans required for every home; increased experience requirements for inspectors; additional number of inspectors; new positions in the plan review process; expanded permitting requirements; increased inspection requirements; adoption of a new wind engineering procedure (ASCE 7-88); greater structural requirements for masonry, wood, steel, and concrete construction; increased performance requirements for roofing products; and required window protection with performance tested glazing or storm shutters.

These are significant changes that will increase the cost of housing. Some of these special measures are more cost-effective than others. Some may be excessively costly relative to the benefit. Ultimately, they will be tested in future hurricanes. Other code jurisdictions may not be able to institute such demanding changes in their building code. Consequently, elements that have the greatest influence on limiting hurricane damage need to be identified and prioritized. This report provides a source of data and detailed damage analyses to help make such vital decisions.

CLASSIFICATION OF HURRICANES

The classification of hurricanes serves as a measure of the potential for damage based on generalized meteorological data. The present classification of hurricanes relies on rudimentary meteorological indexes and does not describe the intricacies that make each hurricane unique. The complexity of meteorological and physiographical factors that interact to produce a severe storm are beyond description in a simple classification system.

The accepted method of classifying hurricanes is the Saffir-Simpson Scale. Hurricanes are categorized into five classes (Table 1) based primarily on the atmospheric pressure depression within the eye of the hurricane. Hurricane Andrew almost reached a Category 5 rating at landfall in Florida, and Hurricane Iniki approached a Category 3. The pressure drop within a hurricane (or any storm system) has been shown to be a reasonable index of intensity. Ranges for wind speeds and storm surge can be estimated for the intensity classifications by application of theory and actual storm records. However, the classification method does not consider site specific factors (natural and manmade) that increase or mitigate the actual impact of a particular hurricane. Natural factors include topographic features, including offshore reefs, vegetation such as trees, and coastal buffers such as marsh lands and dunes. Manmade factors include clearing and development, building heights, and densities.

Table 1
CLASSIFICATION OF HURRICANES
BY THE SAFFIR-SIMPSON DAMAGE POTENTIAL SCALE

Category	Central (Eye) Pressure mb*	Winds, mph**	Surge, ft	Potential Damage
1	≥ 980	74 - 95	4 - 5	Minimal
2	965 - 979	96 - 110	6 - 8	Moderate
3	945 - 964	111 - 130	9 - 12	Extensive
4	920 - 944	131 - 155	13 - 18	Extreme
5	< 920	> 155	> 18	Catastrophic

*Standard atmospheric pressure at sea level is about 1013 mb (14.7 psi)

**Maximum sustained (1-minute) wind speed at an elevation of 10 meters. In its original form, the wind speed ranges represented gust winds—Hurricane Andrew would have been ranked as "catastrophic" (Category 5).

HURRICANE PREPAREDNESS

The forecasting of a severe storm plays a major role in the protection of life. Unquestionably, it should be considered as the primary means of providing protection for citizens in areas prone to hurricanes. Fourteen people were killed in South Florida as a direct result of Hurricane Andrew. The single most important factors that minimized the death toll relative to the physical damage was the forecasting and tracking of the hurricane, which provided time for evacuation.

The ability to forecast hurricanes and predict their paths has advanced such that a 24-hour hurricane warning can be made with reasonable accuracy in most cases.[15] Twenty-four hours of weekend time was available for preparation and evacuation before Andrew struck South Florida. The level of preparedness could be considered higher than that achieved with previous hurricanes or warnings in Dade County.[16] Some home owners took special precautions such as applying tape to windows (thinking this to be sufficient) and cleaning-up loose yard items. However, over the 20 years since the last hurricane and with many false alarms in the interim, the level of concern or awareness had eroded. Very few homes outside of those with permanent storm shutters had effective protection over windows such as precut plywood with a secure method of fastening. This appeared to be the case even for residents who had been through earlier hurricanes. Since residents in or near the path of Hurricane Andrew are now especially aware of the importance of evacuation, automobile traffic may be a problem when the next hurricane is forecast in the Miami area.

Louisiana citizens had even more forewarning for evacuation and preparation. An estimated 1.25 million people evacuated parishes in Southeast and South-central Louisiana. However, many coastal homes still had no special protection against wind damage. While Kauai residents also had ample warning, total evacuation of the island was not practical. Many people remained on the island in designated storm shelters. While some of these shelters suffered minor damage during Hurricane Iniki, they appeared to be adequate to perform their basic function.

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[15] National Weather Service.

[16] Zollo.

PART 1 - HURRICANE ANDREW

DESCRIPTION OF HURRICANE ANDREW

Hurricane Andrew struck metropolitan Dade County, Florida, on August 24, 1992, with violent winds and storm surges characteristic of a high Category 4 rating on the Saffir-Simpson scale of hurricane intensity. In terms of pressure drop, Andrew was the third strongest landfalling hurricane striking the United States in the past century. The hurricane system was marked by a compact eye, isolated coastal storm surge, and intense and sustained winds that reached well inland. The significant characteristics of Hurricane Andrew at landfall in Florida with some related damage statistics are shown in Table 2.

Table 2
CHARACTERISTICS OF HURRICANE ANDREW—FLORIDA

Maximum Wind Speed (fastest-mile) at 10-meter elevation (basis for engineering design) with an open inland exposure	140+ mph[17] 145+ mph[18]
Maximum gust wind speed (2-5 second average) at 10-meter elevation	175+ mph[18,19]
Maximum storm surge	16.9 feet above mean sea level[19] - record high
Rate of travel of the hurricane system at landfall	18-20 mph[19]
Minimum central (eye) pressure	926 mb at landfall[19] (922 mb was the minimum reached before landfall)
Radius of maximum winds	11 to 12 miles[19]
Estimated number of homes damaged (includes single-family, mobile, and apartment dwellings)	25,524 - destroyed (Red Cross)[19] 101,241 - damaged (Red Cross)[19]
Estimated dollar cost of damage	$20+ billion[19]
Deaths	32 total = 14 direct + 18 indirect[20] (direct deaths are those that occurred during the hurricane as a result of physical trauma)

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[17] Timothy A. Reinhold, Peter J. Vickery, and Mark D. Powell, "Wind Speeds in Hurricane Andrew: Myths and Reality" (Prepared for Hot Topics Session, American Concrete Institute Annual Convention, San Juan, PR, October 26, 1992).

[18] Powell and Houston.

[19] National Weather Service.

[20] Centers for Disease Control, "Preliminary Report: Medical Examiner Reports of Deaths Associated With Hurricane Andrew—Florida," *JAMA*, Vol. 268, No. 13 (October 7, 1992): 1644.

Wind speeds recorded under a variety of measurement conditions first appeared to provide conflicting data on the severity of the hurricane winds. However, once the effects of elevation, averaging time, instrumentation characteristics, and other factors were normalized by analytical methods, it became apparent that the reports were converging. While there is still not a total consensus on the actual wind speeds, indications are that the fastest-mile wind speed at a 10-meter (33-foot) height reached about 145 mph at landfall. This estimated fastest-mile wind speed is in theoretical agreement with actual recorded gusts (2 to 5 second duration) of 179 mph at ground level. Two separate strips of notably higher damage have been identified that may be related to localized severe gusts of wind.[21] While no tornadoes were sighted in the Dade County area,[22] several strips of damage indicative of tornado-like winds were identified.[23,24] Overall, the reported wind conditions exceeded the design wind speed in the SFBC as well as all other codes and standards for wind design in the United States.

The results of a complete analytical investigation by NOAA of all available flight and ground data on Hurricane Andrew are shown in Figure 6. The fastest-mile wind speeds shown here are reported in terms of an open, inland exposure (exposure category "C" by ASCE 7-88) at an elevation of 10 meters. The notable difference in these results compared to other reports and reports of earlier hurricanes is that the maximum winds did not necessarily weaken after landfall. Available data suggests that, in this case, the tendency of land roughness to reduce wind speeds was offset by a sustained pressure drop in the hurricane system. The wind speed estimates shown in Figure 6 are considered to be about 3 percent high because of a small positive bias in the analytical methods used to converge all of the ground data and flight level data.

The storm surge of Andrew reached a maximum tide of 16.9 feet (above mean sea level) at Biscayne Bay, which was a record level for that location.[22] The maximum damage from the isolated storm surge occurred in the Perrine area. Storm surge damage in residential areas along the coast was minimal compared to the severity of the wind damage. Several factors mitigated the impact of the storm surge,[25] including:

1. A natural reef barrier (Biscayne State Park) resulting in a highly localized storm surge at impact;
2. The Bahamas platform, which acted as a distant barrier and limited the wave fetch; and
3. The narrow coastal shelf of Florida, which limits tidal build-up.

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[21] Reinhold, Vickery, and Powell.

[22] National Weather Service.

[23] Fujita, "Wind Fields of Andrew, Omar and Iniki, 1992."

[24] Wakimoto and Black.

[25] Robert S. Young, E. Robert Thieler, Orrin H. Pilkey, "Opinions: Geologic and Oceanographic Factors Mitigating the Storm Surge and Flood Damage of Hurricane Andrew in South Florida," *Geology* (February 1993).

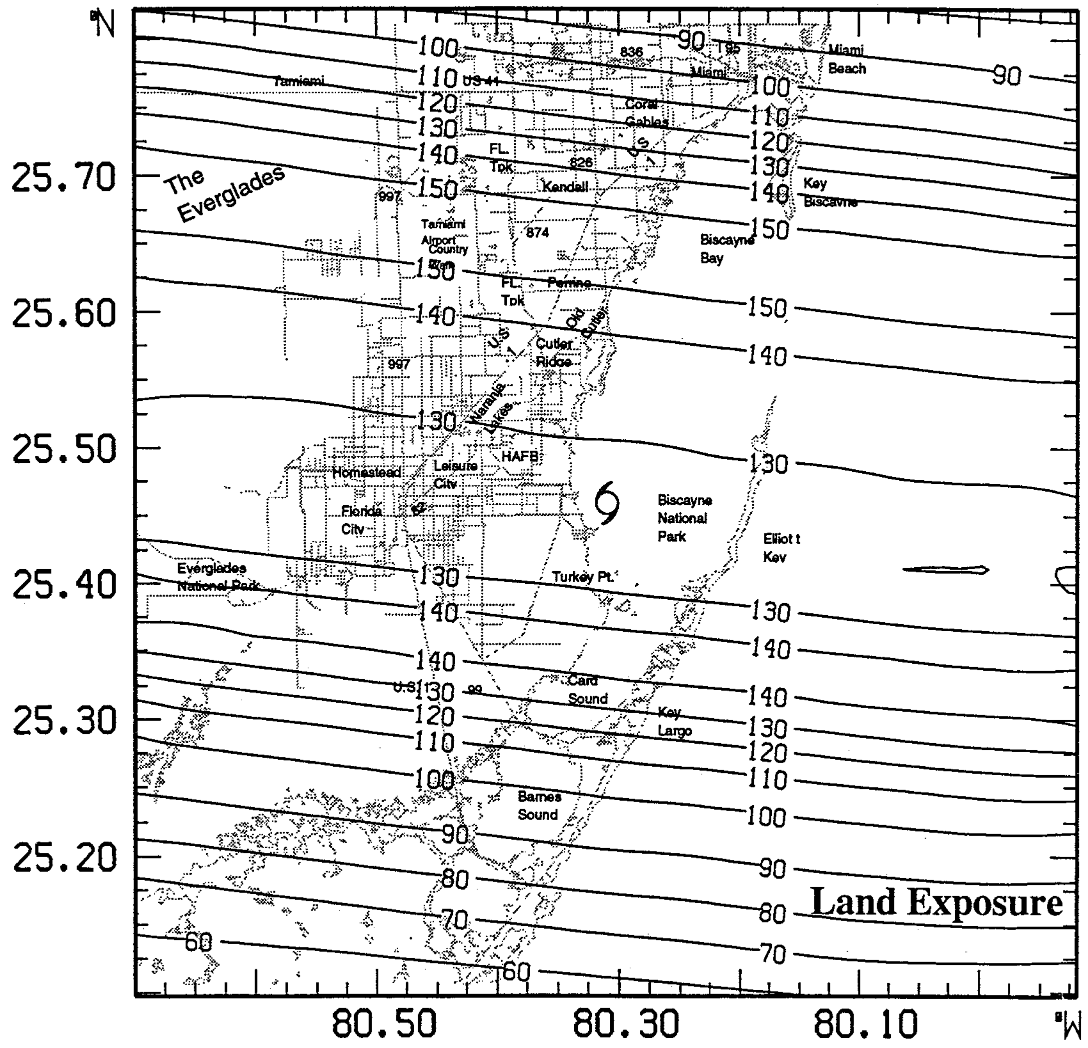

Figure 6. NOAA Hurricane Research Division surface wind analysis of Hurricane Andrew[26]—reported as fastest-mile wind speed (mph) at 10-meter height and open, inland exposure.

These factors are credited with reducing the coastal storm surge damage compared to hurricanes such as Hugo in South Carolina (also a Category 4 hurricane).

Andrew continued across the southern tip of Florida with remarkable staying power. After entering the Gulf of Mexico, it turned north, regained strength, and struck the coast of Louisiana with a Category 3 intensity (Saffir-Simpson scale). Landfall occurred about 23 miles west-southwest of Morgan City on August 26, 1992, in a sparsely populated coastal region. Generally, there is little or no building code enforcement in this rural coastal region of Louisiana. However, several municipalities and parishes (counties) did have some code requirements regarding coastal flood protection. Several damaging tornadoes were spawned from the storm system as it moved inland. Table 3 shows selected characteristics of Hurricane Andrew at its landfall in Louisiana.

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[26] Powell and Houston.

Table 3
CHARACTERISTICS OF HURRICANE ANDREW—LOUISIANA

Maximum sustained wind speed (1-minute average) at 10-meter elevation (exposure may vary)	121 mph at landfall[27]—best track estimate 92 mph at Morgan City[27] several miles inland
Maximum gust wind speed (2-5 second average) at 10-meter elevation	108 mph at Morgan City[27]
Maximum storm surge	6.8 feet above mean tide[27]
Minimum central (eye) pressure	956 mb at landfall[27]
Estimated number of homes damaged	3,301 - destroyed (Red Cross Field Report) 21,626 - damaged (Red Cross Field Report)
Estimated dollar cost of damage	$1+ billion[27]
Deaths	none as a direct result of the hurricane

FLORIDA DAMAGE ASSESSMENT

Damage Assessment Procedure

A preliminary damage assessment was made on August 27, 1992, by an investigator from the NAHB Research Center (Research Center) in company with the American Forest and Paper Association (formerly the National Forest Products Association). On October 5, 1992, a group of eight Research Center engineers in four teams traveled to the damaged area in Florida to conduct a detailed survey of homes for HUD.

On the basis of the preliminary assessment of the area and interviews with the local HUD office, the Florida Department of Community Affairs, and Federal Emergency Management Agency (FEMA) field staff, the damage zone for this study was defined. The survey area is shown in Figure 7. The survey area is bounded on the north by North Kendall Drive (88th Street), on the east by the Atlantic Ocean, and on the south and west by the developed areas adjacent to the Everglades. Lettered boxes indicate the randomly selected map grids for the damage assessment. Other areas or communities sampled, but not a part of the statistical survey, are also labeled. Maps of the damaged areas were initially obtained from FEMA and the Florida Department of Community Affairs' disaster field offices; however, these maps did not contain the detail necessary for the survey. A commercially-available map was obtained that was more suitable (Dade County Street Finder, Rand McNally & Company, 1992).

To select homes for the detailed study, street map grids in the damage zone were numbered. The map grids were equal-sized rectangular sections, each approximately 0.72 square miles in area. There was a total of approximately 90 grids in the damage zone. All streets within the selected grids were numbered. Grids and streets were selected using random number tables (Rand Corporation, 1955). All homes on the selected streets were surveyed, except at the close of each day when time did not allow the longer streets to be completed.

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[27] National Weather Service.

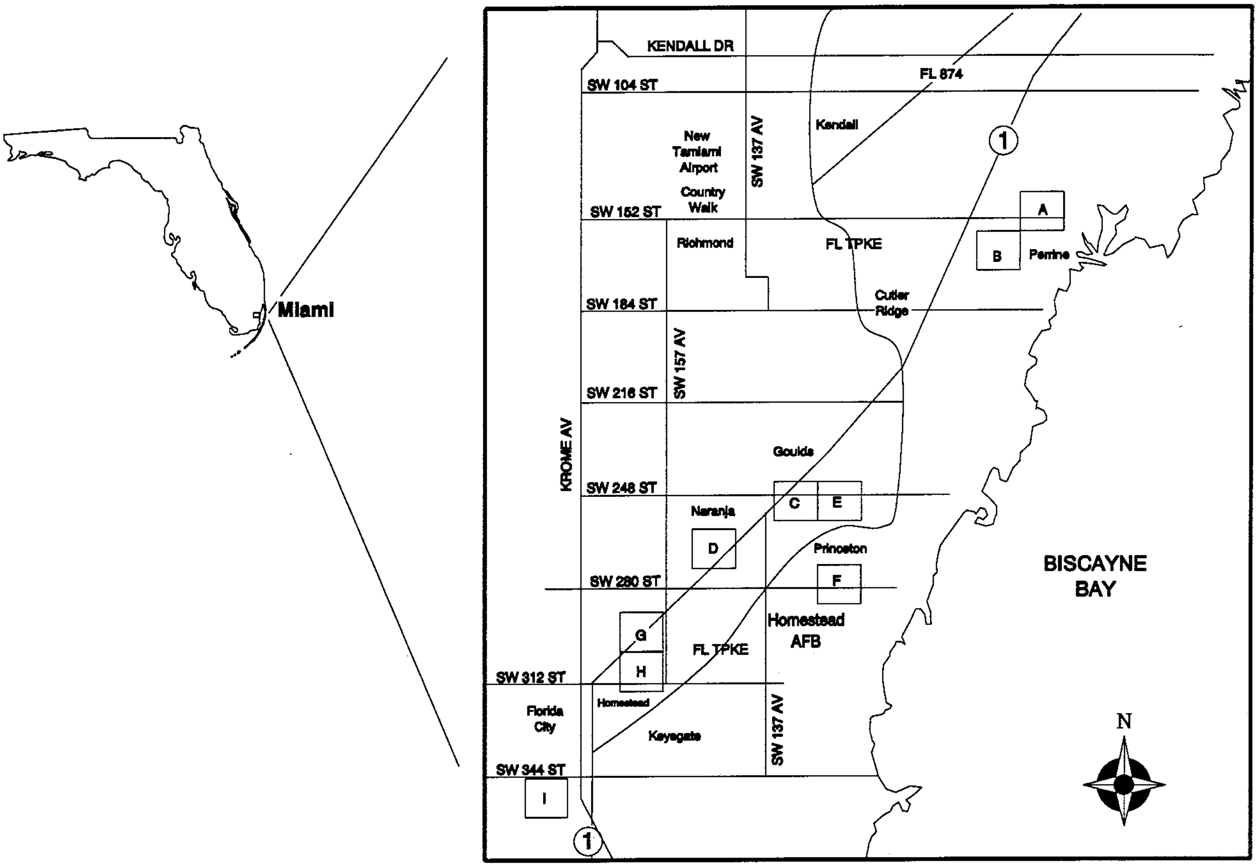

Figure 7. Map of damage zone for random selection of homes in Florida.

The survey team employed the following set of criteria for selecting grids, streets, and homes for damage assessment:

1. Only homes on grids with residential streets defined on the map were assessed.
2. HUD-code (mobile) homes were not assessed. Grids containing only HUD-code units were not considered.[28]
3. Homes within Homestead Air Force Base were not accessible and were not assessed.
4. Houses on grids with less than 10 closely spaced streets were not assessed so that time was not wasted travelling to sparsely populated or agricultural areas.

Teams spent at most one day on each grid and studied as many homes as possible within that day. Houses were surveyed by the order of street selection in the random number process. This two-staged, cluster sampling process[29] yielded homes throughout the damage zone. A total of

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[28] Performance of HUD-code units is being addressed by HUD in a separate report (Marshall).

[29] Ya-lun Chou, *Statistical Analysis for Business and Economics* (New York, NY: Elsevier Science Publishing Co., Inc., 1989).

515 homes in nine grids were surveyed and assessed in the time allotted. The engineers conducting the survey completed a survey form for each home. When possible, an occupant from each home was interviewed. Where a home was unoccupied or inaccessible, only damage directly visible to the engineer was rated. As a result, not all survey forms show data on all construction and damage characteristics. Houses with insufficient data were excluded from the analysis that follows.

At the conclusion of the survey, 466 survey forms representing 90 percent of the total sample were deemed suitable for the analysis. For added breadth of coverage, individual case studies of wood-frame homes and town houses were assessed independent of the sample selection process.

Description of Housing

The housing types encountered in the survey displayed fairly uniform characteristics. Most of the homes surveyed were single-story with masonry walls and gable roofs. Roof construction was often composition shingles over plywood sheathing fastened to metal plate-connected wood trusses. Foundations were slab-on-grade. Most of the houses surveyed appeared to be 5 to 25 years old. The survey team did not attempt to estimate construction dates.

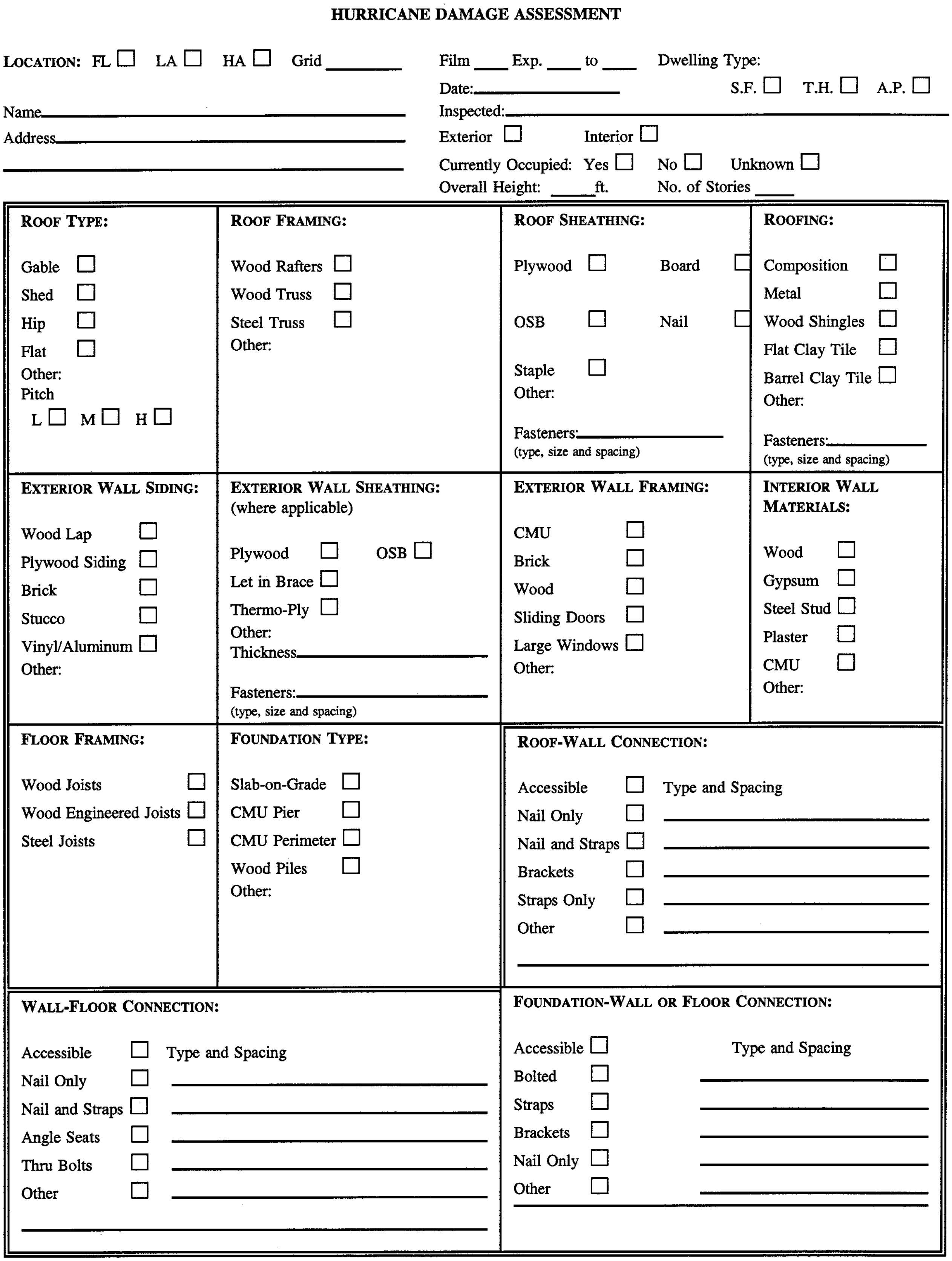
Building characteristics that could aid in the analysis of wind damage were gathered to the extent possible for all homes surveyed. These characteristics are shown on the front side of the survey form used by the damage assessment teams (Figure 8). The terminology used on the form is defined in Appendix B.

Standardization of Damage Ratings

It was important that the survey team make uniform judgments of the damage levels. In order to standardize their approach, each of the teams, including those designated for Louisiana and Hawaii, assessed and graded several selected homes in the Florida damage zone. By comparing the results from each team, it was found that the damage assessments were in close agreement, even in the supplementary notes on the forms. In a few cases where minor inconsistencies were found, the teams came to a consensus on the grading strategy and criteria to be applied. Following this process, the teams assigned to Louisiana and Kauai departed to conduct the surveys in those areas.

Damage ratings for the assessment categories were divided into levels of none, none to one-third, one-third to two-thirds, and over two-thirds. Because so few houses in the sample exhibited no damage, all data falling into the none category was merged with the none to one-third category. These damage rating categories were assigned weights of 1, 2, and 3, respectively, so that average levels of damage could be determined. The damage was rated for different parts of the house, as shown on the backside of the survey form (Figure 9).

Figures 10, 11, and 12 show houses with overall building damage characteristic of the three rating categories. A summary of damage ratings for the overall building, roof, exterior walls, interior (water) and foundation are included with each photograph.



HURRICANE DAMAGE ASSESSMENT

LOCATION: FL ☐ LA ☐ HA ☐ Grid ________

Film ____ Exp. ____ to ____ Dwelling Type:

Date:________________ S.F. ☐ T.H. ☐ A.P. ☐

Name____

Inspected:____

Address____

Exterior ☐ Interior ☐

____

Currently Occupied: Yes ☐ No ☐ Unknown ☐

Overall Height: _____ft. No. of Stories _____

ROOF TYPE:

Gable ☐
Shed ☐
Hip ☐
Flat ☐
Other:
Pitch
L ☐ M ☐ H ☐

ROOF FRAMING:

Wood Rafters ☐
Wood Truss ☐
Steel Truss ☐
Other:

ROOF SHEATHING:

Plywood ☐ Board ☐
OSB ☐ Nail ☐
Staple ☐
Other:
Fasteners:________________
(type, size and spacing)

ROOFING:

Composition ☐
Metal ☐
Wood Shingles ☐
Flat Clay Tile ☐
Barrel Clay Tile ☐
Other:
Fasteners:____________
(type, size and spacing)

EXTERIOR WALL SIDING:

Wood Lap ☐
Plywood Siding ☐
Brick ☐
Stucco ☐
Vinyl/Aluminum ☐
Other:

EXTERIOR WALL SHEATHING:
(where applicable)

Plywood ☐ OSB ☐
Let in Brace ☐
Thermo-Ply ☐
Other:
Thickness________________
Fasteners:________________
(type, size and spacing)

EXTERIOR WALL FRAMING:

CMU ☐
Brick ☐
Wood ☐
Sliding Doors ☐
Large Windows ☐
Other:

INTERIOR WALL MATERIALS:

Wood ☐
Gypsum ☐
Steel Stud ☐
Plaster ☐
CMU ☐
Other:

FLOOR FRAMING:

Wood Joists ☐
Wood Engineered Joists ☐
Steel Joists ☐

FOUNDATION TYPE:

Slab-on-Grade ☐
CMU Pier ☐
CMU Perimeter ☐
Wood Piles ☐
Other:

ROOF-WALL CONNECTION:

Accessible ☐ Type and Spacing
Nail Only ☐ ________________
Nail and Straps ☐ ________________
Brackets ☐ ________________
Straps Only ☐ ________________
Other ☐ ________________
____

WALL-FLOOR CONNECTION:

Accessible ☐ Type and Spacing
Nail Only ☐ ________________
Nail and Straps ☐ ________________
Angle Seats ☐ ________________
Thru Bolts ☐ ________________
Other ☐ ________________
____

FOUNDATION-WALL OR FLOOR CONNECTION:

Accessible ☐ Type and Spacing
Bolted ☐ ________________
Straps ☐ ________________
Brackets ☐ ________________
Nail Only ☐ ________________
Other ☐ ________________

Figure 8. Front of damage survey form for recording the building characteristics.

COMPONENT/LOCATION	DAMAGE LEVEL				COMMENTS
	None	0-1/3	1/3-2/3	Over 2/3	
BUILDING CONDITION					
Integrity of Roof					
Integrity of Walls					
Integrity of Foundation					
Projectile Damage					
Porch/Balconies					
ROOF					
Roofing/Connection					
Sheathing/Connection					
Rafters/Trusses					
Soffit/Fascia					
Roof-to-Wall Connection					
Gable End Condition					
EXTERIOR WALLS					
First Story					
Second Story					
Third Story					
Veneer/Siding					
Sheathing					
Wall to Floor Connections					
Windows					
Doors					
INTERIOR WALLS/CEILINGS					
First Story					
Second Story					
Third Story					
FLOORS					
Floor Framing					
Sheathing					
Water Damage					
Foundation to Floor Connections					
FOUNDATION					
Any Specific Comments					

EXPOSURE A ☐ B ☐ C ☐ D ☐

GENERAL COMMENTS

Figure 9. Back of survey form for recording damage level to different parts of the building.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	1
WALLS	1
INTERIOR	X
FOUND.	1
GRID	B

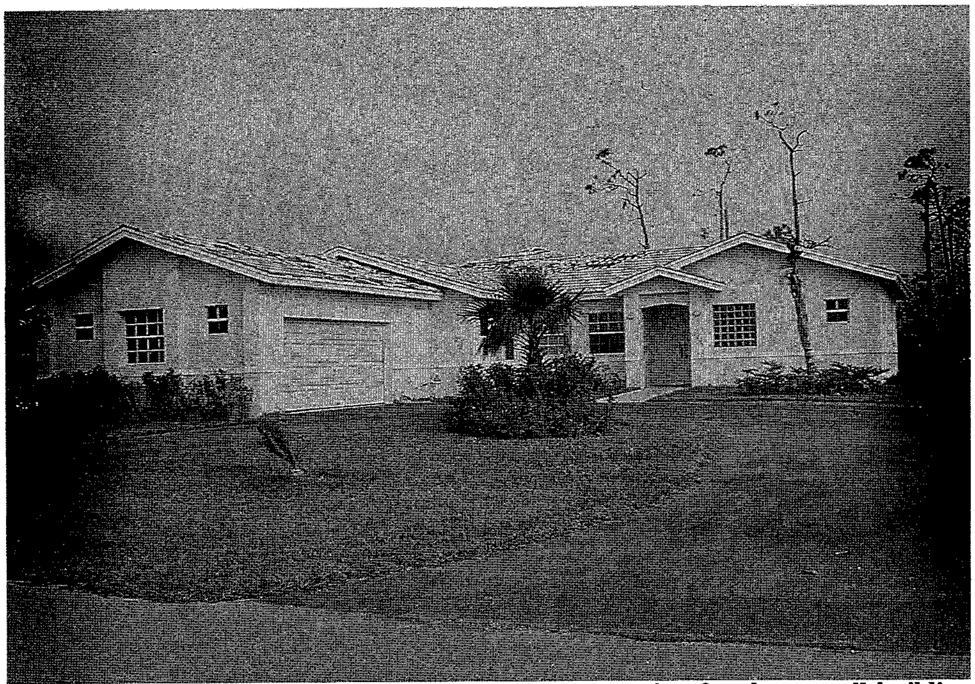


Figure 10. Wind-damaged home with a none to one-third (Level 1) damage rating for the overall building condition. This house had an open inland exposure to the wind. Only one window was broken and the garage door was dented. ("X" means not specified or not accessible to the grader.)

DAMAGE RATING SUMMARY	
OVERALL	2
ROOF	2
WALLS	1
INTERIOR	3
FOUND.	1
GRID	H

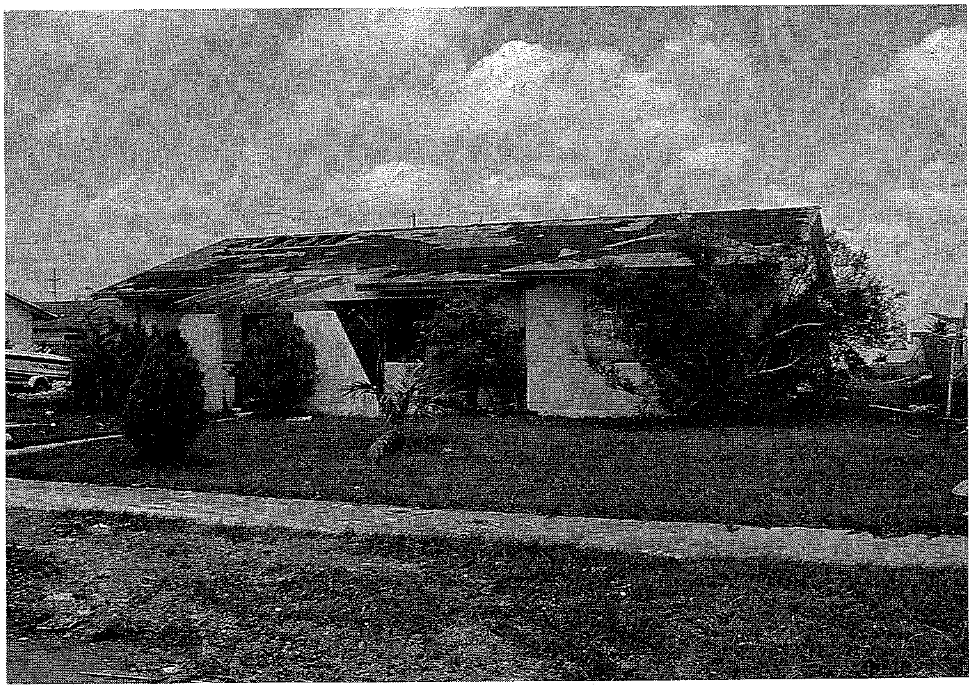


Figure 11. Wind-damaged home with a one-third to two-thirds (Level 2) damage rating for the overall building condition. This level of damage is considered representative of the overall damage to the housing stock in the survey.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	1
INTERIOR	3
FOUND.	1
GRID	E

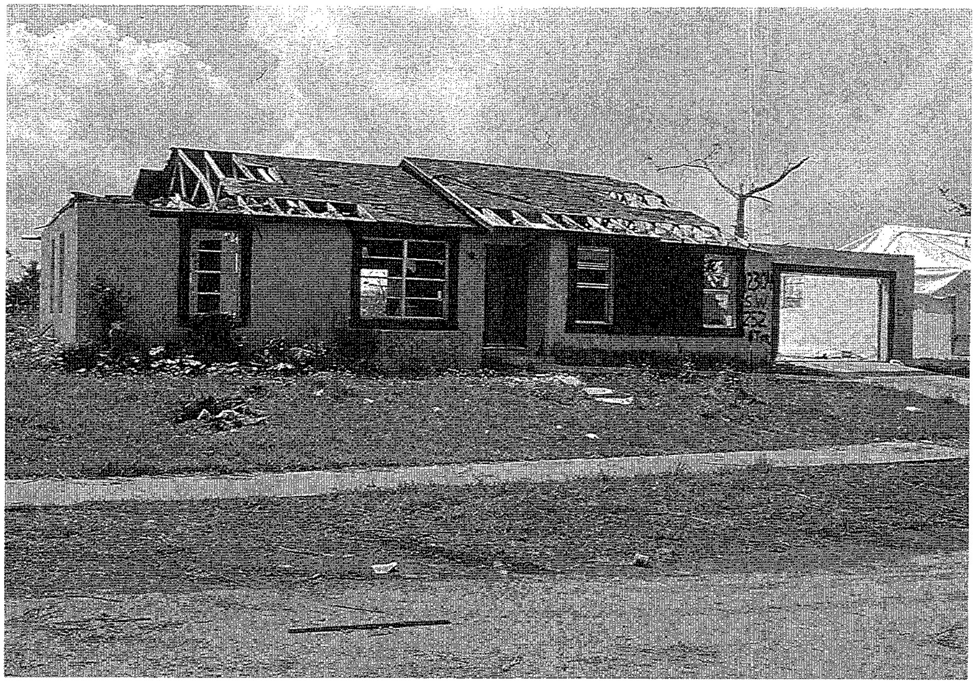


Figure 12. Wind-damaged home with over two-thirds (Level 3) rating for the overall building condition. Both gable ends are destroyed, the roof over the garage is gone, many pieces of sheathing are missing, and all doors and windows were severely damaged.

Damage Survey Analysis

A complete summary of the building characteristics and damage data recorded for the survey is presented in Appendix D. Table 4 shows the distribution of the sample between one- and two-story single-family houses.

Table 4
GEOGRAPHIC DISTRIBUTION OF HOUSES SURVEYED - FLORIDA

GRID	ALL SINGLE-FAMILY		ONE-STORY		TWO-STORY	
	NUMBER	PERCENTAGE	NUMBER	PERCENTAGE	NUMBER	PERCENTAGE
A	38	8%	29	8%	7	9%
B	45	10%	43	12%	2	2%
C	61	13%	51	14%	8	10%
D	52	11%	52	14%	0	0%
E	63	14%	62	17%	1	1%
F	66	14%	3	1%	58	71%
G	39	8%	31	8%	5	6%
H	62	13%	61	17%	0	0%
I	40	9%	37	10%	1	1%
Total	466	100%	369	100%	82	100%

As shown in the table, Grid F contained 71 percent of all two-story houses surveyed. However, two-story homes made up only 17 percent of the entire sample. Thus it must be recognized that the sample may not be a perfect representation of the housing population—just considering the sampled geographic distribution of one- and two-story homes. Nevertheless, the sample provides a good cross-section of housing characteristics for damage analysis.

In order to reduce the possibility of co-variant influences of building height on other characteristics, the statistical analysis that follows focuses on one-story homes, which represent over 80 percent of those sampled. When studying building height, only gable roofs were compared in order to eliminate variation in roof type on the building height investigation. Similar measures were taken to single out other damage affects or building characteristics for statistical analysis.

The Chi-square test was used to judge statistical significance. Chi-square, commonly known as a non-parametric test, provides a simple statistical test based on the difference between observed and expected frequency distributions. It is frequently used because it is easy to understand and calculate and makes few assumptions on the underlying population.[30] Chi-square cannot attribute a level of damage from Hurricane Andrew to a particular characteristic of a house—it can only show that a significant difference exists between the level of damage experienced by a category of houses or house characteristics and the level of damage expected for all homes in the hurricane's wake. Comparative tables showing average damage levels were provided only where results are statistically significant to eliminate the potential for misinterpretation. In many cases, statistical comparisons were not significant or feasible; that data is summarized in graphic form.

All Chi-square tests were performed to the customary 95 percent level of confidence. The tests can confirm, with 95 percent certainty, that there are differences in the levels of damage. Conversely, there is a 5 percent chance that the conclusions drawn through application of the test are incorrect, given the assumption of a random sample that is representative of the housing stock in the damage zone. Further, it is generally accepted that test results are skewed when the expected number of observations for a given characteristic-damage combination is less than five. Therefore, when there are fewer than five expected observations, the results of the analysis were treated as being statistically insignificant. In some cases, categories (adjacent cells) were consolidated to get the higher expected values.

The summary data for the entire random survey in Florida is shown in Tables D-1 and D-2 of Appendix D. The damage and housing descriptive statistics presented in the discussions are derived from the information in Appendix D, or are presented as a separate chart with the text. Photographs are used to illustrate the issues covered. In many cases, a summary of the damage data is given with the photograph to help relate the condition of the house to that of the sample population.

The analysis and discussion of damage is presented under individual subheadings to direct attention to specific issues in a sensible progression. The wind damage assessment topics may be categorized as follows:

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[30] Thomas H. Wonnacott and Ronald J. Wonnacott, *Introductory Statistics for Business and Economics* (New York: J Wiley and Sons, 1990).

- Design Issues
  - » Number of Stories (building height effects)
  - » Roof Type (influence of building shape)
- Structural Integrity (Materials and Methods)
  - » Roof Framing
  - » Roof Sheathing
  - » Wall Type
  - » Foundation Type
- Building Envelope Integrity (Materials and Methods)
  - » Water Damage
  - » Roof Coverings
  - » Windows and Doors
  - » Projectiles

However, some of the topics are interrelated. For example, roof covering damage affects water damage, and both influence the level of overall building damage. Likewise, problems in the area of structural integrity will also impact the level of building envelope performance. Case studies and other aspects of hurricane damage such as storm surge are also covered under separate topics.

Number of Stories - This section analyzes the relationship of building height, as measured by the number of stories, to the wind damage experienced. The distribution of the number of stories in the sample is shown in Figure 13.

When analysis is limited to gable roofs, the dominant style in the sample, two-story buildings suffered significantly more damage than one-story buildings in overall building damage (Table 5) and water damage (Table 6). Table 7 shows a higher level of window damage for two-story homes, which seems reasonable given the greater number of windows exposed and the increased opportunity for damage.

Table 5
OVERALL BUILDING DAMAGE IN GABLE-ROOF HOUSES

Overall Building Damage	One-Story	Two-Story
One-Third or Less (=1)	54	5
One-Third to Two-Thirds (=2)	120	18
Over Two-Thirds (=3)	80	45
Total Responses	254	68
No Data	38	3
Average Damage Rating	**2.10**	**2.59**

Table 6
WATER DAMAGE IN GABLE-ROOF HOUSES

Water Damage	One-Story	Two-Story
One-Third or Less (=1)	24	2
One-Third to Two-Thirds (=2)	39	3
Over Two-Thirds (=3)	126	52
Total Responses	189	57
No Data	103	14
Average Data Rating	**2.54**	**2.88**

Table 7
WINDOW DAMAGE IN GABLE-ROOF HOUSES

Window Damage	One-Story	Two-Story
One-Third or Less (=1)	104	1
One-Third to Two-Thirds (=2)	83	9
Over Two-Thirds (=3)	89	11
Total Responses	276	49
No Data	16	1
Average Damage Rating	**1.95**	**2.56**

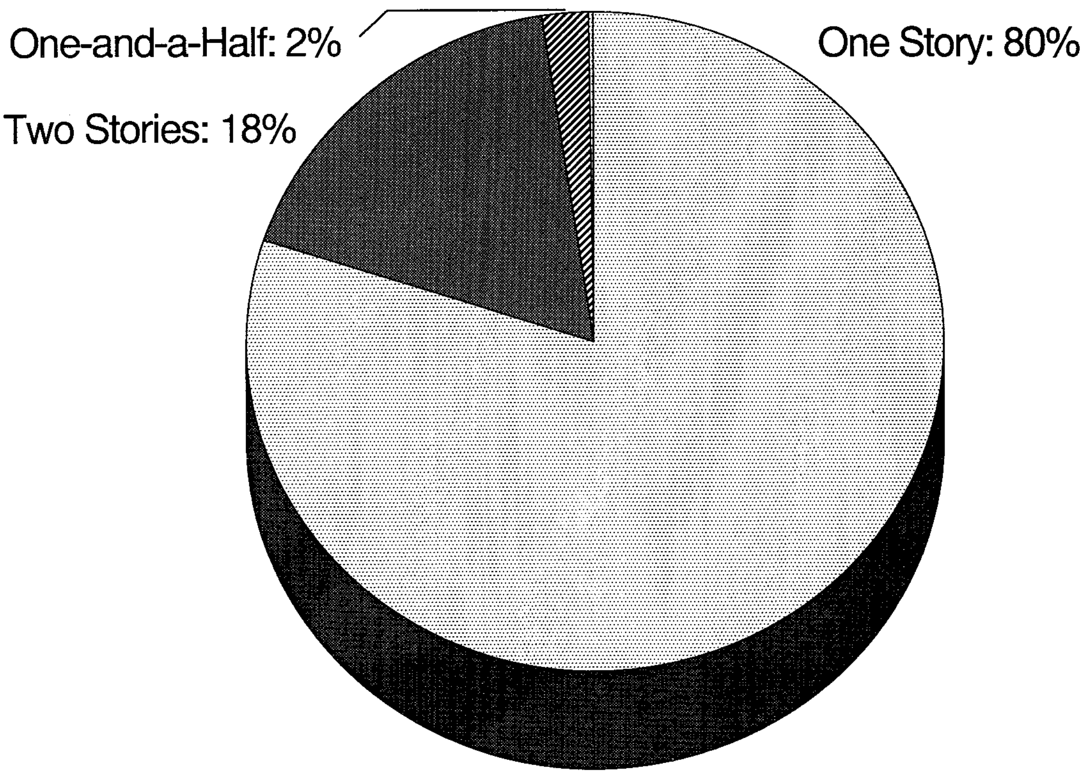

Figure 13. Distribution of one-, one and one-half-, and two-story homes surveyed.

Intuition suggests that one-story construction should be more resistant to wind damage than two-story construction—given that other home characteristics are the same. This understanding tends to be supported in the field survey for the damage categories addressed in Tables 5 through 7. However, differences in the levels of roof damage between one- and two-story homes were not significant. Damages specific to roofs are covered in more detail in the following sections. The reasons for the minimal and insignificant difference in average roof damage and the significant differences in overall damage and water damage between one- and two-story homes may be related to:

- More concern for wind resistance may have been given in the two-story construction sampled, which mitigated the effect of a more severe wind load on the roofs;
- Two-story homes suffered more water damage as a result of a greater number and exposure of windows;
- Two-story homes may suffer less projectile damage to the roof structure; conversely, they may be a prime contributor to projectiles that elevate the roof damage level of lower-profile homes downwind; and
- The dynamic quality of wind (gusts), though theoretically dampened with proximity to the ground, does not appear to be substantially different in terms of destructiveness between roofs on one- and two-story homes.

Many of the homes surveyed survived the extreme winds with minimal structural damage. However, for both one- and two-story construction, it was not uncommon to find two apparently identical homes next to each other with drastic differences in damage. The destruction of one of the adjacent buildings was frequently so complete that a full understanding of minute differences in construction was not possible. However, observations suggest that small, but serious oversights related to structural or architectural design, construction deficiencies, or inadequate window protection, may have precipitated very different degrees of survival. Similarly, small differences in location of a building can subject it to higher wind loads attributed to "hot spots" and wind funneling (Bernoulli effects). It appears that there is a fine line between survival and massive destruction. Examples of damages sustained by one- and two-story homes are shown in Figures 14, 15 and 16.

Roof Type - In the previous section on building height, the differences in roof damage between one- and two-story gable-roof houses was not found to be significant. Only gable-style roofs were examined for the relationship of height to damage levels because there were too few two-story houses of other styles in the sample to allow statistical study. One-story structures proved more varied, with examples of gable, hip, shed, flat, and gable-on-hip type roofs included in the sample. Figure 17 shows the distribution of roof types in one-story homes. Gable and hip roofs dominate the sample and account for 79 and 16 percent of all one-story houses, respectively.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	1
INTERIOR	3
FOUND.	1
GRID	E

Figure 14. Example of a one-story, wind-damaged house. This home had three gable-end walls of which two failed.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	1
INTERIOR	3
FOUND.	1
GRID	F

Figure 15. Example of a two-story, wind-damaged house (concrete block). It was noted that all windows were broken and that sheathing was lost from the roof perimeter. The gable ends did not collapse, but the water damage was substantial due to stripped shingles, broken windows, and lost sheathing.

DAMAGE RATING SUMMARY	
OVERALL	2
ROOF	2
WALLS	1
INTERIOR	3
FOUND.	1
GRID	G

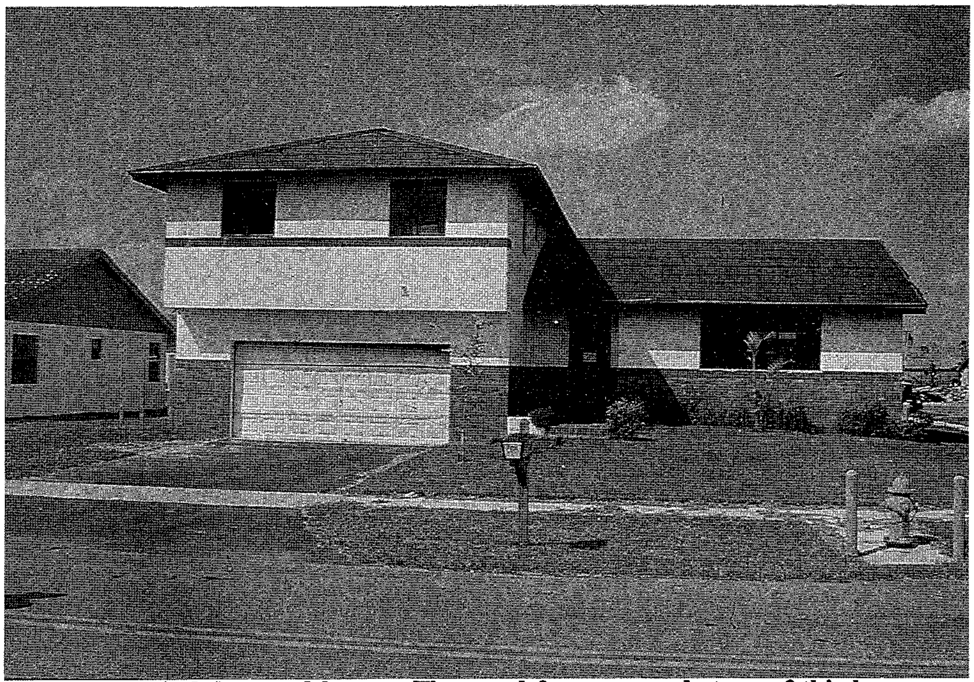

Figure 16. Example of a two-story, wind-damaged house. The wood-frame second story of this house was stressed, but it survived. The crucial damage was from water entering through broken windows, damaged roof coverings and some lost sheathing panels.

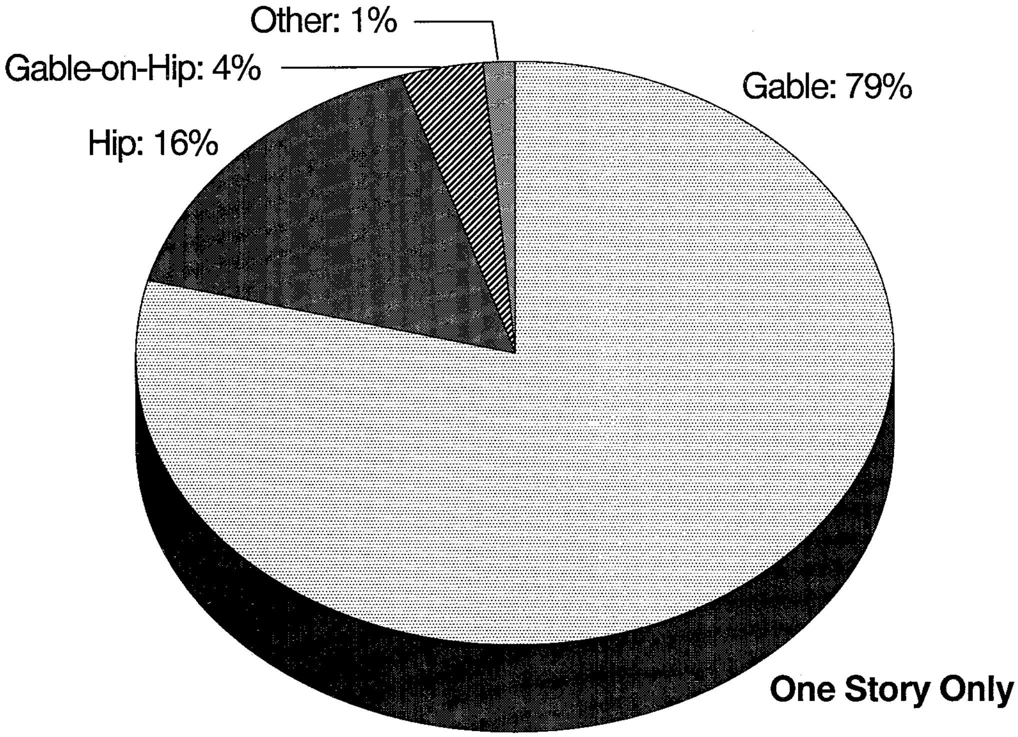

Figure 17. Distribution of roof types in sample.

Table 8 shows the distribution of gables and hips by damage level. The Chi-square test confirmed a statistical difference in the distribution of damage between gable and hip roofs for one-story buildings in levels of roof damage. Analysis also revealed statistical differences between gables and hips in overall building damage, window damage, and water damage as shown in the following Tables 9, 10, and 11.

Table 8
ROOF DAMAGE IN ONE-STORY GABLES AND HIPS

Overall Roof Damage	One-Story Gables	One-Story Hips
One-Third or Less (=1)	54	33
Two-Thirds (=2)	99	17
Over Two-Thirds (=3)	78	3
Total Responses	231	53
No Data	61	6
Average Damage Rating	**2.01**	**1.43**

Table 9
OVERALL BUILDING DAMAGE IN ONE-STORY GABLES AND HIPS

Overall Building Damage	One-Story Gables	One-Story Hips
One-Third or Less (=1)	54	27
Two-Thirds (=2)	120	18
Over Two-Thirds (=3)	80	5
Total Responses	254	50
No Data	38	9
Average Damage Rating	**2.10**	**1.43**

Table 10
WINDOW DAMAGE IN ONE-STORY GABLES AND HIPS

Window Damage	One-Story Gables	One-Story Hips
One-Third or Less (=1)	104	29
Two-Thirds (=2)	83	16
Over Two-Thirds (=3)	89	6
Total Responses	276	51
No Data	16	8
Average Damage Rating	**1.95**	**1.55**

Table 11
WATER DAMAGE IN ONE-STORY GABLES AND HIPS

Water Damage	One-Story Gables	One-Story Hips
One-Third or Less (=1)	24	12
Two-Thirds (=2)	39	9
Over Two-Thirds (=3)	126	14
Total Responses	189	35
No Data	103	24
Average Damage Rating	**2.54**	**2.06**

It can be said with a high level of confidence that the damage incurred by one-story homes with hip roofs was significantly less than similar homes with gable roofs. Figure 18 presents this finding in terms of roof damage levels. Examples of wind-damaged gable and hip roofs are pictured in Figures 19 and 20, respectively. It should be noted that about 22 percent of single-story homes with gable roofs in the survey suffered high damage levels (Levels 2 and 3) to the gable (see Appendix D, Tables D-1 and D-2). In general, about one out of five homes from the total sample had gable roofs with high levels of damage. Of those remaining, three out of five homes were gable roofs with little structural damage, and one out of five were hip roofs with little structural damage.

The damage to gable roofs represents a major portion of the structural damage experienced by the surveyed homes. Approximately 90 percent of the homes with roof structural damage of Levels 2 and 3 had a gable roof.

There are a number of possible reasons for the significantly better performance of the hip-roof homes surveyed. These include:

- The framing geometry of hip roofs inherently braces the roof and end walls against lateral loads.
- Hip roofs are more efficient aerodynamically and therefore introduce lesser loads to the structure and its components.
- Framing of hip roofs requires a higher level of carpentry skill to build than gable ends and, therefore, may tend to be built to a higher standard of workmanship.
- The surveyed homes with hip roofs showed a higher frequency of wind resistant roof coverings (see upcoming section, Roof Coverings) and, coincidently, also appeared to have made greater use of window protection, which could explain the lower levels of window damage.

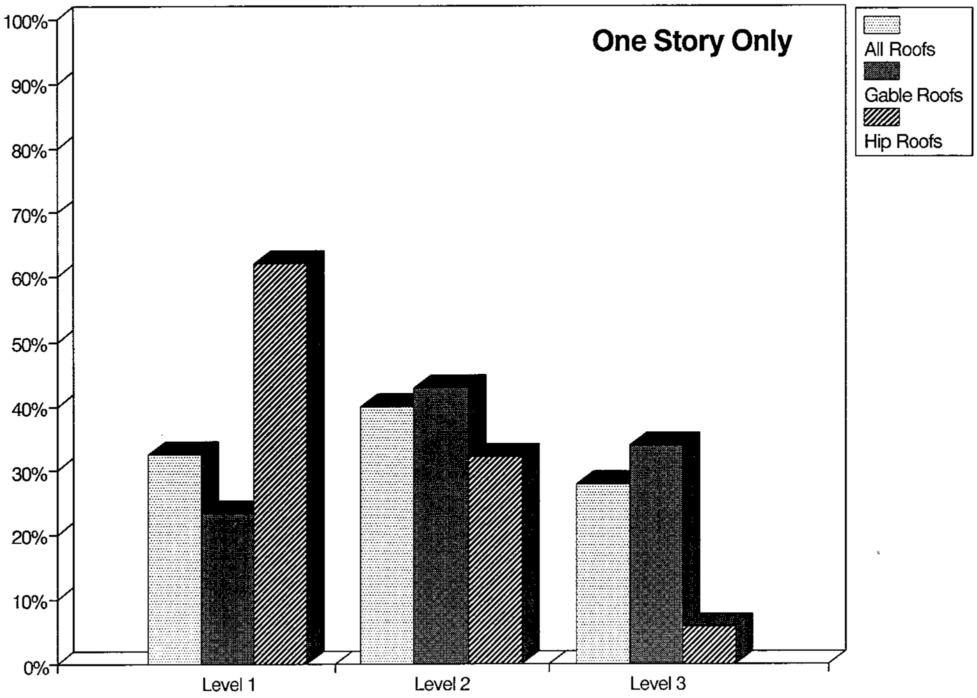

Figure 18. Distribution of roof damage to hip and gable roof types.

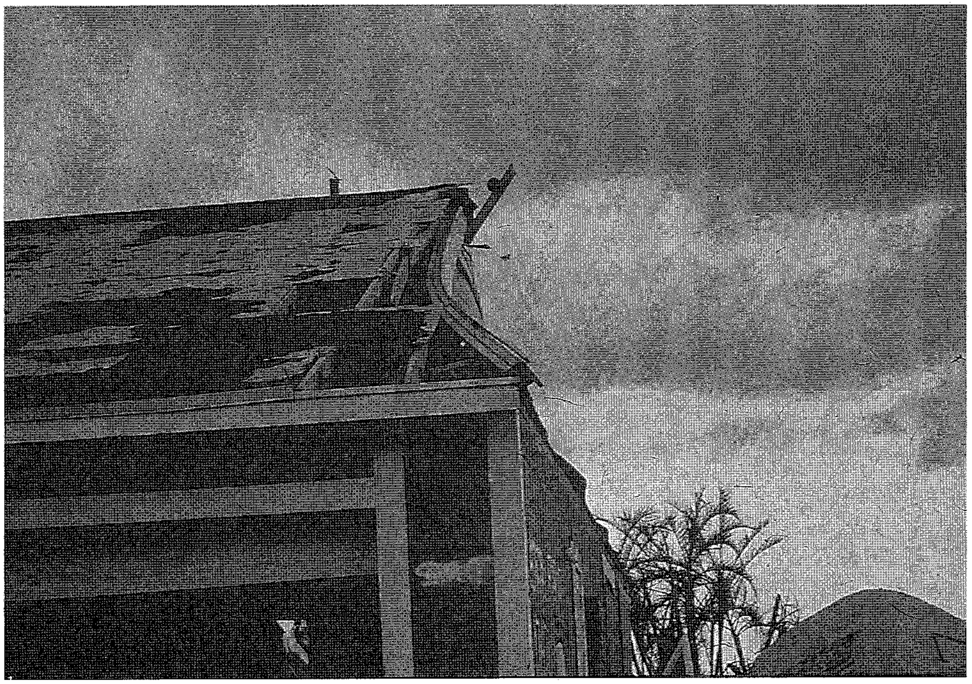

Figure 19. Wind damaged gable end wall. This home was not part of the random sample.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	1
WALLS	1
INTERIOR	1
FOUND.	1
GRID	A

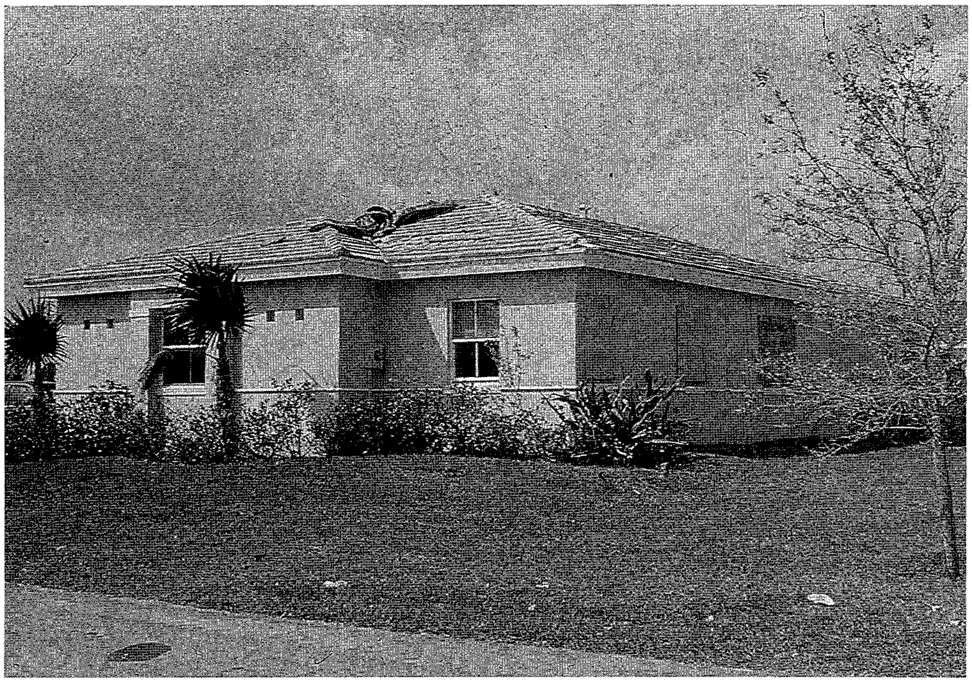

Figure 20. A low-profile hip roof with minimal wind damage. Loss of unprotected windows was the primary reason for the limited water damages noted on the survey sheet.

Table 12 shows the grid location of one-story gables and hips sampled. The large proportion of hip roofs in Grids A, B, C, and D stands out, as does the predominance of gable roofs in Grids E and H (see Figure 7). Grids A and B are the northernmost grids in the survey area and are believed to have borne the highest sustained winds,[31,32] as shown in Figure 6.

Table 12
GRID LOCATIONS OF ONE-STORY GABLE- AND HIP-ROOF HOUSES

Grid	All One-Story		One-Story Gables		One-Story Hips	
	Number	Percentage	Number	Percentage	Number	Percentage
A	29	8%	15	5%	9	15%
B	43	12%	22	8%	14	24%
C	51	14%	37	13%	14	24%
D	52	14%	41	14%	10	17%
E	62	17%	58	20%	3	5%
F	3	1%	0	0%	1	2%
G	31	8%	25	9%	6	10%
H	61	17%	61	21%	0	0%
I	37	10%	33	11%	2	3%
Total	369	100%	292	100%	59	100%

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[31] Reinhold, Vickery, and Powell.

[32] Powell and Houston.

Gable ends create not only larger, more abrupt obstructions to the wind (less aerodynamic) but also create higher pressures at discontinuities in the building geometry (such as at the roof perimeter). It follows that the gable-end construction is less forgiving of deficient design or construction. In a number of cases where gable-end roofs had failed, it was apparent that nailing of roof sheathing at the top chord of the gable-end truss was inadequate at this most critical location.

Roof Framing - Figure 21 shows the distribution of roof framing types found in the survey. Structural damage to roof systems, particularly gable roofs, accounts for about 97 percent of the overall structural damages observed in Florida. Most homes sampled used metal plate-connected wood trusses. There were an insufficient number of observations of wood rafter homes to allow a statistical comparison to the performance of wood trusses. Many homes with rafter construction also used wood trusses, which complicated attempts to analyze this topic comparatively.

Wood trusses, as individual components, performed satisfactorily. However, the loss of a few panels of roof sheathing often led to structural failure and collapse of the roof system. Gable-end trusses were left hanging by their hurricane straps (see Figure 22) or were severely stressed in nearly one out of four single-family homes with gable roofs. Again, this represents the most significant element of structural damages experienced by the single-family homes surveyed. Some manufacturing defects of roof trusses were observed as shown in Figure 23, but these were uncommon and probably had little influence on the overall performance.

Most observed failures in roof systems (rafters and trusses) were attributed to installation and design shortcomings such as inadequate fastening of roof sheathing, and insufficient anchoring at rake overhangs. There was a notable lack of secondary bracing at gable ends; however, it cannot be overstated that secondary bracing will provide little benefit in limiting overall building damages without solving the primary problem associated with sheathing fastening. In fact, with proper sheathing connections to provide lateral bracing, most roofs survived intact with minimal secondary (lateral) bracing. Nevertheless, in the few situations where well-designed lateral bracing was used at gable-ends, the roof structural framing was usually intact even though sheathing may have been lost. Secondary bracing appeared to be more important to taller roofs with larger gables. Lateral bracing was not an issue with hip roofs, which are inherently braced by their framing geometry, as mentioned in the previous section.

It is common practice to rely on the diaphragm of the roof sheathing and ceiling drywall to provide lateral support to the roof framing. This engineering condition is based on the assumption that the diaphragm skins are attached according to code or acceptable practice. In order to perform their function, the roof sheathing or other diaphragm materials must survive intact.

An important problem in roof framing was also observed for features such as soffits or overhangs. Any extension of the roof beyond the wall surface elevates wind pressures on both the sheathing and the framing system at these locations. In some cases where rake overhangs were used, nailing of the roof sheathing to the top of gable end trusses was inadequate. The photograph in Figure 24 demonstrates the result of a common framing problem at rake overhangs, which resulted in the loss of sheathing and the rake as shown.

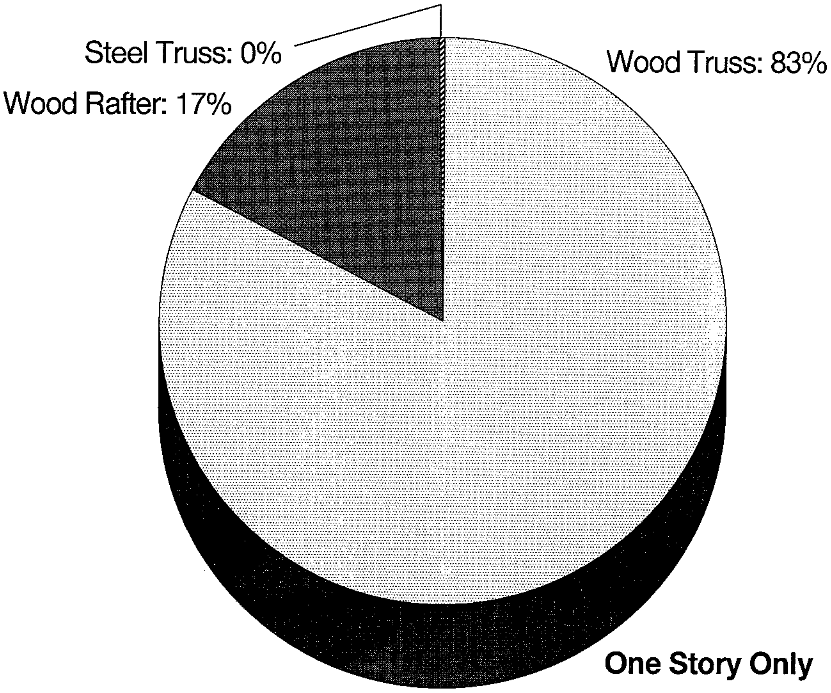

Figure 21. Distribution of roof framing methods and materials.

Figure 22. A gable-end truss dangling by hurricane straps.

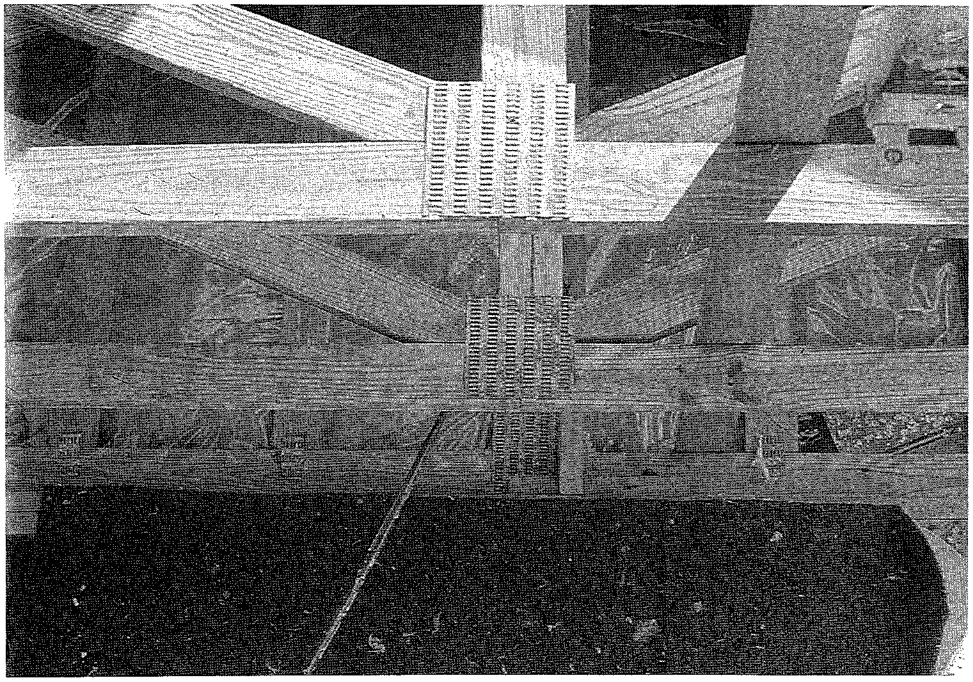

Figure 23. Misplaced (or undersized) steel connection plates on wood trusses.

Figure 24. Illustration of wind damage to rake overhangs when overhang framing was not anchored back into the roof system.

Roof Sheathing - The most frequently used sheathing material in the sample was plywood. Figure 25 shows the distribution of materials in the houses sampled. There were an insufficient number of observations of either board- (lumber) or OSB-sheathed roofs to allow statistical comparison with the performance of plywood sheathing.

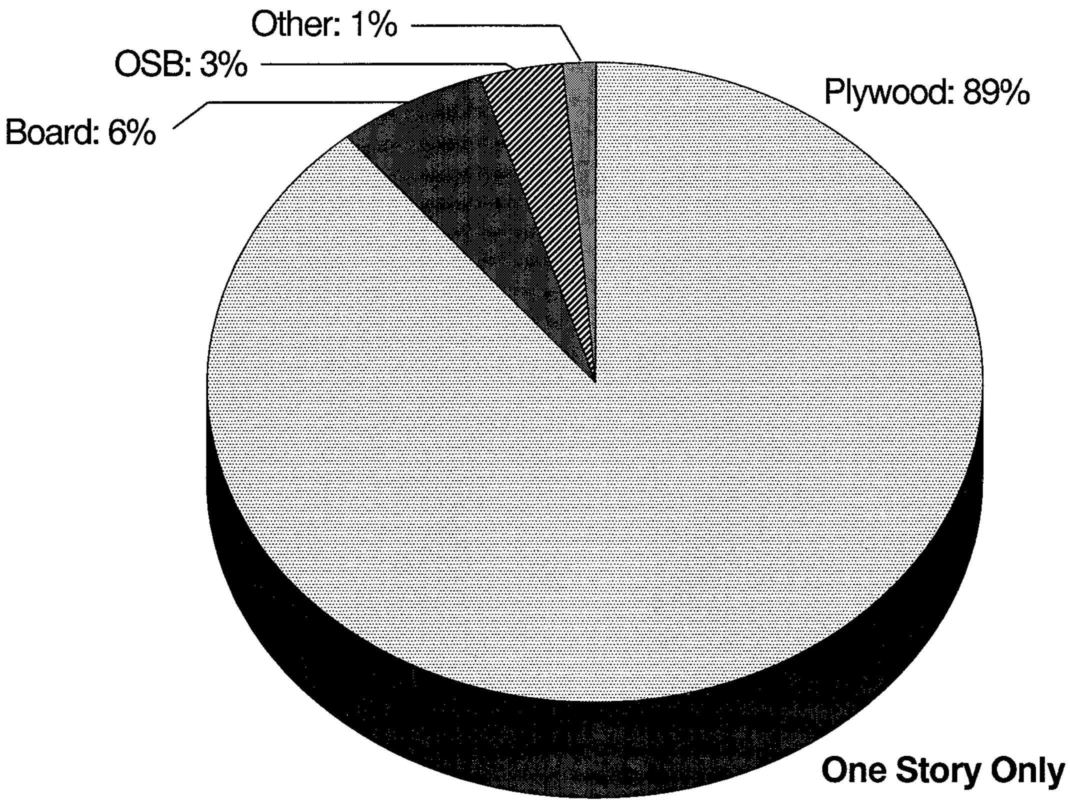

Figure 25. Distribution of roof sheathing materials.

About 24 percent of accessible homes in the survey were rated at damage Levels 2 and 3 for roof sheathing (more than one panel missing or severely damaged). Detailed data was not obtainable for fastener spacings on roof sheathing; however, scattered observations by those conducting this survey tend to confirm reports by others that indicate inadequate fastening of sheathing is a major causative factor to the structural damage observed. There were no indications from the field observations that one particular roof sheathing product was inferior to another. Some faults in sheathing installation noted in the field by this report and others are:

- Inadequate adherence to recommended nail spacings.
- Fasteners missing framing.
- Fasteners overdriven into sheathing.
- Fasteners driven too close to the edge of sheathing panels.
- Poor roof framing details at rake overhangs, which over-stressed sheathing and connections.

Commonly observed loss of roof sheathing in high-pressure areas of the roof is illustrated in Figure 26. The roof sheathing is a critical component that locks the roof structure together. When the sheathing was lost the roof frequently collapsed, which led to failures in other components of the building. This in turn drastically increased the levels of water damage. Wind damage to roof sheathing was probably exacerbated in some cases by window and door failures, which produced internal pressures and significantly higher loads on the roof sheathing.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	3
INTERIOR	3
FOUND.	1
GRID	1

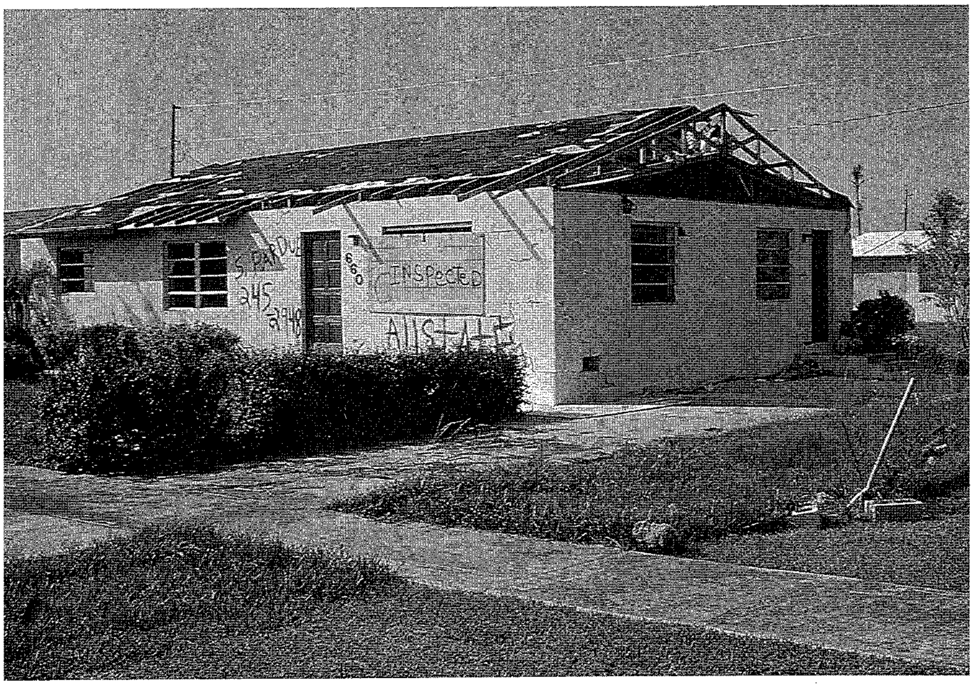

Figure 26. Loss of roof sheathing in high-pressure areas of the roof, especially at gable ends where rake overhangs were commonly framed for appearance and not for strength. Note also the fracturing of the block wall.

Wall Type - The materials used in exterior walls were classified into two major categories: concrete masonry and wood framing. Of the various components or characteristics of the homes surveyed, materials used for exterior wall construction were the most homogeneous—99 percent of all homes in the sample had concrete block and stucco (CBS) systems on the first story. Of the small percentage of two-story homes in the survey, 17 percent had wood framing on the second floor. Since wood-frame homes are thought to be in the order of 10 percent (or greater) of the housing stock in Dade County, wood framing is addressed in more detail in a case study later in this report.

For the sample as a whole, only 7 of 466 houses surveyed exhibited first-floor wall damage greater than Level 1, and only one two-story home was judged to have second-story wall damage exceeding Level 1. However, there was insufficient variation in construction to make any statistical comparisons from the sample of wall types obtained.

Severe structural damage to concrete block and stucco (CBS) walls was infrequent. Damage was usually associated with insufficient reinforcement for continuous load paths from the upper tie beam, through the wall, to the foundation. Similarly, a few cases (outside of the survey) were observed where discontinuities in the reinforcement of concrete tie beams or insufficient overlap at corners resulted in collapse of CBS walls. Generally, damage to the walls of the CBS homes surveyed was limited to minor damage from projectiles and cracking. Damage to a CBS wall under construction is shown in Figure 27.

In the random survey, wood-frame wall construction was found in only 5 percent of the homes surveyed, and almost all of this was in wood-frame second stories over CBS first stories. The wood-frame second stories in the survey had higher levels of structural damage than their CBS counterparts, although the amount of water damage tended to level differences in overall damage. A common failure in the wood-frame second stories was related to improper connections of top plates at the corner joint. Wood-frame walls rely heavily on the roof system to provide lateral support. When the roof structure fails, the wood-frame walls may lack the strength by themselves to withstand severe wind loads. Damage to a wood-frame wall is shown in Figure 28. The failure of this wall may be attributed in large part to inadequate fastening at the corner. The top plate members were not overlapped or otherwise fastened to provide a structural connection at the corner. This is discussed further in the wood-frame case studies later in this report.

In practice, interior walls may serve as shear walls to add lateral stiffness to the exterior load-bearing walls. Interior walls experienced high wind pressures when doors, windows or exterior walls failed. Under these circumstances, it was observed that light-gauge metal stud partition walls often buckled or collapsed. These walls are not designed to withstand high (over 5 psf) lateral loads.

Figure 27. Wind damage to a CBS wall under construction. Note the rebar withdrawal at the corner of the concrete tie beam and the absence of rebar for the wall in the foreground.

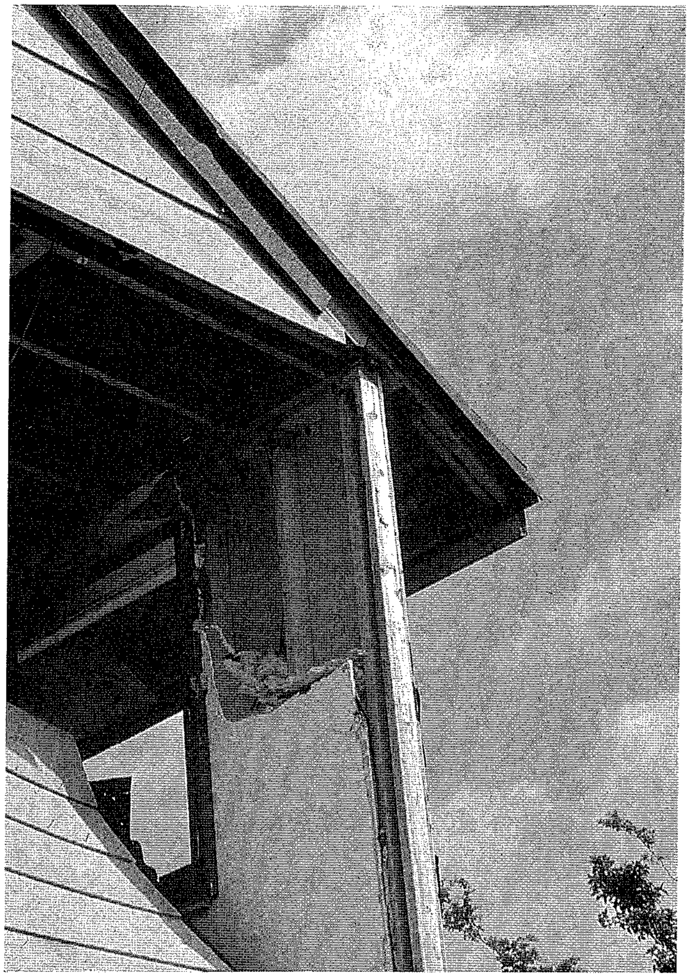

Figure 28. Wind damage to a wood-frame wall (two-story) showing improperly connected corner.

Foundation Type - The most common foundation type used in South Florida is slab-on-grade. All of the homes surveyed had this type of foundation. Of the accessible slab-on-grade foundations, all but one were judged to fall in the lowest damage category and most had no visible damage. The one observed slab-on-grade foundation with notable damage had a large crack that the owner found underneath damaged carpeting, which was removed after the hurricane. This crack was not likely a result of wind damage.

Water Damage - Many of the homes surveyed suffered severe losses from water damage to interiors. Though the survey team could not gain access to all homes, more than 65 percent of homes examined were classified as a near total loss due to water damage (Level 3). Items damaged by water varied, but represented a substantial portion of property loss and cost of repairs. The high level of water damage relative to overall building damage in the surveyed homes is shown in Figure 29. The overwhelming significance of water damage cannot be understated.

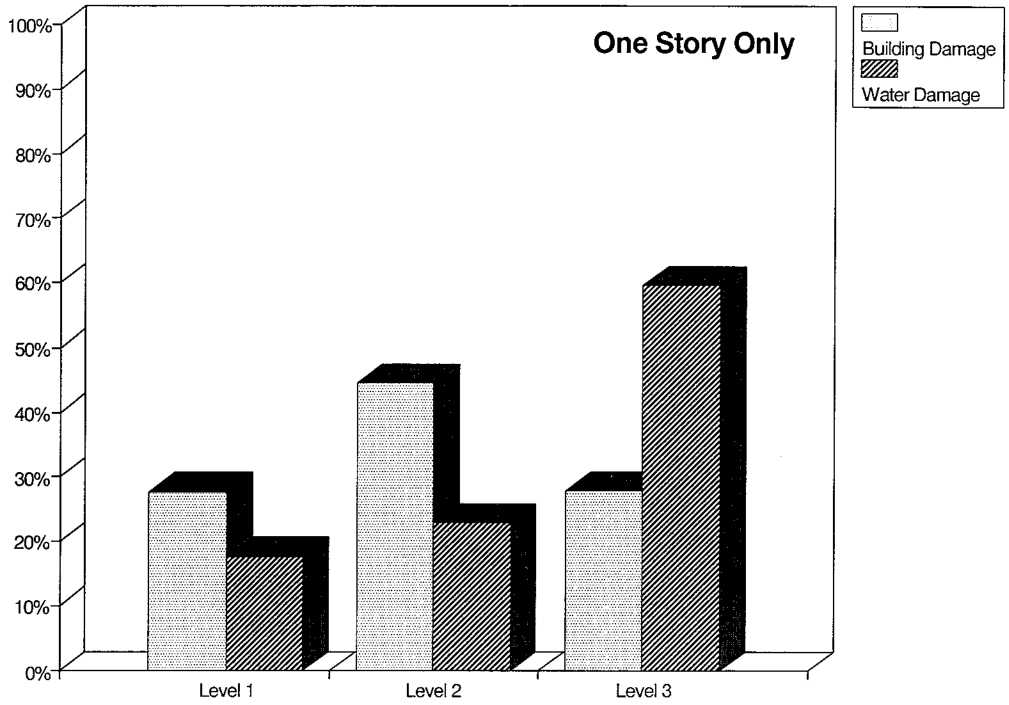

Figure 29. Level of water damage exhibited by one-story homes.

Between the onslaught of Hurricane Andrew on August 24 and the arrival of the survey team on October 5, interior water damage progressed even further. Damage to buildings in the affected area was so extensive that little could be done to protect them from further water damage. Interiors in many homes were soaked several times by successive rainstorms before temporary measures, such as tarpaulins, were available. Other homes were abandoned.

Building components vary in their susceptibility to water damage. Home contents vary, too. Major items that are more susceptible to water include drywall, carpet, and furnishings. Some interior finishes, particularly terrazzo or grouted tile floors and stucco interior walls, survived with little or no damage. Severe but common losses from water damage are pictured in Figure 30.

In most cases, there was no way for the survey team to distinguish between water damage from Hurricane Andrew and the ensuing rains. However, findings in the preliminary survey and discussions with home owners indicate that drywall ceilings did fail during the hurricane, as shown in Figure 31. Failure of a drywall ceiling of this type will weaken the roof system and reduce lateral support to exterior walls.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	1
INTERIOR	3
FOUND.	1
GRID	F

Figure 30. Items commonly damaged by water are piled in front of this home, which lost all of its windows, the garage door, much of the roof covering, and some roof sheathing. This severely damaged home is essentially intact structurally.

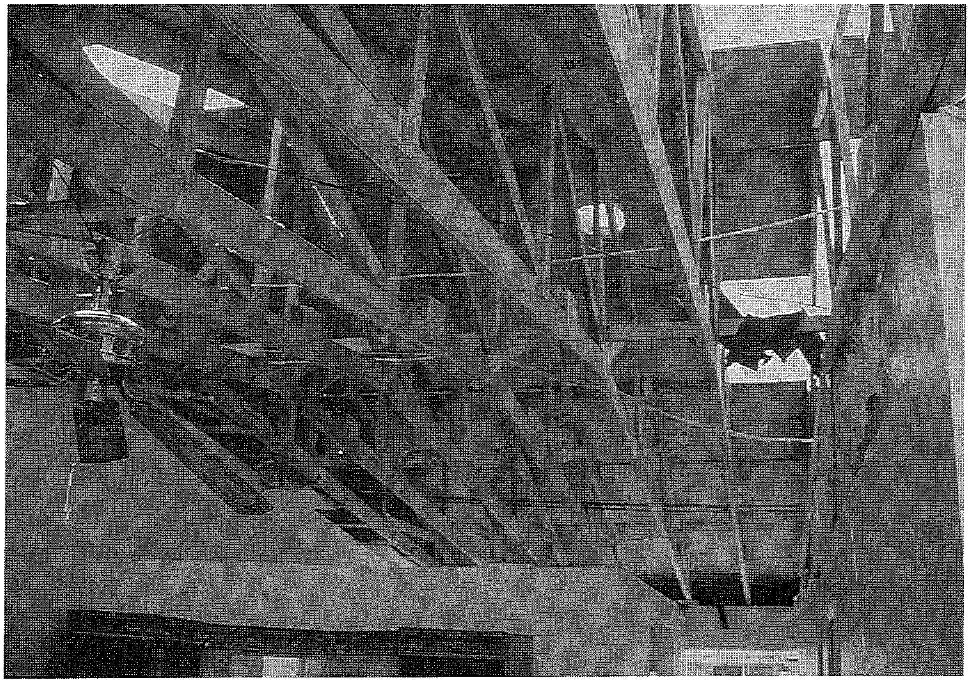

Figure 31. Illustration of a collapsed drywall ceiling from water damage.

Roof Coverings - Figure 32 shows the types of roof coverings found in all homes, one-story gable-roof homes, and one-story hip-roof homes in the survey.

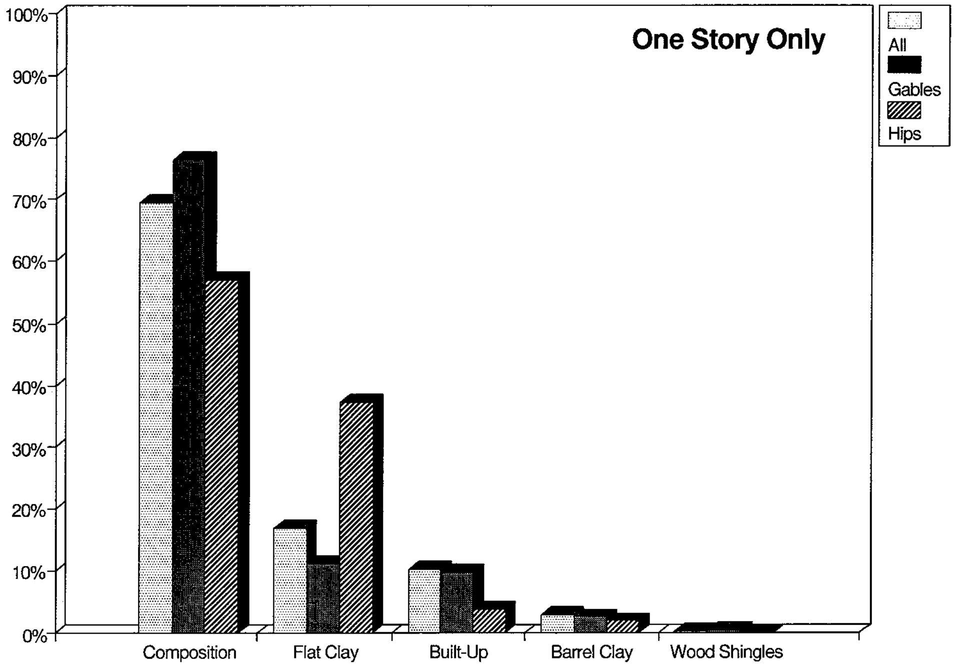

Figure 32. Bar graph showing roof coverings for gable, hip, and all single-story houses surveyed.

Roof covering failures represent a major factor in the high level of water damage experienced. Of the accessible homes, 77 percent were rated at Levels 2 and 3 for roofing damage. However, there were not enough observation points to conduct a statistical analysis on the performance of the different types of coverings, partly because of repairs or temporary coverings.

Common performance problems affecting roof coverings included poor installation and inadequate material characteristics relative to the storm severity. It should be recognized that most roof coverings were not designed to weather a hurricane such as Andrew. As expected, some materials were observed to perform better than others. However, all types of roofing were subject to severe damage.

Flat tile roof systems seemed to exhibit the best resistance to both projectile damage and wind uplift, and provided a higher degree of protection against water damage. The hip roofs surveyed had a much larger proportion of flat tile roofing than homes of other roof types, which may have contributed to the higher rate of survival for hips. While contoured clay tile (barrel shaped, etc.) seemed to out-perform composition shingles, there were some problems observed. It appears that the higher profile of the contoured tiles provided greater opportunity for projectile damage and wind uplift. Consequently, deficient installation practices were magnified. A common factor in the tile roofs was the lack of a full mortar bed and a good bond to the mortar. Also, it was observed that holes provided in the tiles for mechanical fasteners were occasionally not used, or undersized fasteners were used. It was apparent that the waterproof underlayment beneath all types of tiles provided an additional degree of protection against water damage.

Composition shingles, which are the most common roofing material in most areas of the United States, provided the lowest level of protection, primarily because of material characteristics. However, some installations of higher quality composition shingles appeared to perform well. Additional measures required by SFBC for applying roofing cement to cap shingles and certain other locations did not appear to be very effective in the severe winds experienced. Wind damage to different roof coverings is pictured in Figures 33 through 35.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	1
WALLS	1
INTERIOR	1
FOUND.	1
GRID	B

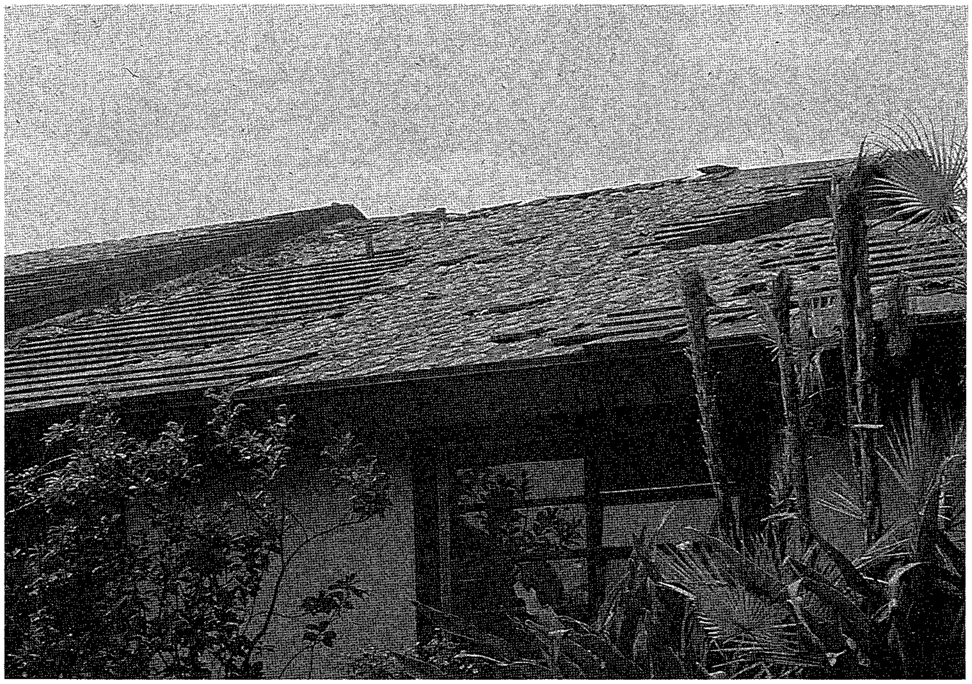

Figure 33. Wind damage to a flat tile roof. In part, the use of insufficient beds of cement mortar contributed to this unusual level of damage for flat tile roofing. Roofing underlayment prevented serious water damage. The "Roof" damage rating includes all elements of structural integrity along with water resistance.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	2
WALLS	1
INTERIOR	1
FOUND.	1
GRID	E

Figure 34. Wind damage to a barrel clay tile roof. In part, the use of insufficient beds of cement mortar contributed to this level of damage for some barrel-clay tile roofing. Roofing underlayment normally prevented serious water damage.

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	2
WALLS	1
INTERIOR	3
FOUND.	1
GRID	C

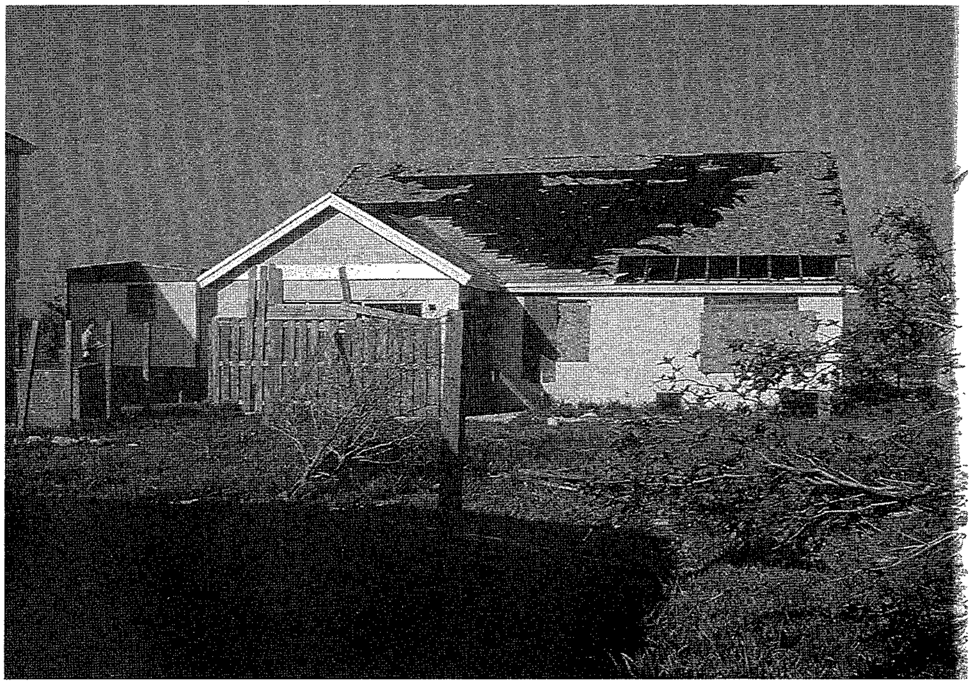

Figure 35. Wind damage to a composition shingle roof. Composition shingles were almost completely removed on many homes by Andrew's winds. The extensive water damage overrides the relatively sound structural condition of this house.

Windows and Doors - Window or door failures are often the first step in a rapid chain of events leading to severe damage of homes. In a storm of the magnitude of Hurricane Andrew, wind entering through breaches in the building envelope, an open or broken window or door, can produce high internal pressures. At the same time, aerodynamic drag, resulting from high winds passing over the building's exterior, create suction pressures on the other sides. These two forces acting in the same direction (outward) can have an explosive outcome with wind pressures twice as high as before the building envelop was breached. Windows, doors, interior walls, and roof sheathing are more likely to fail under these conditions. Field observations and interviews with home owners lend consistent support to this scenario.

The distributions of window damage and door damage in one-story homes are shown in Figures 36 and 37, respectively. About 64 percent of the homes experienced at least one broken window. Observations taken immediately before and after Hurricane Andrew indicate that as many as 80 percent of the homes did not exhibit adequate window protection. A simple, but effectively applied plywood window covering on these homes may have dramatically reduced the levels of damage. However, storm shutters alone did not completely guarantee protection for windows in the fierce winds of Hurricane Andrew. The survey team noted that even windows with considerable protection suffered damage. Metal grating and shutters were often severely bent or even penetrated by flying debris. One home owner related that he witnessed a fractured clay roof tile projectile puncture his metal hurricane shutters, break the window, and continue across the room, slamming into a piano. However, the storm shutters still provided sufficient resistance to the wind in this case. Generally, hurricane shutters appeared to notably reduce the potential for water damage and structural damage resulting from internal pressurization of the building. A common example of damage to unprotected windows is shown in Figure 38. The effective use of hurricane shutters on windows is shown in Figure 39.

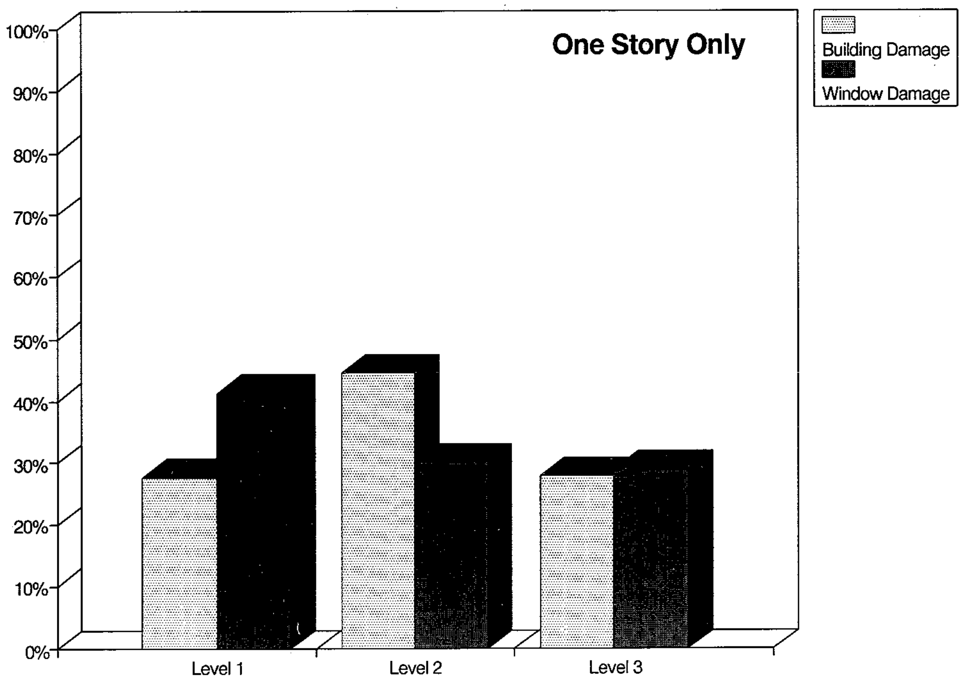

Figure 36. Distribution of window damage experienced by homes in the sample.

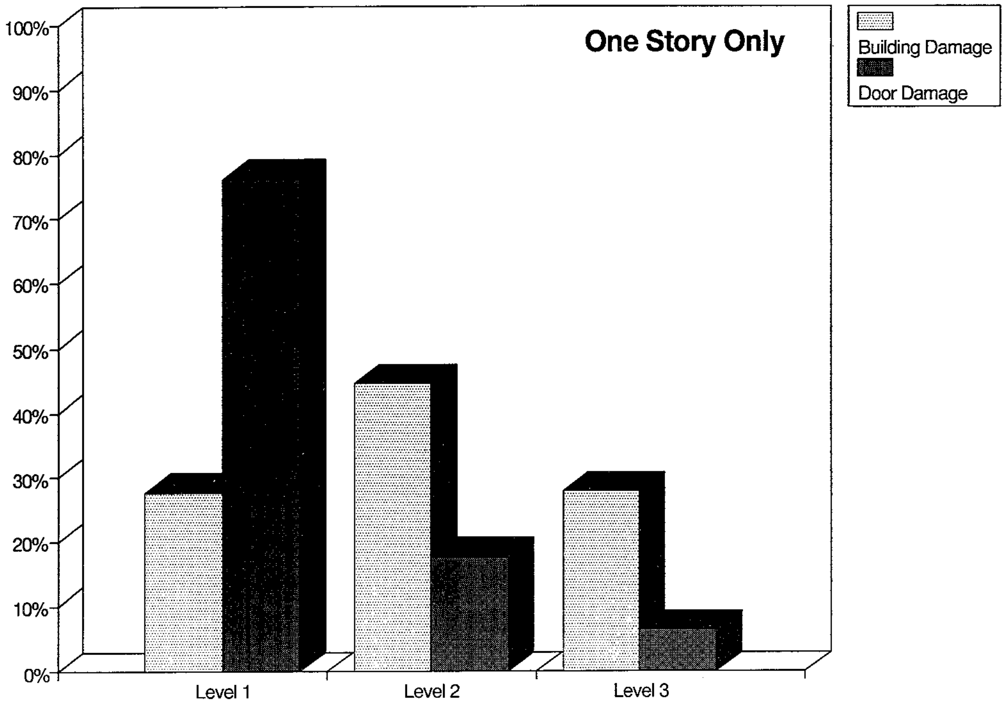

Figure 37. Distribution of door damage.

Figure 38. Illustration of damage to unprotected windows.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	2
WALLS	1
INTERIOR	1
FOUND.	1
GRID	B

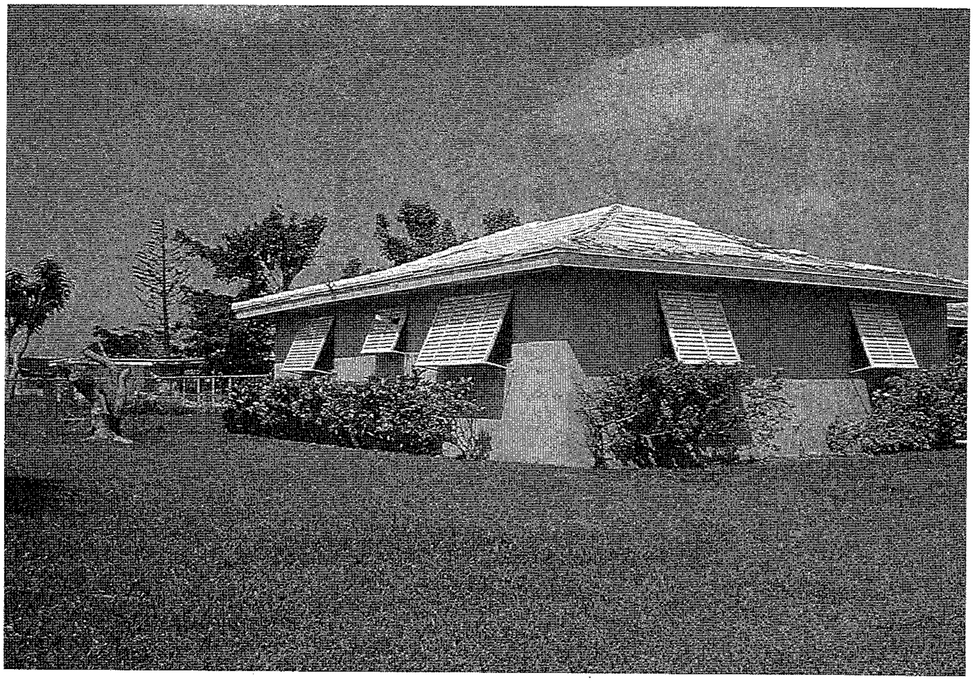

Figure 39. Simple hurricane shutters provided adequate window protection for this home. Water damage was minimal.

The survey team also noted many cases of entrance door failures. Most designs put the entire wind load on the hinges and the latch. Doors that are fitted with strong floor and jamb deadbolts, or open outward so that the jamb stops give support against inward wind forces, limit the potential for door failure. Damage to a pair of double doors is shown in Figure 40.

Figure 40. Illustration of damage to double entrance doors.

Garage doors provided another weak link in the building systems surveyed. Though not broken out on the survey form, team members examined many garage doors and found them to be reinforced with two-by lumber fastened edgewise to the back of the door as required by code. However, garage doors often failed because the fastening of the door track to the wall opening failed, or the track and wheel system failed. All of the garage doors surveyed were installed so that the track fasteners were loaded in the more severe direction of withdrawal from the inside edge of the opening. This is common practice and is not very forgiving of fastening deficiencies or overloading. An example of a garage door failure is shown in Figure 41.

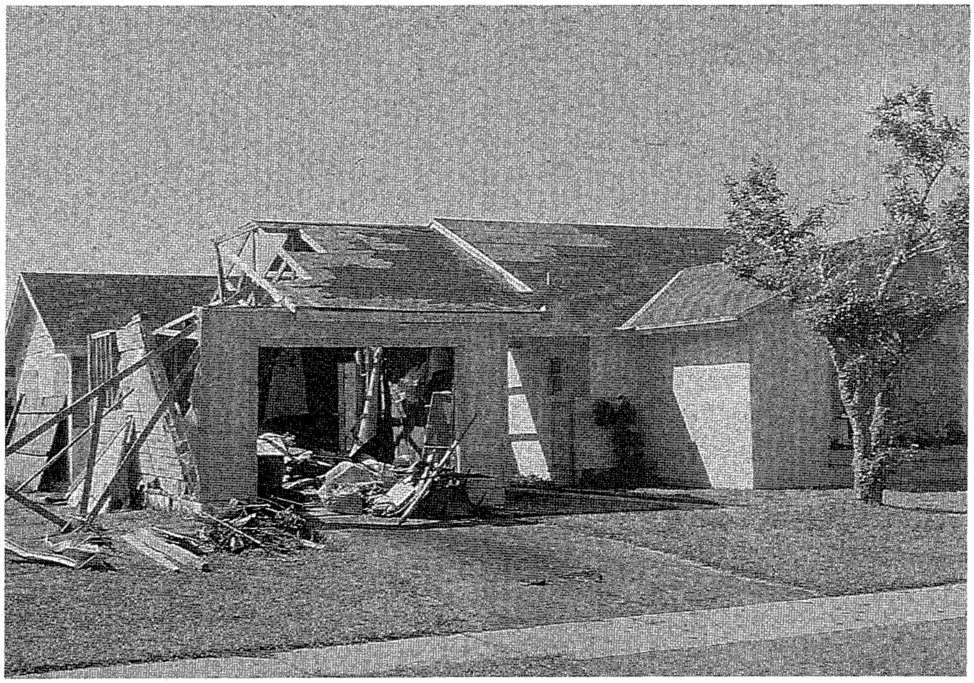

Figure 41. This garage door failure lead to internal pressures that contributed to blowing out the roof and the improperly connected wall corner joint of the garage.

Projectile Damage - All structures exhibited some damage from flying debris or projectiles. Projectile damage to walls, windows, and roofs was interrelated with water damage. Flying debris is a major cause of unprotected window damage, which contributes to internal pressurization and more serious structural and water damage. Recognized projectile sources contributing to the damage incurred during Hurricane Andrew included:

- Accessories to homes (e.g., porches, storage buildings, pool enclosures, and fences);
- Roofing materials (e.g., shingles, tiles, and gravel);
- Inadequately attached storm protection (e.g., plywood window covers);
- Inadequately attached or over stressed components and cladding of buildings (e.g., sheathing and siding); and
- Natural debris (e.g., rocks and tree limbs).

These sources were observed in the damage area during the survey and confirmed in discussions with home owners who weathered the hurricane in their houses. In a few cases, the projectile was part of a roof or other major section of an upwind structure. The distribution of projectile damage to surveyed homes is shown in Figure 42.

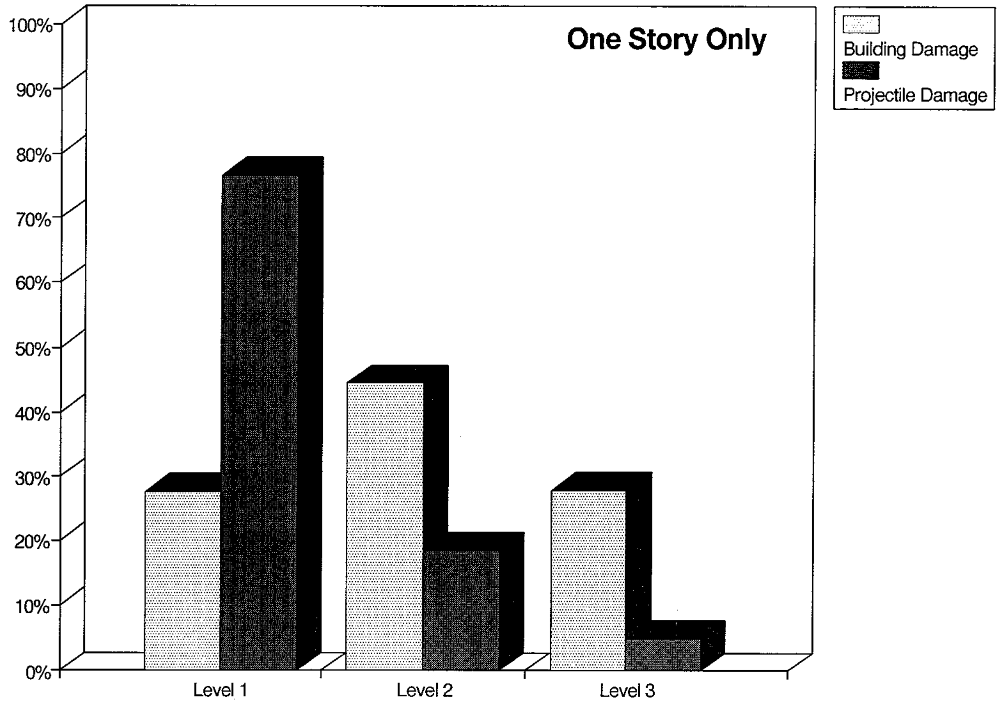

Figure 42. Severity of projectile damage relative to overall building damage.

Although much of the projectile damage was rated in the lower category, even small projectiles can have a major impact (see Figure 43). On the other hand, the projectile damage to elements such as CBS walls was relatively low or superficial. Improvements in areas such as roofing systems (materials and installation) and window protection (preparedness) will not only improve the performance of individual homes but will also reduce the proliferation of projectiles and their associated damages.

Case Study of Wood-Frame Construction

The selection process for the main survey resulted in few homes with wood framing, and no homes in the sample were constructed entirely of wood-frame. Wood framing is used in about 10 to 15 percent of new housing built in southern Florida in recent years.[33] Because wood framing is relatively new to southern Florida, it probably represents a much smaller, but growing, proportion of the overall housing stock. Therefore, at HUD's request, a group of wood-frame homes were selected outside of the statistically based survey sample to obtain information on this type of construction.

Most of the selected wood-frame homes were located in or near the communities of Country Walk and Keysgate. Their locations are shown on the map in Figure 7. These communities had been reported as suffering some of the worst damage. Both CBS wall construction and wood

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[33] NAHB Research Center, *Annual Building Practices Survey* (Upper Marlboro, MD: NAHB Research Center, 1990).

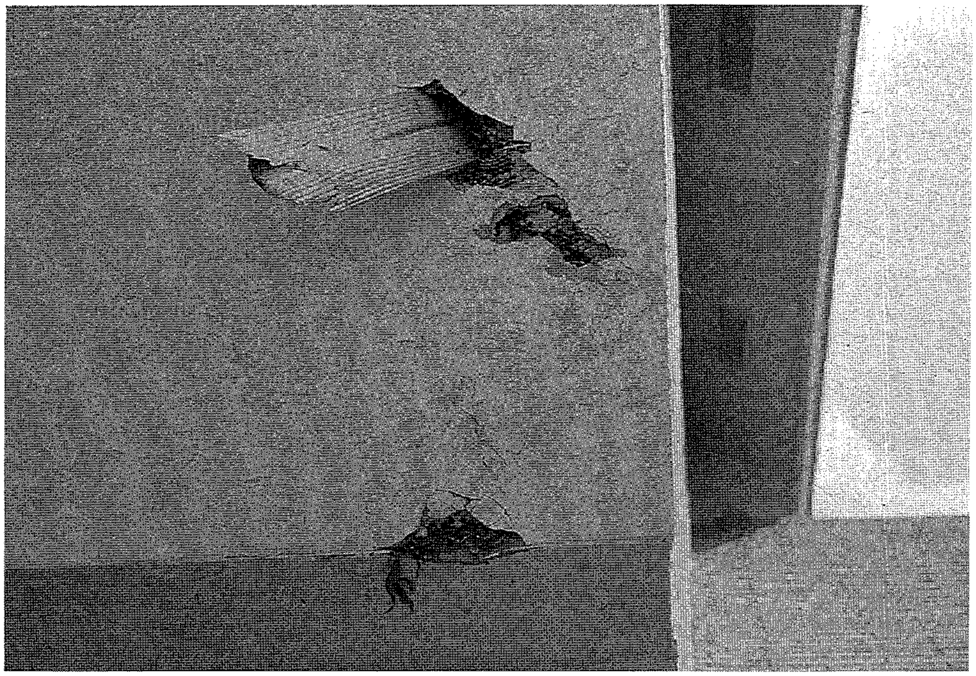

Figure 43. An example of projectile damage—a 1x fence board pierces the stucco finish and sheathing on a wood-framed wall.

framing were found in these communities and adjacent areas. The summary data for all case study single-family homes (both wood-frame and CBS) is presented in Appendix D, Tables D-3 and D-4. Summary data exclusively for the wood-frame homes in this case study sample, including those with CBS lower levels, is shown in Tables D-5 and D-6 of Appendix D.

The study homes were of one-, one and one-half, or two-story wood-frame construction, with truss-frame roofs and composition shingle roofing. There was a higher proportion of one-and one-half- and two-story homes in the wood-frame case studies. Roof types varied, but gable roofs were the most common. Many of the wood-frame homes had notably steeper and taller roofs than in the survey sample. The majority of the wood-frame homes in the case studies had wood fiber (hardboard) lap wall siding. All of the wood-frame homes in the case studies had composition shingles, whereas 73 percent of the homes in the survey used composition shingles. All were built on slab-on-grade foundations. Collectively, these differences in characteristics tend to increase the susceptibility to wind damage.

Some homes experienced failures in which exterior walls collapsed or racked because of inadequate stiffness from the siding materials used. Roofs on these homes were usually severely damaged, with pronounced shingle and sheathing loss. Steeper pitched roofs aggravated wall problems by placing greater loads on the walls, secondary roof bracing, and roof sheathing.

The interiors of these homes generally suffered heavy water damage and many were abandoned. The severe damage to these homes may be attributed to a combination of higher risk conditions including: design (e.g., steep gable roofs), materials (e.g., composition shingles), workmanship (e.g., fastening and connections), and lack of preparedness (e.g., window protection). Also, the area of Country Walk was likely subject to the worst of Hurricane Andrew's maximum winds (see Figure 6).

Figures 44 to 48 depict the type of damages found in the wood-frame homes. The more prominent damage was to roof sheathing and to walls, particularly on second stories, which was certainly influenced by roof failure. Substantial improvement could be expected in wind resistance of wood-frame homes by improved roof sheathing attachment, improved roof covering methods or materials, skilled connection of wall framing at corners (particularly at top plates), improved wall siding performance, and storm protection of windows. Secondary lateral bracing needs should be evaluated, particularly for tall gable roofs on all types of homes.

Figure 44. Complete failure of a wood framing system: shattered windows, failed porch overhang, detached roof sheathing, collapsed gable end, and fallen drywall ceiling. Exterior walls are severely racked from reduced lateral support from the tattered roof structure and inadequate shear wall construction.

Figure 45. Sheathing blown-out at a gable end wall with a steep pitched roof.

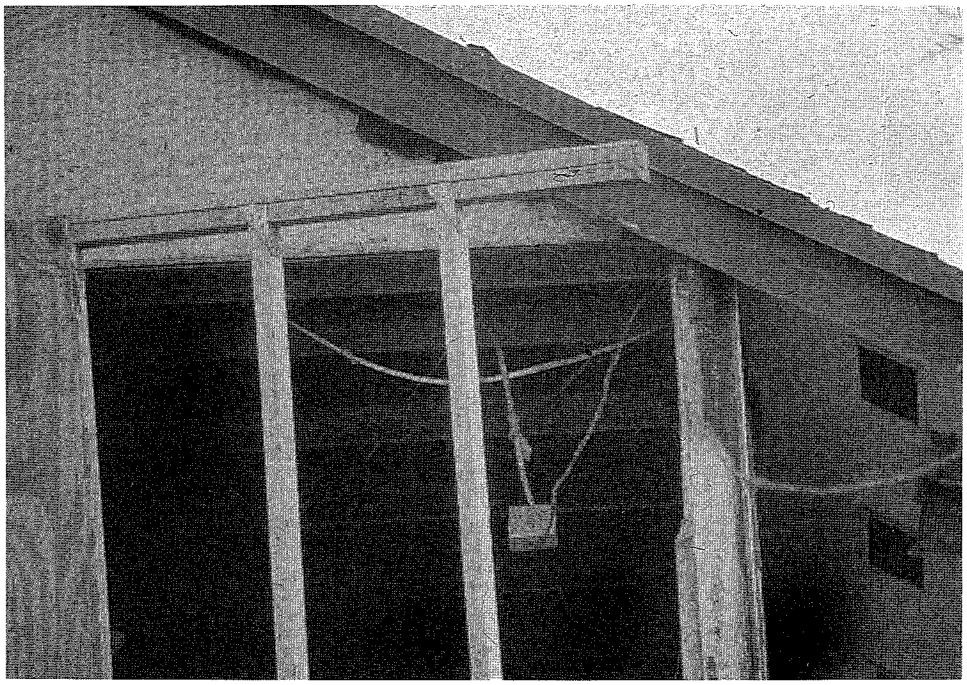

Figure 46. Improper connection of a corner in a blown-out wall section.

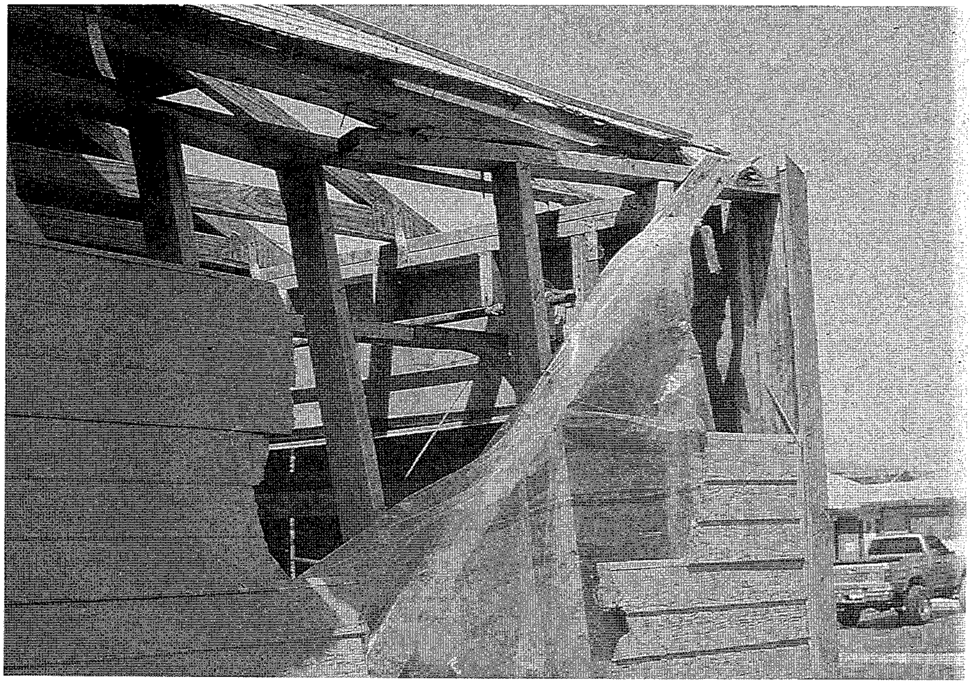

Figure 47. Failure of hardboard exterior wall siding with a let-in brace.

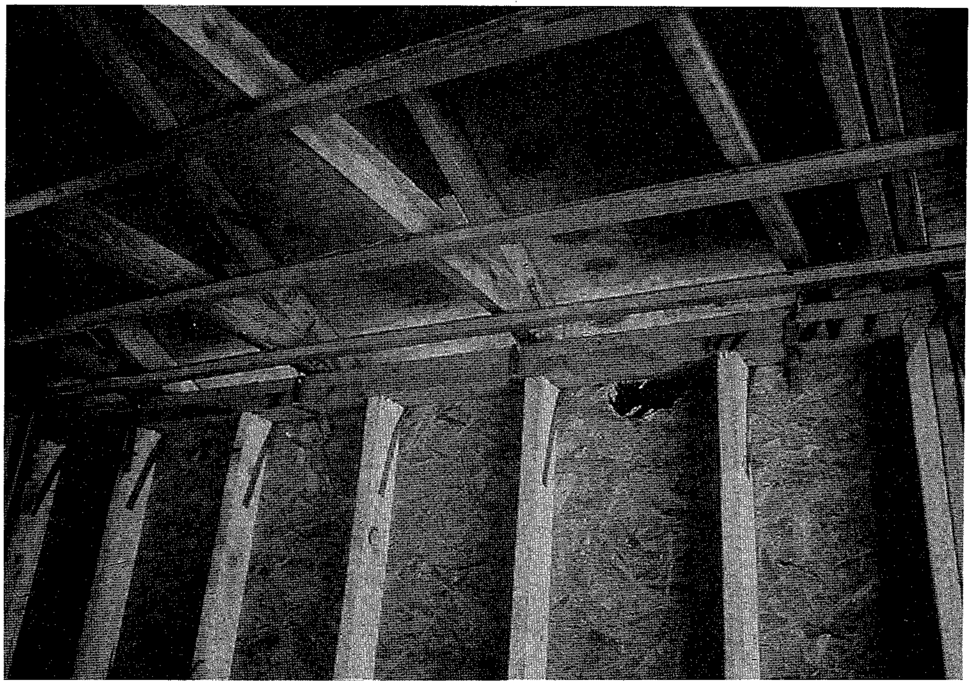

Figure 48. Resilient steel channels used behind drywall render the ceiling diaphragm less effective by detaching the drywall from the roof trusses.

Case Study of Town Houses

Since the selection process in the statistical survey focused on detached homes, HUD requested that a sampling of town houses be selected to obtain information on this type of housing. Three town house developments were selected in the Kendall, Cutler Ridge, and Homestead areas (see locations on map in Figure 7). Two of these developments contained single-story, slab-on-grade town houses, with walls constructed primarily of CBS and with gable roofs covered with composition shingles. Units were separated by concrete block fire walls extending above the roof level.

Typically, the roofs of the middle units in these two developments sustained minor to moderate shingle loss and suffered minor window and door damage from projectiles (Figure 49). Party walls that extend above the roof gave additional protection to the roofing of the interior units. The end units generally exhibited greater roof damage because of the increased exposure (Figure 50), and several gable ends were destroyed. The interiors of all units observed suffered minor to moderate water damage.

The third town house development contained one- and two-story units. These units were wood-frame construction with concrete block party walls. Wood floor trusses spanned between the party walls. Roof coverings were composition shingles. These homes were built on crawl space foundations. These units suffered a high degree of roof damage. Shingle loss was more pronounced and much of the roof sheathing was lost. The attention to nail spacings on roof sheathing was notably poor. There was a high percentage of broken windows and doors, and the interiors of several units were severely damaged by water. These units may have also suffered less concern by the occupants for preparedness. The walls of these units survived intact.

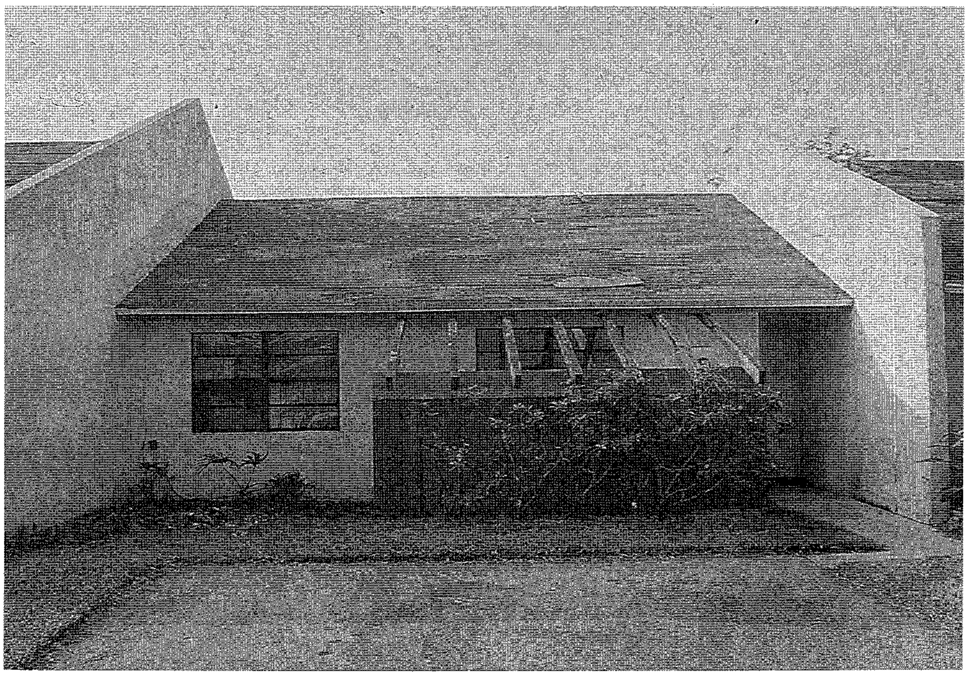

Figure 49. Typical damage to the middle unit of one-story town houses.

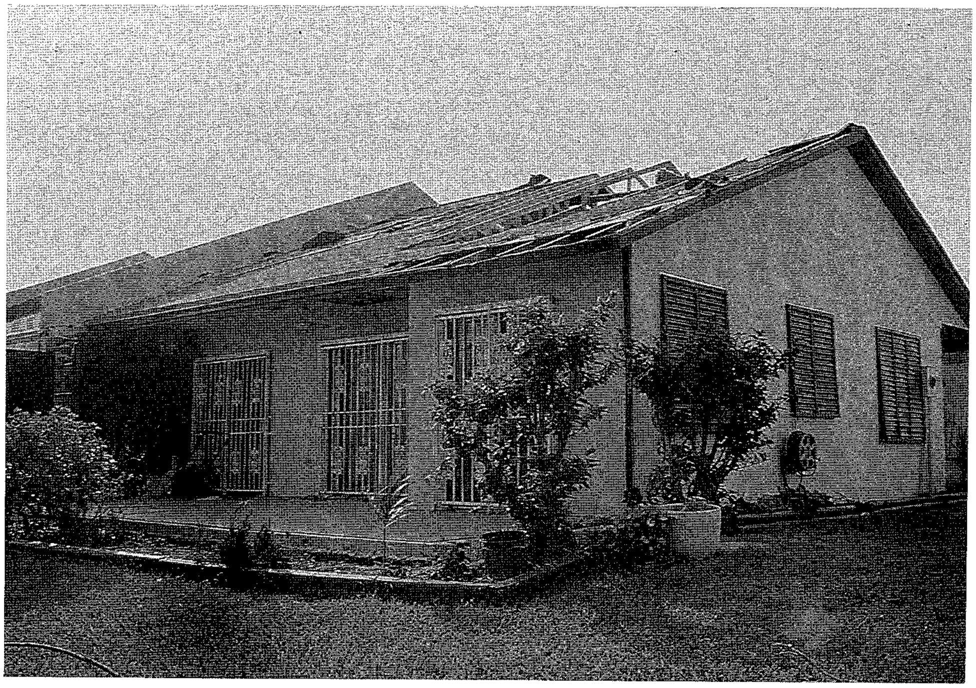

Figure 50. Damage to the end unit of a group of one-story town houses.

Analysis of Estimated Wind Speed vs. Damages

Actual ground wind speed is an important factor in analyzing and understanding the performance of homes relative to engineering or code performance expectations. Yet this elusive parameter is the most difficult to quantify at a given location, and just as difficult to generalize on a larger scale. Several hurricane damage reports have struggled with this issue, and some may have misrepresented the reasons for damages based on premature information on wind conditions. The wind speed map (Figure 6) used in this report combines an extensive analysis of all air reconnaissance and ground data available on Hurricane Andrew.[34] Even yet, there are problems with extrapolating this data for use at the ground level (less than 10 m elevation).

To demonstrate the potential shortcomings of associating damage to estimations of above ground level winds, the damages recorded by this survey are compared to the estimated wind pattern in Figure 6. The houses in the sample were assigned a wind speed value according to their location on the map of Figure 6. Survey Grids A and B were assigned to a high wind category (145 mph), and Grids G, H, and I were classified in a low wind category (125 mph). Table 13 shows the distribution of one-story gable houses in the 125 mph and 145 mph areas and the respective levels of roof damage.

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[34] Powell and Houston.

Table 13
WIND SPEED v. DAMAGE TO ONE-STORY GABLE ROOFS

Overall Roof Damage	**125 mph**	**145 mph**
One-Third or Less (=1)	21	16
Two-Thirds (=2)	40	14
Over Two-Thirds (=3)	26	1
Total Responses	87	31
Advanced Repairs	32	6
Average Damage Rating	**2.06**	**1.56**

The results of this analysis seem to indicate that roof damage was inversely related to the estimated wind speeds. In other words, as wind speed increases, using the sampled houses and the estimated wind values and pattern, the average level of roof damage decreases. Possible explanations for this counter-intuitive result might include the following:

- The surveyed homes in areas of higher estimated wind speed performed better because of better construction practices or more effective, older wind barriers, among other things.
- Analytical models used to estimate wind speeds do not adequately account for the variability in wind speed at ground level during a hurricane.
- Fastest-mile wind speed at 10 meters elevation is not the only significant design parameter that explains damage. Other design factors might include dynamic or impact loading from projectiles; short-duration gusts; structural fatigue from vibration and load reversal; duration of wind loading; extreme wind phenomena in the eye-wall; or exposure characteristics not clearly defined in the survey data.

Improved qualification of details in the differences between the overall wind resistance of these homes, their location, and the actual site wind speeds is needed before rational conclusions can be drawn regarding the correlation of home characteristics to damage from extreme winds. Likewise, a better resolution of near-ground wind speed data is needed during such events.

In a similar fashion, damage to homes within a narrow range of wind speeds may be compared. Intuition suggests that for like homes, the damages would not differ significantly. Grids C and E are particularly interesting because they are adjacent to each other, which limits variations introduced by geography and storm intensity. Comparisons of roof damage among one-story gables between these grids are shown in Table 14.

Table 14
ROOF DAMAGE TO ONE-STORY GABLES IN GRID C AND GRID E

Roof Damage	Grid C One-Story Gables	Grid E One-Story Gables
One-Third or Less (=1)	9	3
Two-Thirds (=2)	14	17
Over Two-Thirds (=3)	5	24
Total Responses	28	44
Advanced Repairs	9	14
Average Damage Rating	**1.86**	**2.48**

On average, the buildings in Grid E, to the east, were judged by the survey team to have suffered a higher level of roof damage than those buildings in Grid C. Other more detailed characteristics of the homes, highly localized storm effects,[35] and differing exposure conditions may have caused the differences in reported damage.

LOUISIANA DAMAGE ASSESSMENT

The developed areas struck by Hurricane Andrew, along Louisiana's rural gulf coast, did not lend itself to a statistical assessment. The housing characteristics varied greatly, and there was scattered damage. Two engineers from the Florida survey team spent two days observing the damage in Louisiana.

The area of Louisiana affected by Hurricane Andrew is shown on the map in Figure 51. The larger municipalities are further inland. There are only a few villages near the coast, which have small populations and depend primarily on the commercial seafood and sport fishing industries. The houses along the coast varied in age, upkeep, and type. Many were used as cottages; some were manufactured (mobile) homes that were placed on pilings to elevate them above local flood levels. Stick-built homes were also elevated with a few using concrete piles instead of treated timber piles. Some of these homes included breakaway walls on the ground level. The coastal areas had little or no code enforcement relative to wind design. Typical construction characteristics and damages to homes in the coastal areas are shown in Figures 52 to 59.

Commonly, provisions for a continuous load path were not considered or were inadequately devised (Figure 54). Even so, there were relatively few serious structural failures observed in single-family housing along the coast of Louisiana.

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[35] Wakimoto and Black.

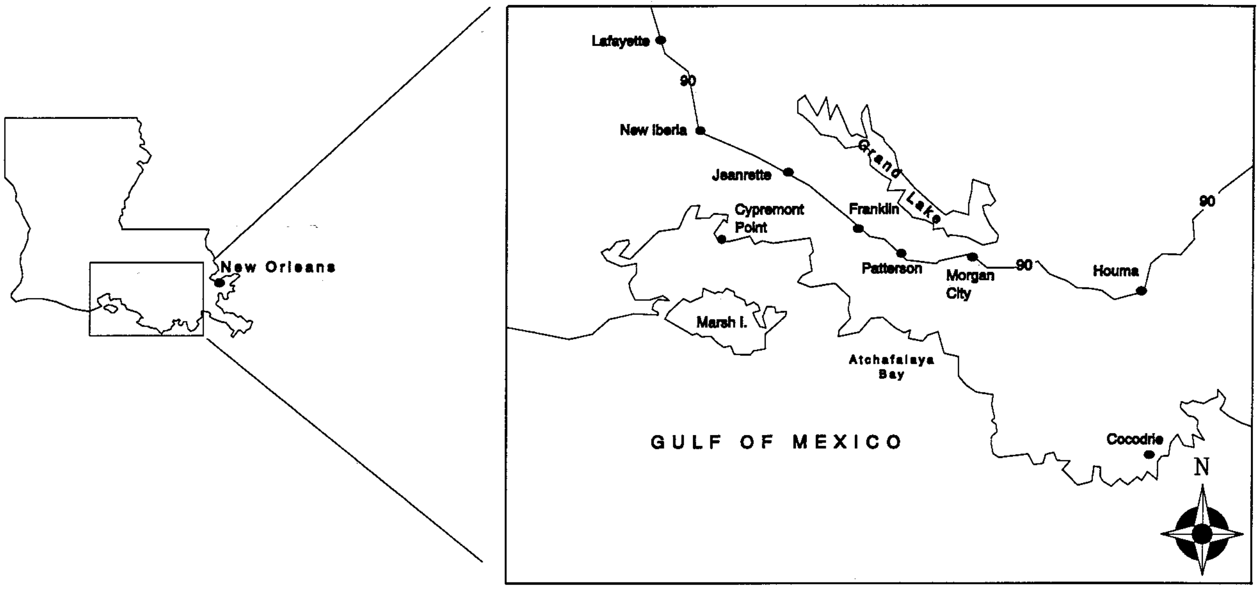

Figure 51. Map of damaged survey area in Louisiana.

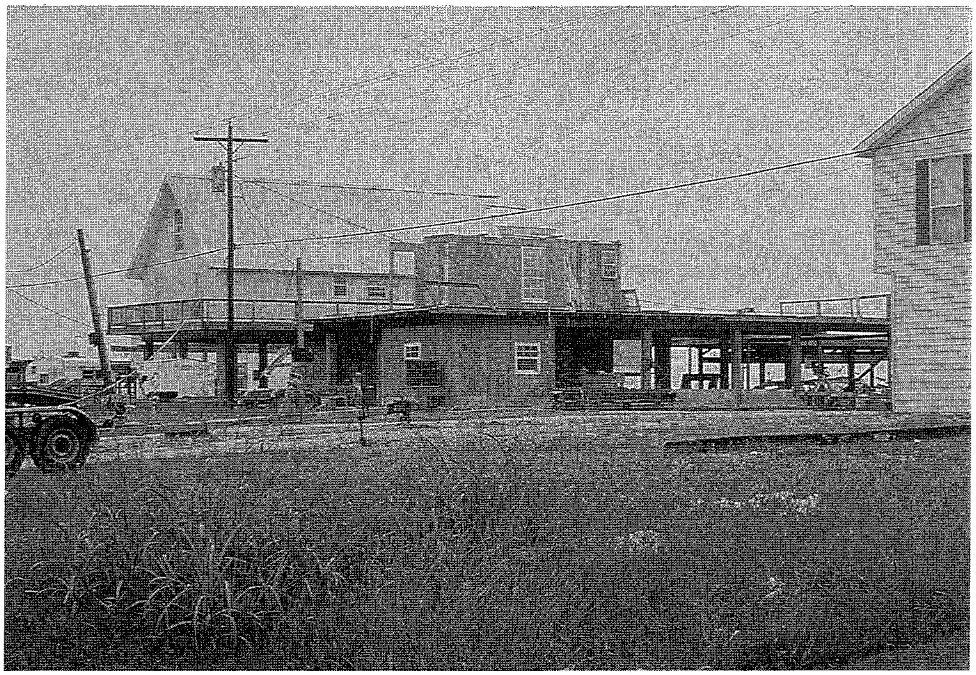

Figure 52. Destroyed coastal home on a concrete pier and heavy timber foundation.

Figure 53. Upper story and roof of the home shown in Figure 52 (50+ yards downwind).

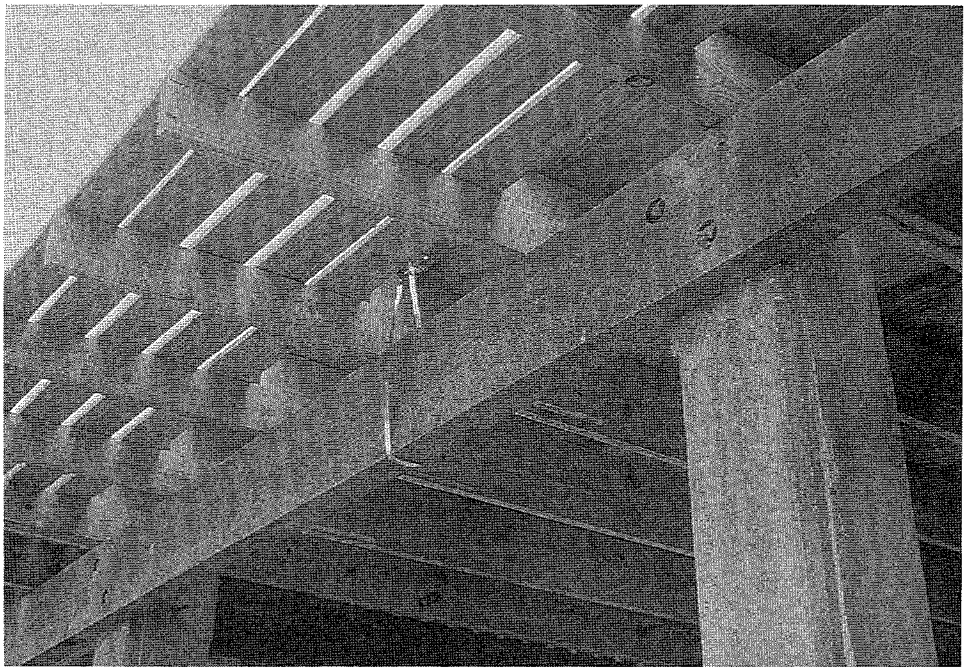

Figure 54. Steel bands were used to tie the now missing upper story walls to the foundation beams of the home shown in Figures 52 and 53.

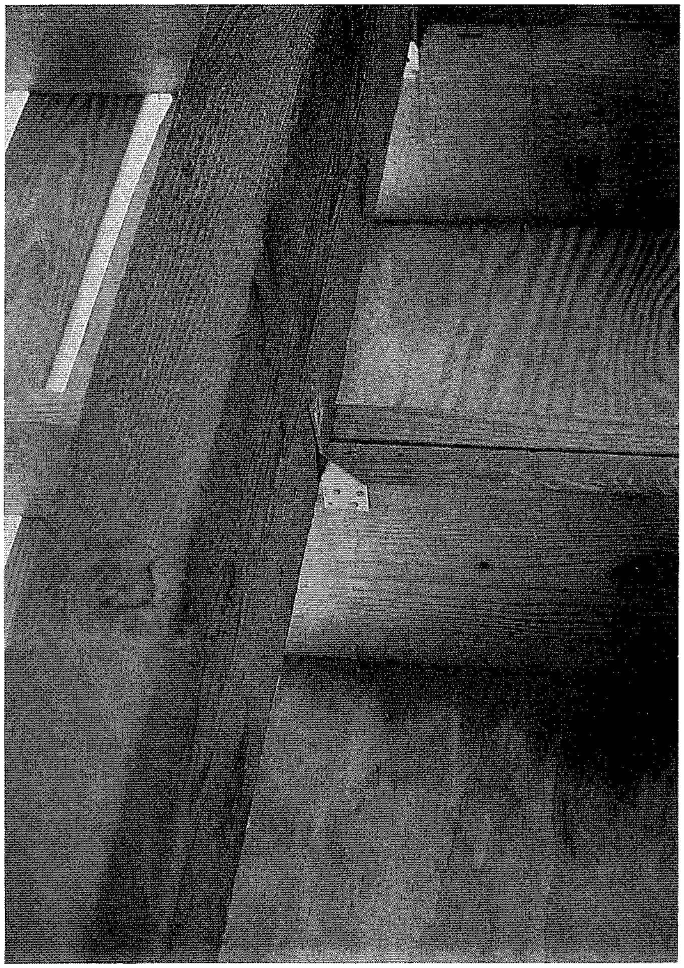

Figure 55. A small twist strap (six 6d nails total) was used to tie the floor joist to the foundation girder in this coastal home.

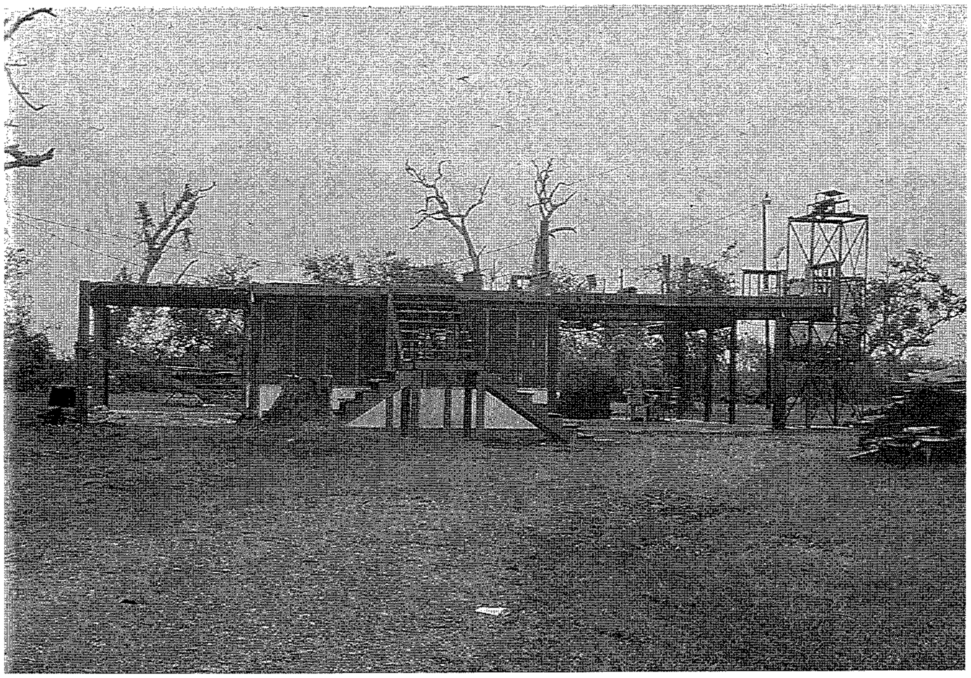

Figure 56. The manufactured (mobile) home, once positioned on this elevated foundation with an open exposure on the coast, was found some distance downwind.

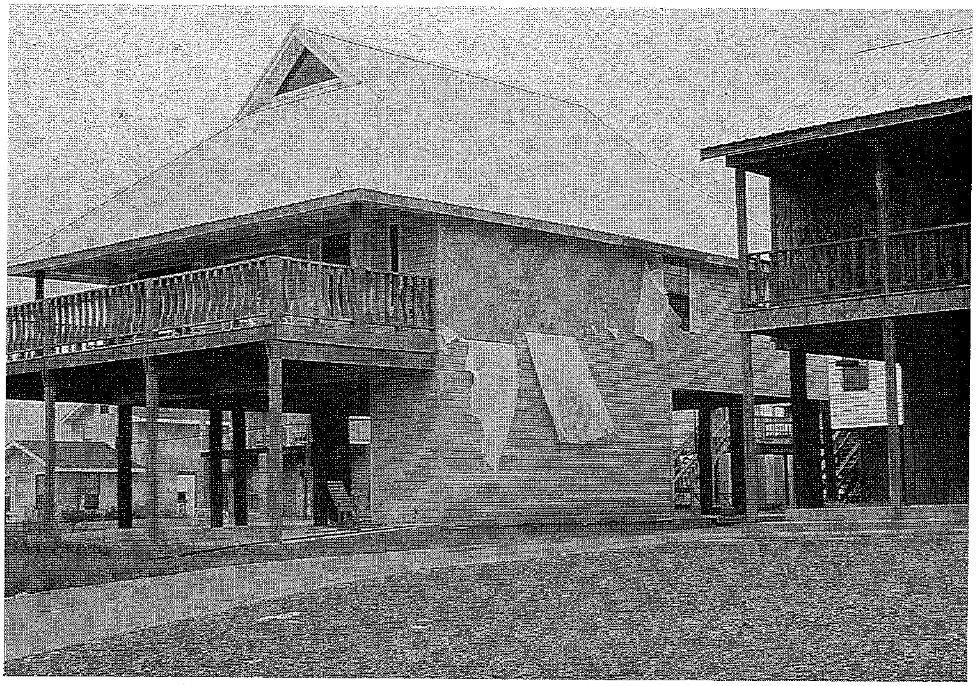

Figure 57. Vinyl siding and trim was cited as a special problem by one builder.

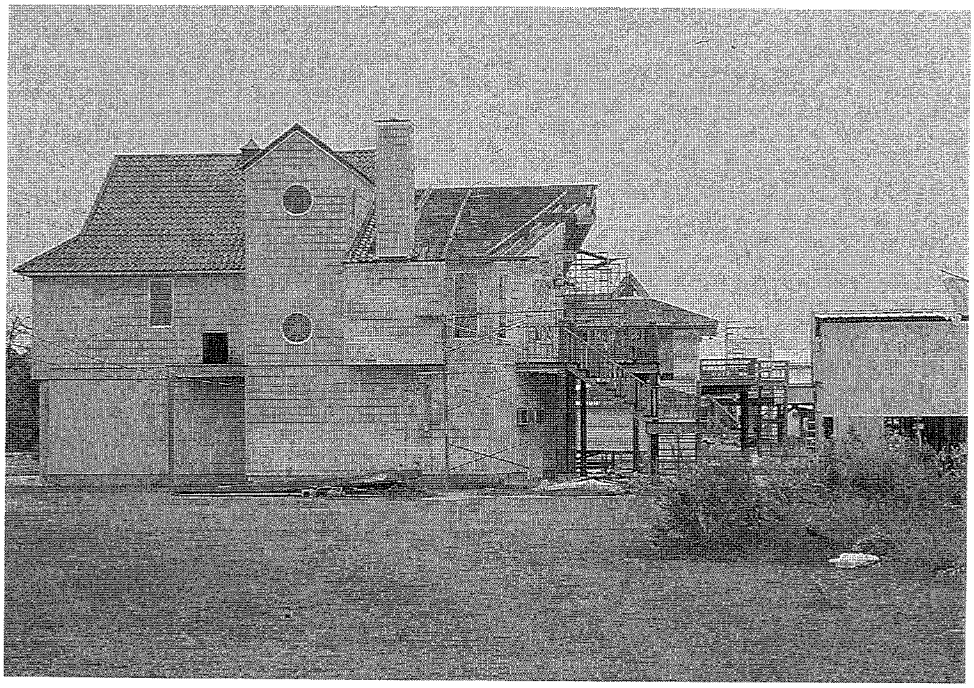

Figure 58. Gable ends and overhangs presented some problems in Louisiana, similar to Florida.

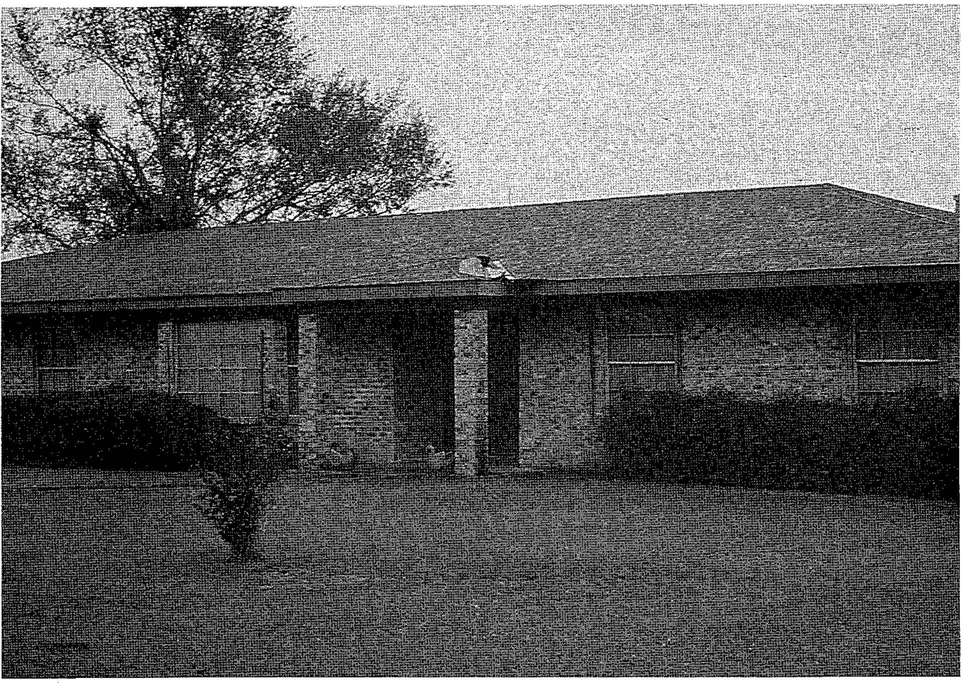

Figure 59. Inland home with minimal damage to roof shingles.

Inland homes ranged from single-story construction with hip roofs, as shown in Figure 59, to older tenant homes and manufactured homes. Damage to these homes was mainly due to water damage from loss of roofing. In a very few cases, over-stressed or collapsed gable-end walls were observed. In some cases the damages were thought to be related to localized high winds or tornados.

SUMMARY AND CONCLUSIONS - HURRICANE ANDREW

The winds of Hurricane Andrew provided a revealing test of wind engineering, building code requirements, code enforcement, code compliance, construction workmanship, material performance, and preparedness. An understanding of Hurricane Andrew, the damage incurred, and the nature of construction in South Florida should serve as a base of information to guide decisions related to construction in high wind areas in the future.

South Florida

Water damage to the interior of homes had the greatest impact on the overall damages experienced. The prevalence of water damage can be attributed to widespread failures in the building envelope, particularly roof coverings and openings (windows and doors). Damage to unprotected windows were aggravated by large quantities of projectiles originating from tattered components of the building envelope, among other sources. In turn, damaged openings contributed to the level of structural failures through the effects of internal pressurization. In general, structural components of most homes remained intact and serious structural problems were usually related to the roof systems. Damage to roofs were commonly associated with inadequate attachment of roof sheathing, especially at gables. In short, the most critical areas for improvements in wind resistant construction include window protection, roof coverings, and roof sheathing connections.

The following conclusions are drawn from this investigation through statistical evaluation and field observations in South Florida:

1. In the damage zone defined for this study, the winds of Hurricane Andrew exceeded the design wind speed established by engineering and construction codes, including the SFBC and ASCE 7-88 for building loads, based on actual wind speed estimates in terms of sustained, fastest-mile, or gust wind speeds. Residential storm surge damage, though present, was not notably severe or widespread because it was mitigated by the natural buffers (reefs) protecting the South Florida coast. Hurricane forecasting and evacuation procedures were very effective in minimizing injury and loss of life in Hurricane Andrew.

2. As covered in the damage survey analysis, the topical conclusions regarding wind damages are:

    a. Increased building height (number of stories) for typical single-family dwellings, does not, in itself, signify a greater likelihood of structural damage to the roof, but does substantially increase exposure to water damage after roof covering or window damage occurs.

    b. Homes with gable roofs suffered significantly higher levels of damage than those with more aerodynamically efficient hip roofs. Considering only single-story homes, about 33 percent of the gables roofs were rated in the highest level of damage. Only 6 percent of the hip roofs surveyed received this rating. Problems with gable roofs account for approximately 90 percent of the homes with structural damages.

    c. About 97 percent of all structural problems were related to the roof systems. The problems with roofs, particularly gables, were primarily associated with deficient sheathing connections, rake overhang framing details and, to a lesser degree, a lack of secondary bracing of roof framing. Substantial sheathing loss was experienced on about 25 percent of all assessed homes. Structural wall failures were infrequent among the sampled homes (of mostly concrete and masonry construction). Under the SFBC, wood-frame walls are more dependent on the integrity of the roof system, and case studies indicate a higher susceptibility to damage. Improper connections, particularly at top plate corner joints, exacerbated damages. In a very few cases, reinforcement defects in concrete and masonry construction were also observed.

    d. Most surveyed homes were constructed on slab-on-grade foundations and none of these suffered significant damage from the hurricane.

    e. Water damage to interiors of homes was the most costly and consistent element encountered in the survey. About 65 percent of the assessed homes experienced the highest level of water damage.

   f. Widespread failure of roof coverings, seriously affecting 77 percent of the homes, resulted in severe water damage during and after Hurricane Andrew, which was one of the greatest factors in the amount of damage.

   g. Failure of unprotected openings (windows and doors), also contributed to high levels of water damage, and increased the susceptibility to structural failures by leading to build up of internal pressure. About 64 percent of the homes experienced at least one broken window. Generally, homes with hurricane shutters appeared to have lower levels of damage. Observations indicate that nearly 80 percent of the homes did not utilize adequate temporary protective measures such as effectively attached plywood coverings.

   h. Projectile damage was widespread and was exacerbated by failures in roof coverings and poorly anchored accessory structures such as porches, fences, and storage buildings.

3. Case studies were performed on wood-frame construction and town homes with the following findings:

   a. Wood-frame homes were subject to the same types of damages as other types of construction. However, failures in components such as the roof system increased the likelihood of damage to conventional wood-frame walls. Inadequate field connections and higher risk design attributes also contributed to damages.

   b. Town homes were also subject to the same types of damages as other types of homes. However, end units often experienced greater amounts of damage than interior units. Party walls that extended above the roof structure protected the roofing on interior units.

4. Large-scale estimates of above-ground wind speeds do not correlate well with damages. Greater resolution of actual near-ground wind speeds is needed before structural performance can be analyzed in absolute terms.

5. The SFBC contains numerous prescriptive requirements for hurricane resistant construction. The more obvious requirements (e.g., hurricane straps) were generally installed in an effective manner; however, less obvious details such as fastener spacings on roof sheathing, which ultimately determine the structural capacity of the roof system, were frequently not in compliance with the code. In effect, structural failures were commonly related to detailed component failures (e.g., roof sheathing connections), which affected the lateral stiffness of the entire structural system.

Louisiana

The damage in Louisiana was not as severe as that experienced in Florida. Hurricane Andrew had lost some of its strength by landfall in Louisiana, and the coastal area struck was rural in nature. Inland areas were protected by large stands of trees along the coast, which provided a natural barrier from the winds. The following points summarize observations in Louisiana:

1. Wind damage to homes on the coast ranged from minor loss of roof coverings to complete destruction. Severe wind damage was concentrated in a few small coastal villages that included many cottages and manufactured (mobile) homes.

2. Building codes were not rigidly enforced or present in most rural areas of southern Louisiana. As a result, wind-resistant construction practices, if considered, were varied in style and effectiveness.

3. Inland homes suffered most from loss of roof coverings and the resultant water damage. Isolated cases of tornado damage were also reported, and a few cases of gable-end wall damage or failure were noted.

4. Storm surge damage was notable in the small coastal towns located in Hurricane Andrew's wake. Although many houses were elevated and secured by various means, several non-elevated structures suffered severe damage.

5. Evacuation measures and warnings were apparently effective in mitigating injury and the loss of life.

PART 2 - HURRICANE INIKI

DESCRIPTION OF HURRICANE INIKI

Hurricane Iniki hit the Hawaiian island of Kauai on Friday, September 11, 1992. The hurricane's eye passed directly over Kauai. The recorded winds of Iniki exceeded those of all U.S. design standards and codes for the Hawaiian Islands. Hurricane Iniki was one of the most intense hurricanes documented for the Hawaiian Islands.[36] However, no official determination has been made concerning its Saffir-Simpson category, in part because of limited data. Selected characteristics of Hurricane Iniki are summarized in Table 15.

Table 15
CHARACTERISTICS OF HURRICANE INIKI—KAUAI

Maximum sustained wind speed at 10-meter elevation[37]	84 mph (NOAA station memo, Lihue Airport) 97 mph (Lihue Airport[38])
Maximum gust wind speed at 10-meter elevation[37]	114 mph (NOAA station memo, Lihue Airport) 121 mph (NOAA station memo, Malcahuena Point) 143 mph (Malcahuena Point[38])
Maximum storm surge	10 to 20 feet above mean lower low water (mllw)[38]
Minimum central (eye) pressure	966 mb (NOAA station memo)
Estimated number of homes damaged	1,446 destroyed (Red Cross) 13,021 damaged (Red Cross)
Estimated dollar cost of damage	$1.2 to 1.8 billion (NOAA station memo,[38])
Deaths	3 (NOAA station memo)

Occurrences of extreme winds (i.e., tornadoes) within Hurricane Iniki were reported, but there is not complete scientific agreement as to the nature of these localized phenomena. Some of these are described as "downbursts," such as those associated with several airplane accidents in thunderstorm systems, while others are described as tornado-like "hurricane swirls."[39,40] Other researchers believe that these phenomena are related to near-ground wind effects related to Kauai's topography. Fujita analyzed video taped footage of a roof being torn from a building during Hurricane Iniki. As reported, the flexure of the building components was related to the

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[36] Dale C. Perry, et al., *Hurricane Iniki—Preliminary Observations of WERC Post-Disaster Team* (College Station, TX: Wind Engineering Research Council, Inc., September 25, 1992).

[37] The fastest mile-wind speed (basis for design) will fall somewhere within these wind speed measurements.

[38] Federal Emergency Management Agency, *Building Performance: Hurricane Iniki in Hawaii* (Washington, DC: GPO, 1993).

[39] Fujita, *Memoirs of an Effort to Unlock the Mystery of Severe Storms, During the 50 Years, 1942-1992.*

[40] Fujita, "Wind Fields of Andrew, Omar and Iniki, 1992."

cyclical loading of 1 to 4 second duration gusts. Fujita concludes that in a 100 mph wind, an unsecure roof can be removed in a matter of 1 to 2 seconds.

KAUAI DAMAGE ASSESSMENT

Damage Assessment Procedure

On October 7, 1992, two engineers from the Research Center arrived in Kauai to conduct a detailed damage investigation of single-family homes for HUD. Each had participated previously in surveying damage from Hurricane Andrew in Florida. The engineers obtained prior approval to survey homes for structural damage from the Housing Administrator for the County of Kauai Housing Agency.

The FEMA Damage Assistance Center provided street maps of Kauai (Belknap Productions, Honolulu, HI, 1988) that were used to select a sampling of homes. The maps of Kauai showed 11 populous areas along the coast of the island (Figure 60). Four to five streets were preselected in each of these areas prior to the actual survey. If selected streets were found to be agricultural or commercial areas, other streets were selected to replace them.

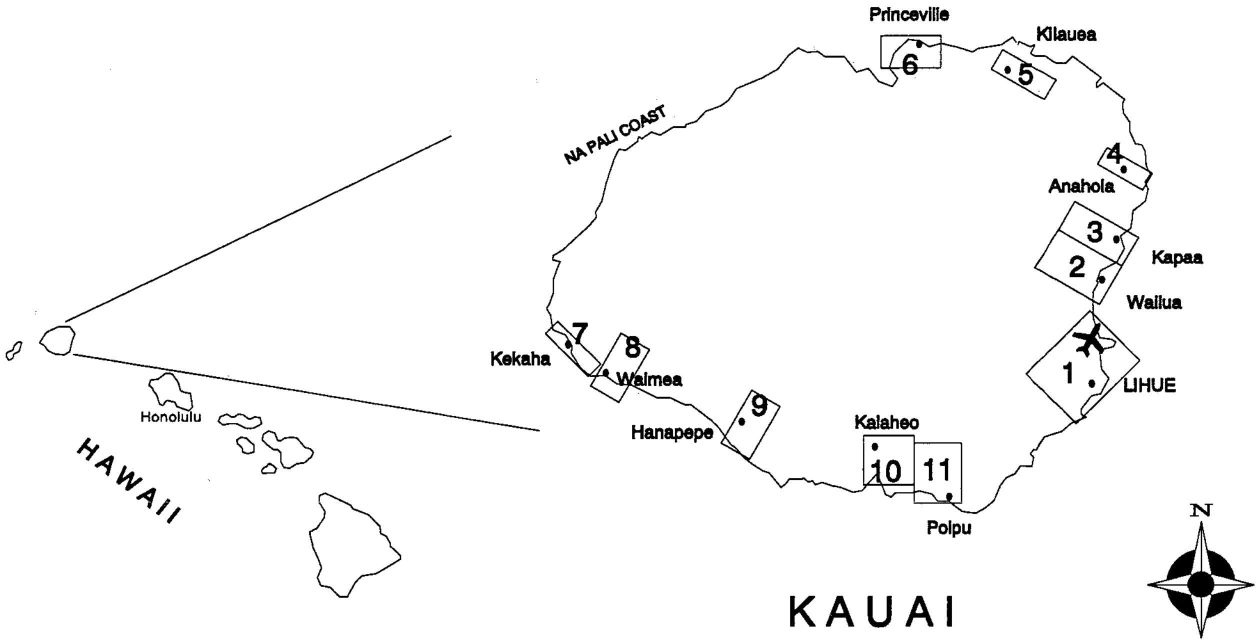

Figure 60. Map of survey regions on the Island of Kauai.

The study was designed to classify and assess damage to each dwelling surveyed. On the selected streets, an initial home was assessed. From that point, every fourth or fifth house was assessed. If the selected street was short or if there were few houses on that street, every third home was assessed. Although the selection process did not provide an ideal random sample, it provided a good cross-section of home construction on the island and the damage suffered from Hurricane Iniki. When possible, the engineers conducting the survey interviewed occupants and entered homes to inspect their interiors. Observations were also made on pertinent damages not specifically included in the survey form.

Description of Housing

Kauai homes were predominantly one-story. Approximately nine out of ten Kauai homes were wood frame of various styles. Of the wood-frame homes, many were of indigenous single-wall construction, as illustrated in Figure 61. Single-wall construction is recognized in a local standard with basic prescriptive guidelines.[41]

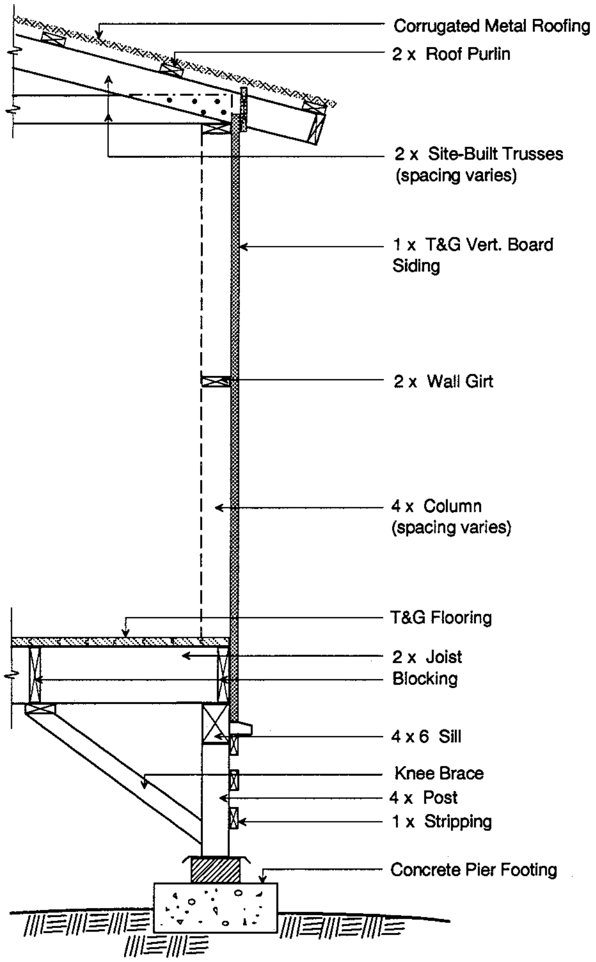

Figure 61. Illustration of typical single-wall construction.

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[41] Federal Housing Administration, "Local Acceptable Standard No. 5a" (Honolulu, HI: HUD, July 1966).

A wide variety of roof types were observed; however, a combination hip/gable design was common. Engineers observed approximately equal numbers of composition and metal roofing, which together represent most of the roof coverings used. Typical roof construction consisted of either plywood sheathing or corrugated metal with wood purlins, installed over site-built wood trusses. Pier foundations were used most often, with wood posts being used more commonly than masonry. Many newer homes were constructed of pressure-treated plywood and dimension lumber with conventional or "main-land" framing details, and slab-on-grade foundations.

Standardization of Damage Ratings

Following the same approach used in Florida, the engineers chose several homes on which to standardize damage ratings on the styles of homes and somewhat different types of failures found in Kauai. The same damage assessment form was used for the Kauai survey (see Figures 8 and 9), but some categories such as wall type required modification to accommodate unique styles of construction. Figures 62, 63, and 64 show homes with damage characteristic of Levels 1, 2, and 3 for the overall building condition category.

DAMAGE RATING SUMMARY	
OVERALL	1
ROOF	1
WALLS	1
INTERIOR	1
FOUND.	1
GRID	2

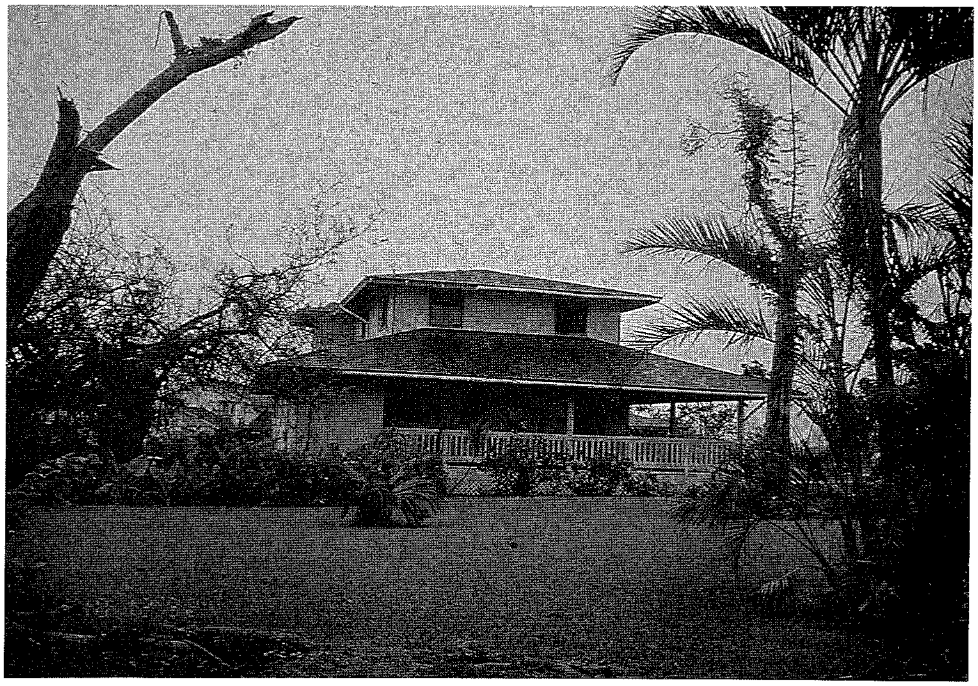

Figure 62. Wind-damaged home with a Level 1 damage rating for overall building condition. This two-story home was built using conventional wood framing with T1-11 siding. The roof is hip shaped with large overhangs and porches. The survival of this home was noted as "excellent," but minor water damage and damaged rain gutters were recorded on the survey form.

DAMAGE RATING SUMMARY	
OVERALL	2
ROOF	2
WALLS	X
INTERIOR	1
FOUND.	1
GRID	6

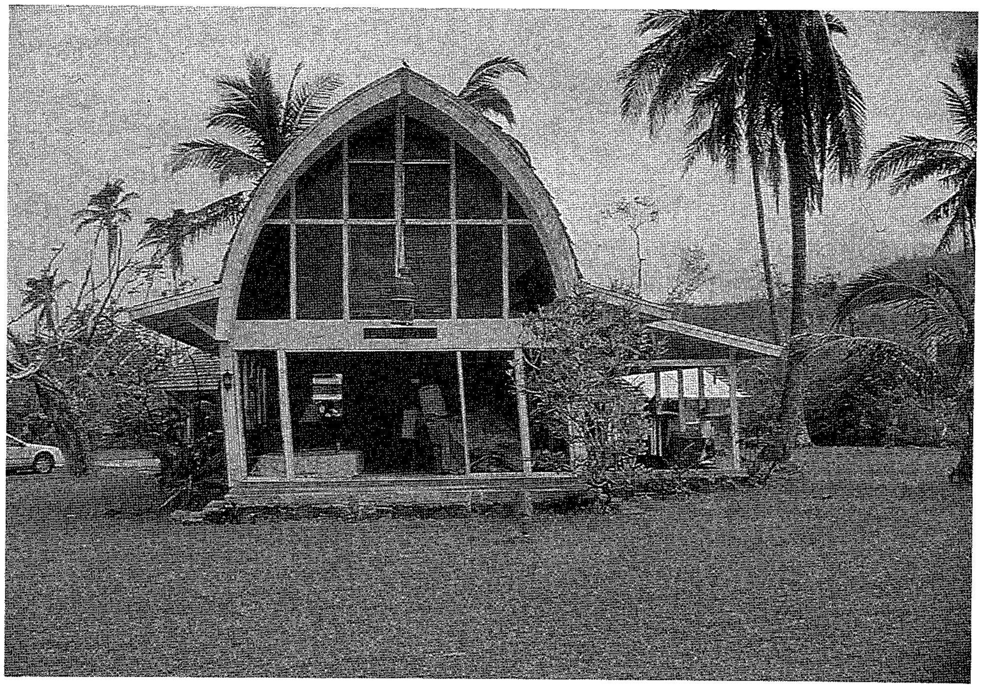

Figure 63. Wind-damaged home with a Level 2 damage rating for overall building condition. This custom home was built in 1965 using site-built, nail-laminated arches (not be confused with modern glue-laminated arches). The roof (and wall) was made of wood decking fastened to the arches and wood shingle roofing. As shown, this home suffered severe racking as a result of delamination of the arches and insufficient lateral bracing. The racking appears to have broken some of the glazing. The slab-on-grade foundation was unharmed. ("X "means the wall rating was combined with roof for this home.)

DAMAGE RATING SUMMARY	
OVERALL	3
ROOF	3
WALLS	1
INTERIOR	3
FOUND.	1
GRID	10

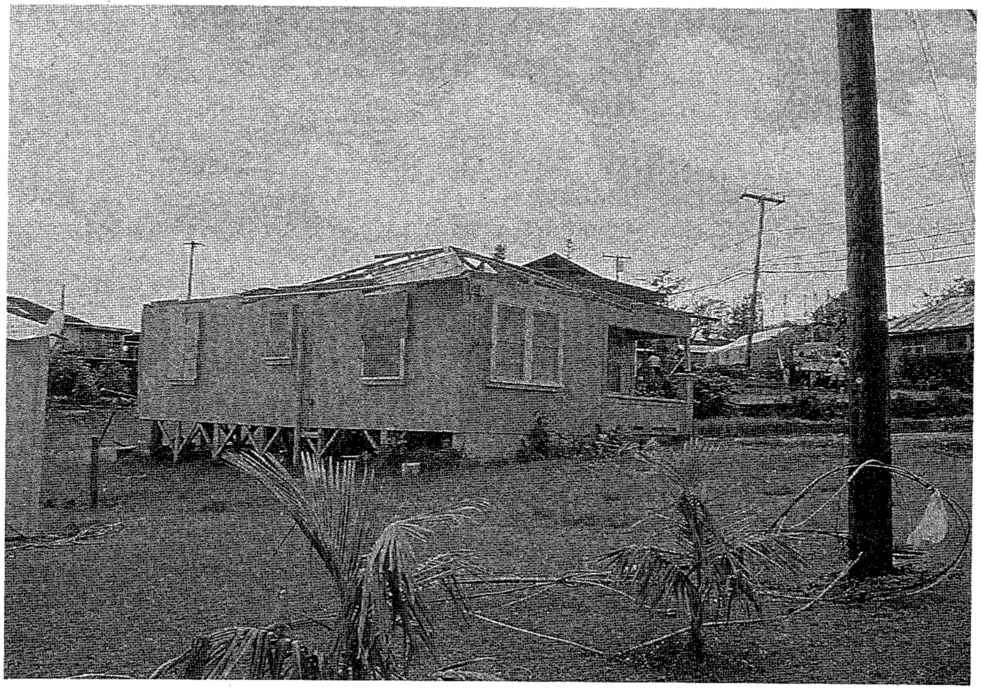

Figure 64. Wind-damaged home with a Level 3 damage rating for overall building condition. This single-wall home suffered severe damage to the roof—both structurally (roof framing) and in envelope soundness (loss of metal sheathing/roofing). Though interior water damage was severe, the exterior walls and foundation remained intact.

Damage Survey Analysis

By sampling homes from each of the eleven populous locations around the entire island, the survey provided a good geographic distribution of homes. Generally, the number of samples taken in each area followed the proportion of the total housing stock included in each survey region, based on larger surveys conducted by the Red Cross. Table 16 shows the distribution of the sample for all single-family houses, and one- and two-story houses. A summary of the building characteristics and damage data recorded for the survey is presented in Appendix D, Tables D-7 and D-8.

Table 16
DISTRIBUTION OF HOUSES SURVEYED ON KAUAI

Grid	All Single-Family		One-Story		Two-Story	
	Number	Percentage	Number	Percentage	Number	Percentage
1	23	14%	21	16%	2	7%
2	11	7%	8	6%	3	11%
3	19	12%	15	11%	4	14%
4	14	9%	12	9%	2	7%
5	14	9%	11	8%	1	4%
6	12	7%	7	5%	4	14%
7	17	10%	16	12%	1	4%
8	11	7%	7	5%	4	14%
9	17	10%	17	13%	0	0%
10	17	10%	13	10%	4	14%
11	8	5%	5	4%	3	11%
Total	163	100%	132	100%	28	100%

The Chi-square test was used to judge whether a significant difference existed between the level of damage experienced by a category of houses or house characteristics and the level of damage expected for all homes in the hurricane's path. The data were found to be statistically insignificant, largely because the number of samples for specific characteristics was low. Also, for certain characteristics, such as roof covering, the items had frequently been repaired or reinstalled and the level of original damage was not discernable.

Much of the damage observed on Kauai was similar in nature to that observed from Hurricane Andrew. Therefore, this part of the report will focus on the differences in housing characteristics and related failure modes that provide additional insights on hurricane damage in Kauai compared to that found in South Florida. Factors that set the Kauai damage apart are: island topography; storm surge damage; differences in roof and wall construction; and foundation type.

The analysis and discussion of damage is presented under individual subheadings to direct attention to specific issues in a sensible progression. The damage assessment topics may be categorized as follows:

- Design Issues
    - » Number of Stories (building height effects)
    - » Roof Type (influence of building shape)
- Structural Integrity (Materials and Methods)
    - » Roof Framing
    - » Roof Sheathing
    - » Wall Type
    - » Foundation Type
- Building Envelope Integrity (Materials and Methods)
    - » Water Damage
    - » Roof Coverings
    - » Windows and Doors
    - » Projectiles

Some of the topics are interrelated. For example, roof covering damage affects water damage, and both influence the level of overall building damage. Likewise problems in the area of structural integrity will also impact the level of building envelope performance. Other aspects of the hurricane damage such as storm surge are also covered under separate topics.

Number of Stories - As shown in Figure 65, one-story construction was predominant for single-family homes surveyed. As noted previously, single-wall construction was found in many existing single-story homes, particularly the older ones. Levels of structural damage appeared to follow other building and/or wind characteristics such as topographic wind effects more than building height. The small number and wide variation in construction and location of two-story homes in the survey was not amenable to statistical analysis. However, the potential for higher levels of water damage in two-story construction, is consistent with observations in Florida. In Kauai, two-story homes were either western platform framed, masonry, heavy timber post and beam variations, or one of numerous custom framing systems such as laminated wood arches or log.

Roof Type - The distribution of roof types found in the survey is shown in Figure 66. The categorization of roof type was not always clear because roof types were often mixed (e.g., part gable and part hip). The variation of roof types, non-uniformity in other building characteristics, and the damages incurred do not allow singling-out of roof type for a valid statistical analysis. However, field observations agree that hip style roofs were more resistant to damage, as found in Florida.

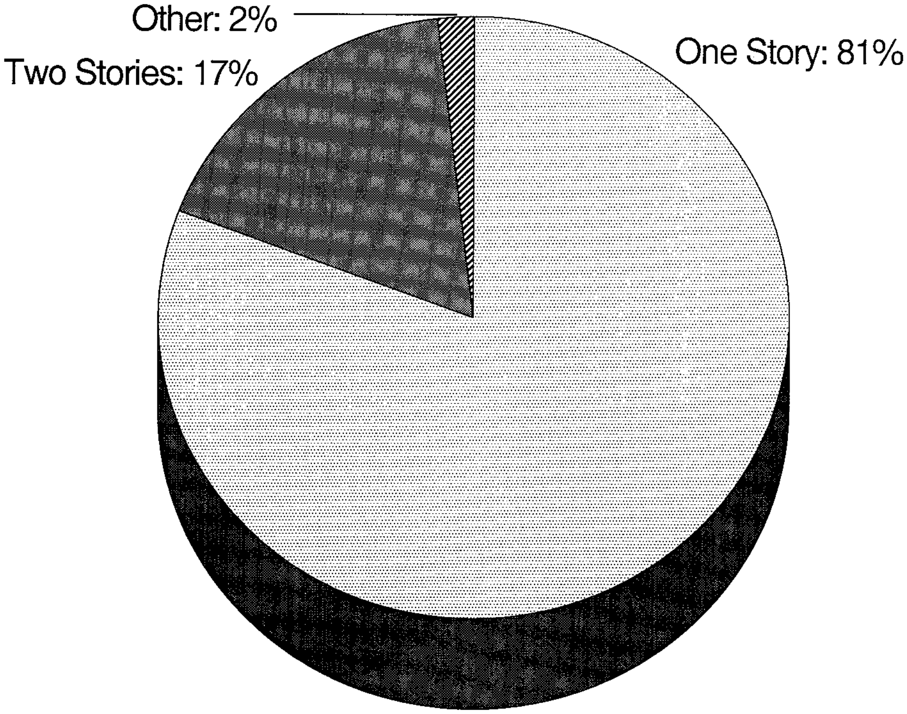

Figure 65. Distribution of homes by number of stories.

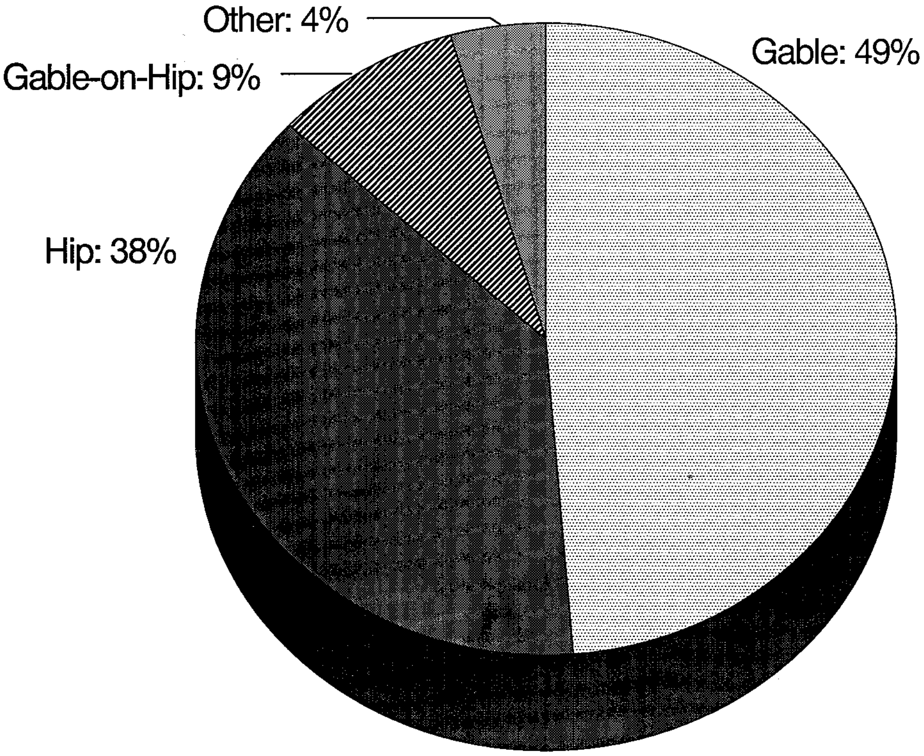

Figure 66. Distribution of roof types in Kauai.

Roof Framing - The majority of roof framing found in Kauai was wood trusses; however, a large proportion of wood rafters was also used (Figure 67). Many of the wood trusses were site built, particularly on single-wall homes. In some cases, it was apparent that site-built trusses did not have adequate panel point connections. In lieu of metal or plywood gusset plates, webs and chord members were sometimes simply lapped and joined together with a few nails. Cases of inadequate anchorage (continuous load paths) were also observed in older homes, and several homes were missing their entire roof structure. Other damage to porches, roof sheathing overhangs, and eaves were frequently observed.

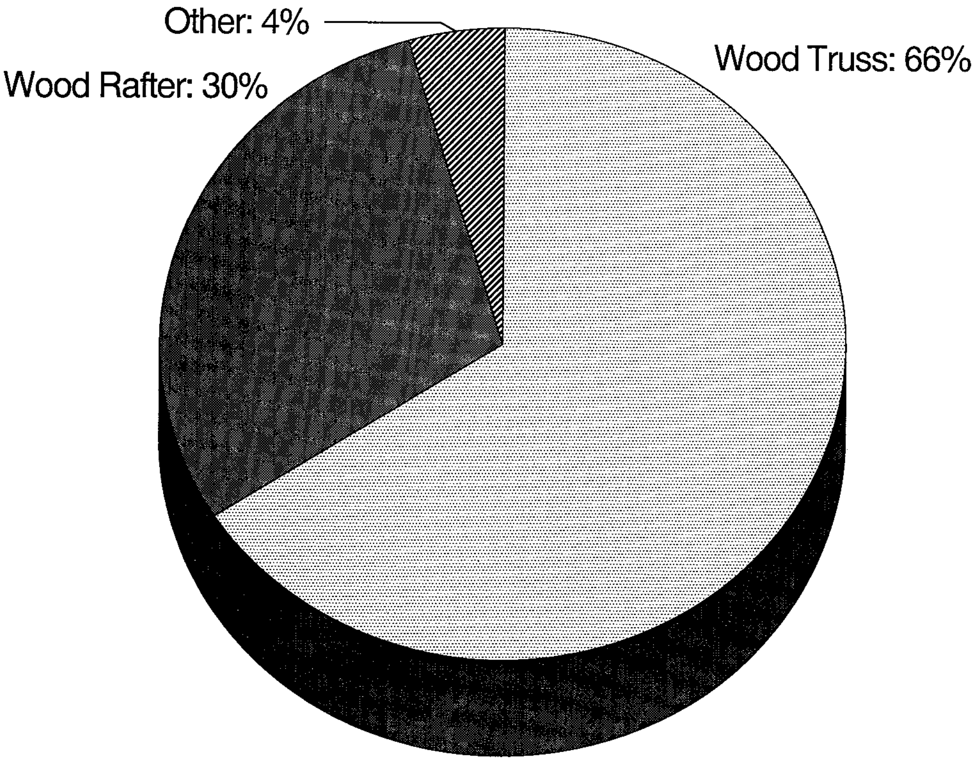

Figure 67. Distribution of roof framing methods.

Many homes in Kauai had roofs covered with corrugated sheet metal on wood purlins. Frequently, the sheet metal roofing was completely stripped and often the purlins as well. Purlin-to-truss connections and metal roofing-to-purlin connections both appeared to be weak points. When metal roofing was stripped, the homes lost their structural sheathing as well as their water resistance.

The overall roof damage recorded for all one-story homes in the survey is shown in Figure 68. Some of the observed problems in roof framing are illustrated in Figures 69 to 74. Similar to that found in the Florida survey, roof damages were responsible for 70 percent or more of the overall structural damages observed in Kauai (see Appendix D, Table D-8).

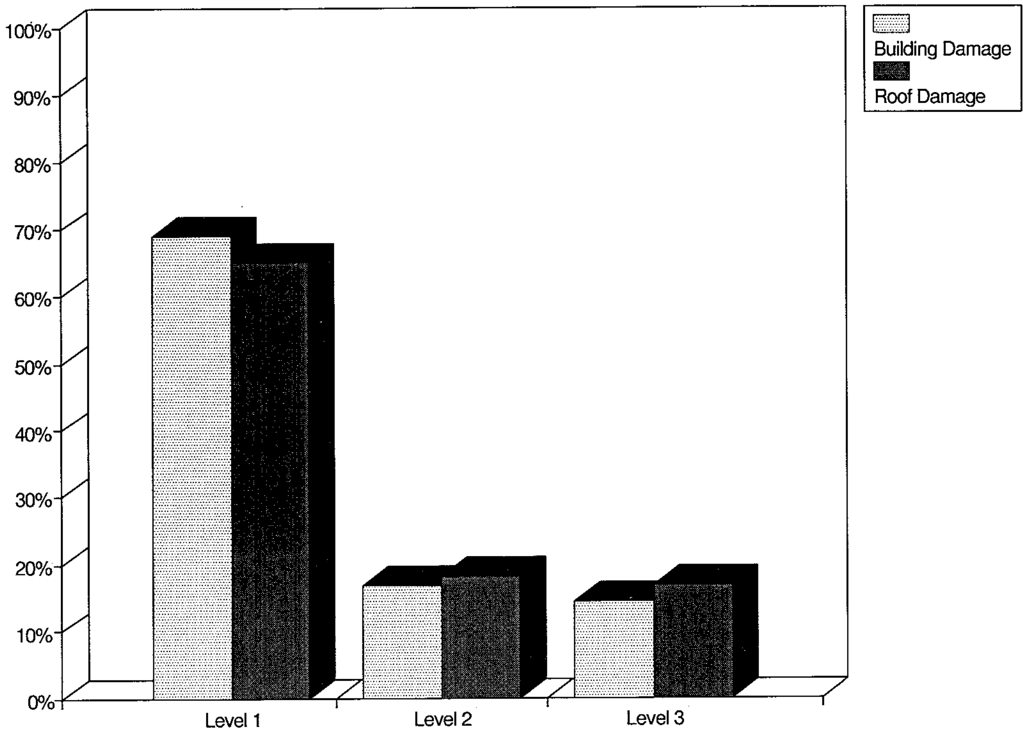

Figure 68. Distribution of overall roof damage to all homes surveyed.

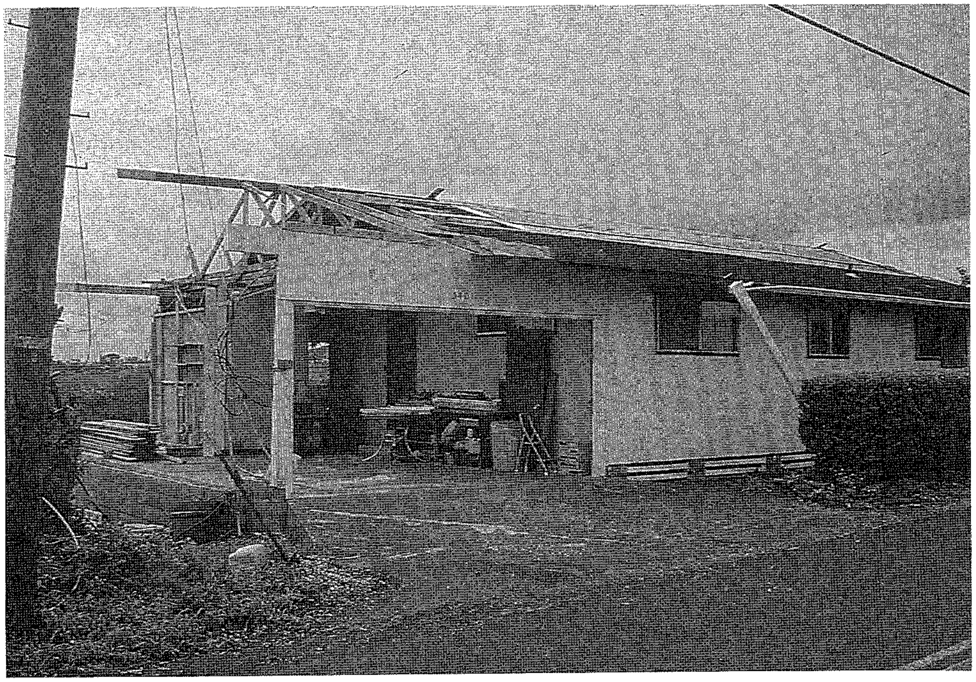

Figure 69. Site-built trusses on a single-wall home with lapped and nailed joints in lieu of metal or plywood gusset plates.

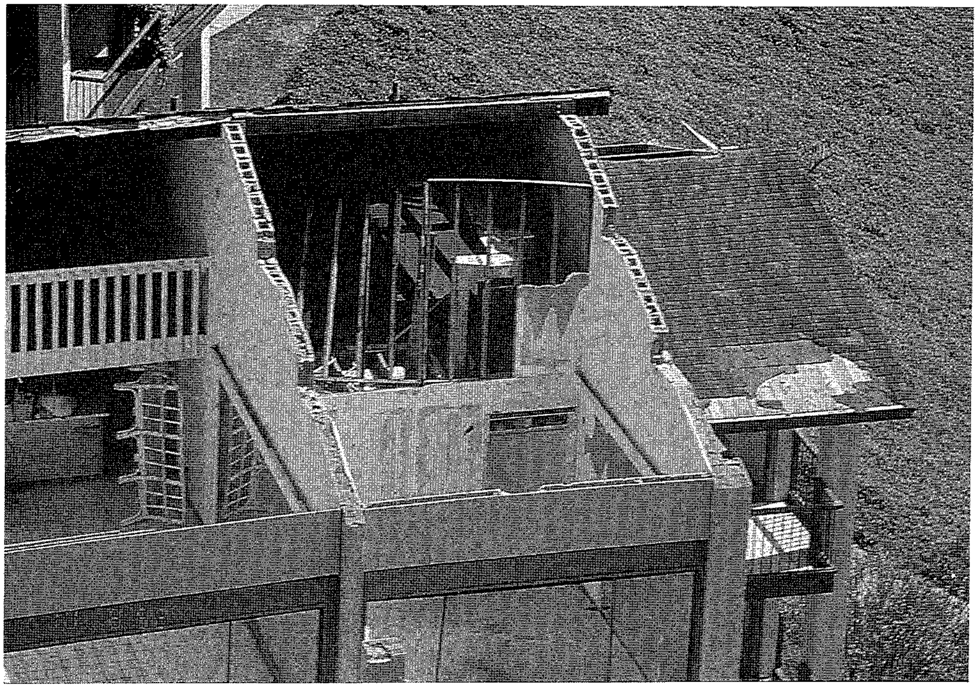

Figure 70. Heavy timber and plank roof blown away due to inadequate tie downs.

Figure 71. Roof framing at overhangs was particularly vulnerable.

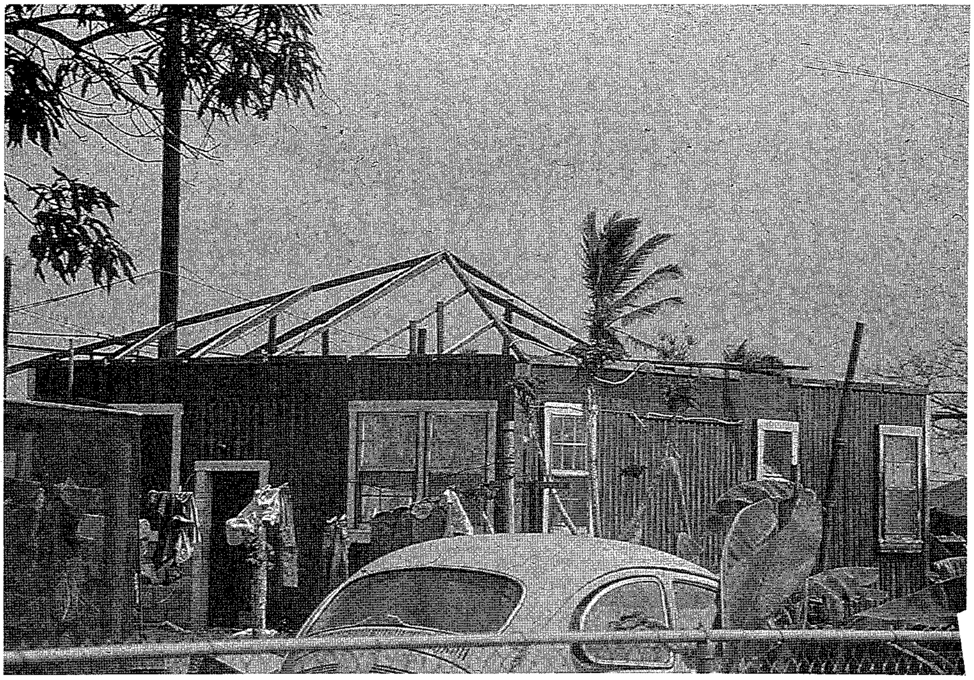

Figure 72. Light-frame wood roofs with corrugated metal roofing on single-wall homes did not fare well.

Figure 73. This home lacked a continuous load path from the roof to the walls and lost its entire roof.

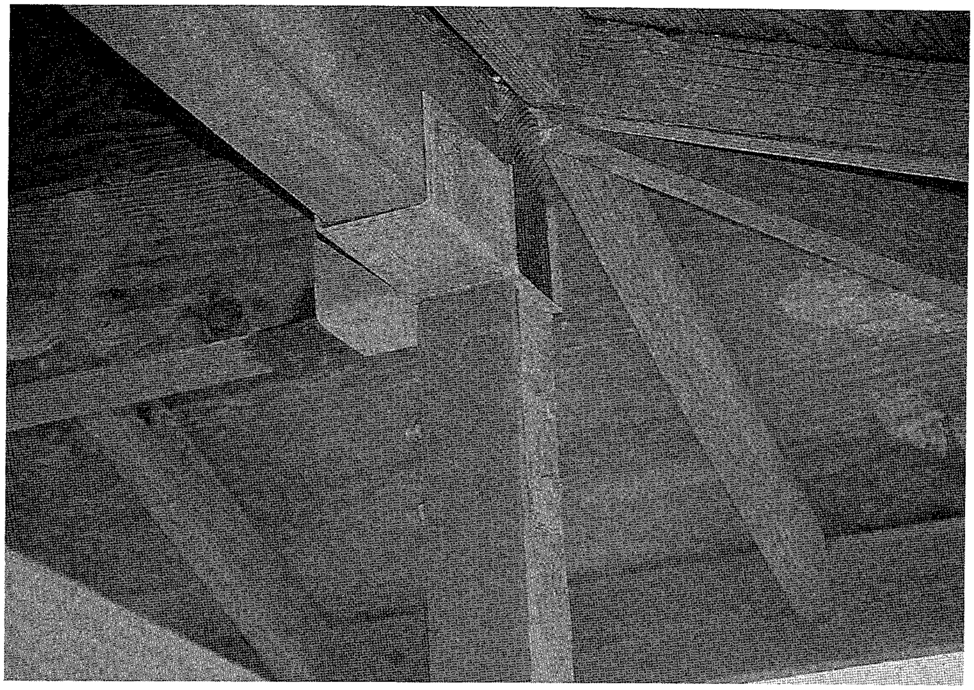

Figure 74. This roof beam connection to a column provided resistance against uplift and also created a stiff joint for lateral forces.

Roof Sheathing - The majority of roofs in Kauai are sheathed with plywood. The distribution of roof sheathing is illustrated in Figure 75. The "metal" category is primarily corrugated metal roofs with purlins, which is predominant among the single-wall homes. The "other" category covers many cases of heavy timber-framed roofs with tongue and groove boards or planks.

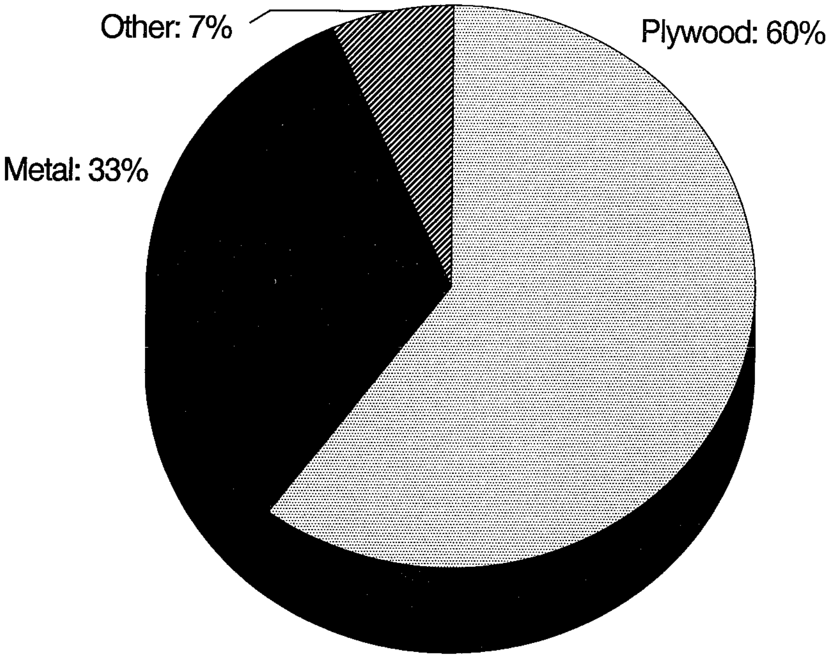

Figure 75. Distribution of roof sheathing materials.

The distribution of roof sheathing damage relative to overall roof damage is shown in Figure 76. About 38 percent of the surveyed homes were rated in the higher levels (Levels 2 and 3) of roof sheathing damage, which implies at least one lost or severely damaged sheathing panel. Roof sheathing loss was notable in Kauai because of inadequate connections or materials, particularly in higher wind pressure locations on the roofs such as overhangs. Common problems with roof sheathing are shown in Figures 77 and 78. As in Florida, much of the roof structural damages can be related to the detachment of roof sheathing. But, other factors such as inadequate continuous vertical load paths were notable mainly in the older homes on Kauai.

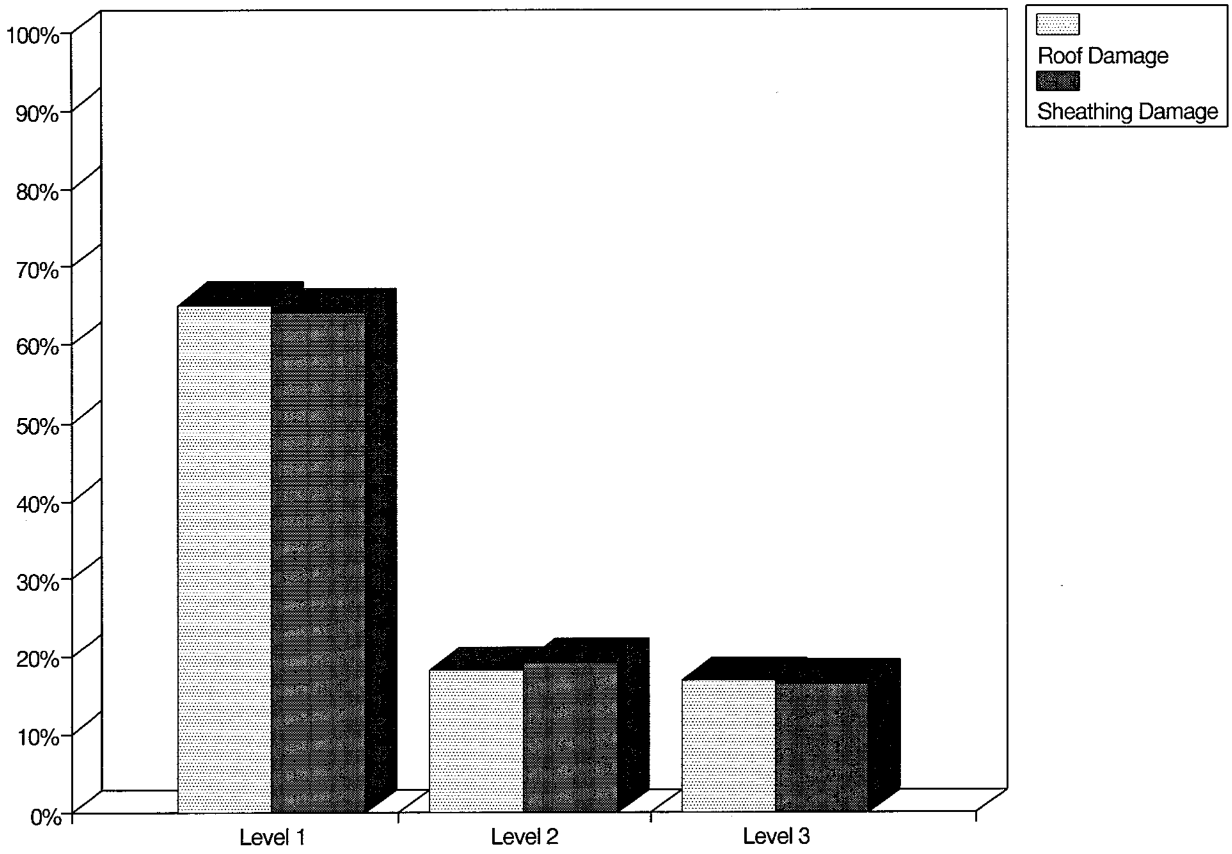

Figure 76. Distribution of roof sheathing damage and overall roof damage for all homes surveyed.

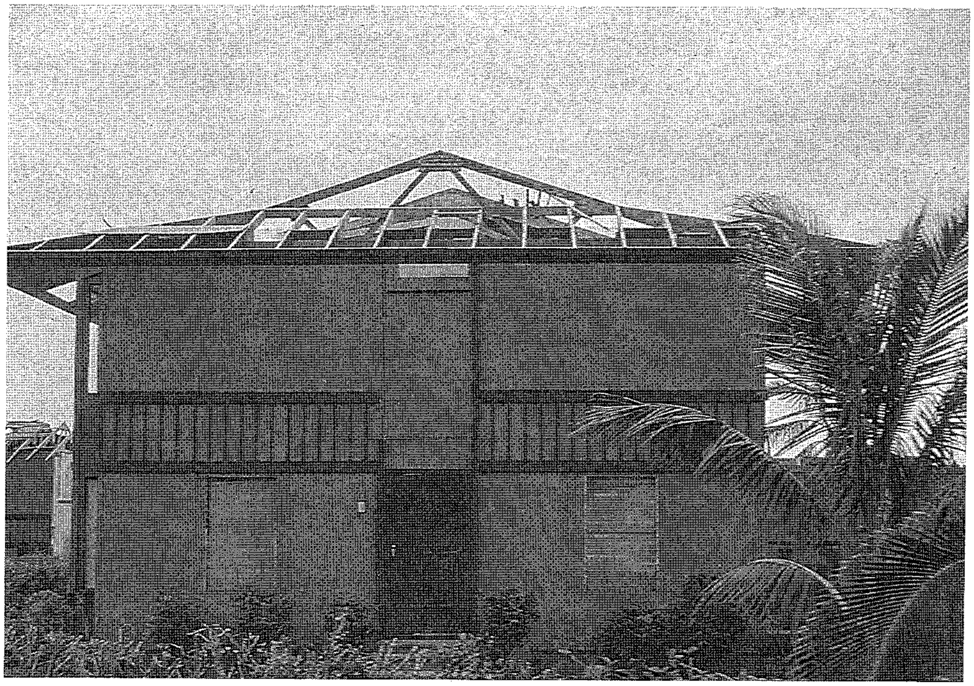

Figure 77. Severe loss of plywood roof sheathing indicating inadequate connections.

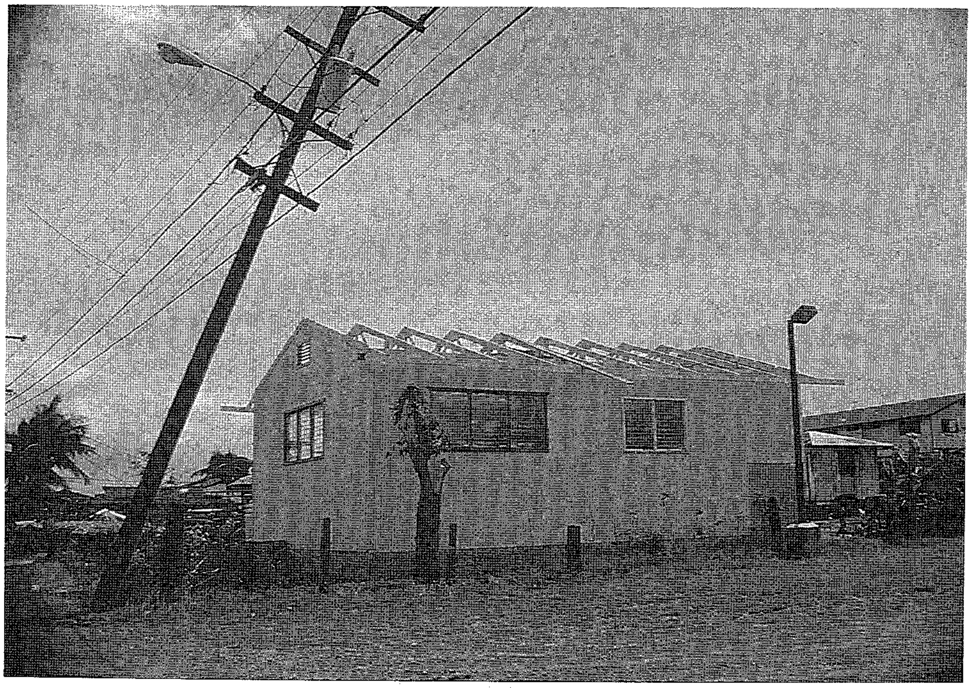

Figure 78. Roof purlins stripped from roof along with metal roofing. Purlins were commonly fastened to trusses with only one nail at each intersection.

Wall Type - Wall construction in Kauai was very different from that found in the Florida survey. The predominant use of wood construction in walls is reflected in Figure 79. As with roof type, variation in the use of wood for constructing walls was found. About 90 percent of the homes in the survey were wood construction with nearly equal amounts of single-wall homes and conventional wood-frame homes. The newer homes with wood walls typically used pressure-treated dimension lumber with conventional wood stud framing and pressure-treated plywood sheathing.

The distribution of wall damage is shown in Figure 80. About 88 percent of the surveyed homes were rated in the lowest category (Level 1) for wall damage. Some examples of the wall construction variations and damages are shown in Figures 81 through 86. Examples of deficient design and construction were found in all wall types surveyed, including wood, steel, and masonry. Some coastal homes on elevated foundations did experience problems with continuous load paths or structural connections from the wall to the foundation members (see Figure 86).

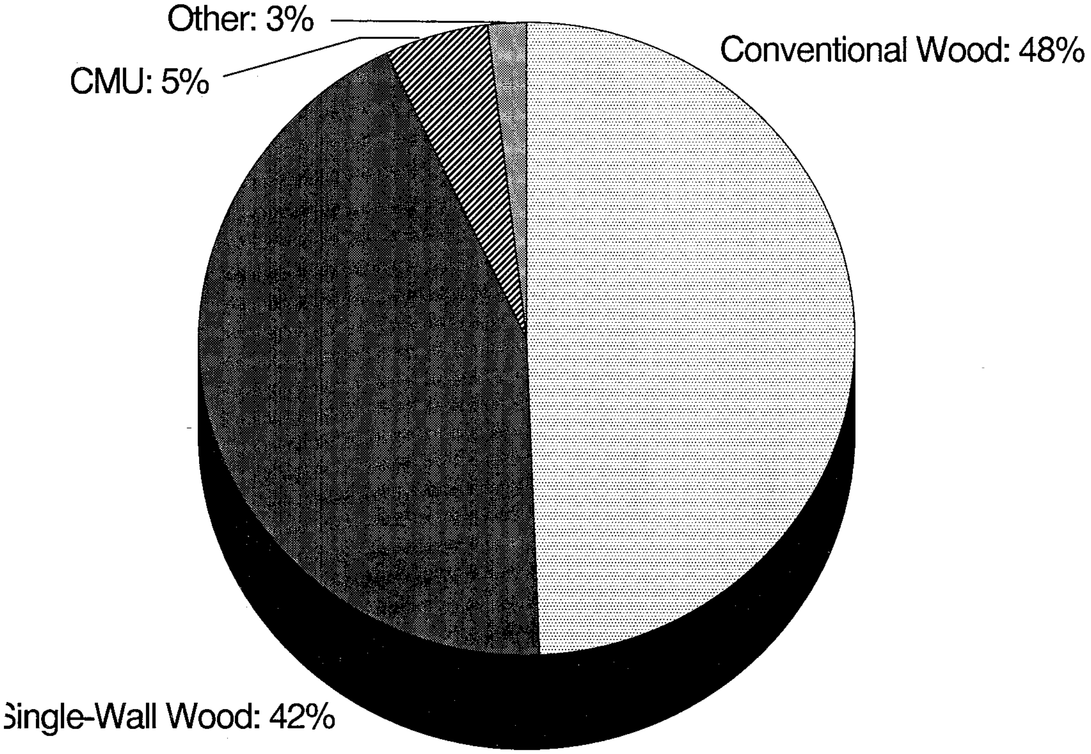

Figure 79. Distribution of exterior wall construction methods.

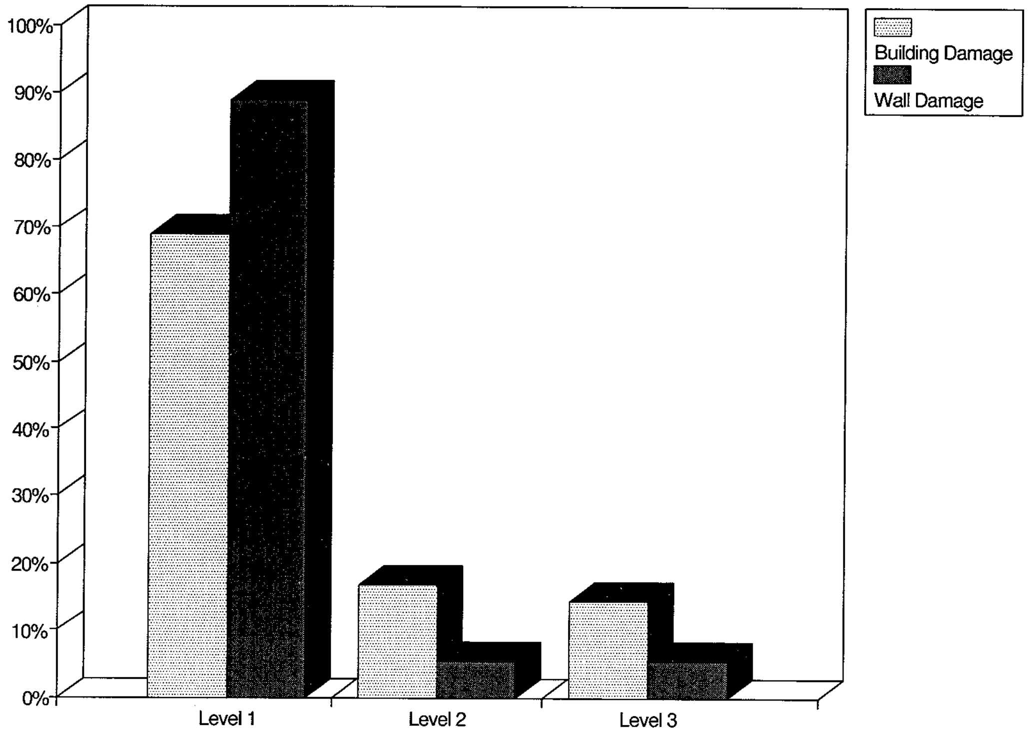

Figure 80. Wall damage distribution for all homes surveyed.

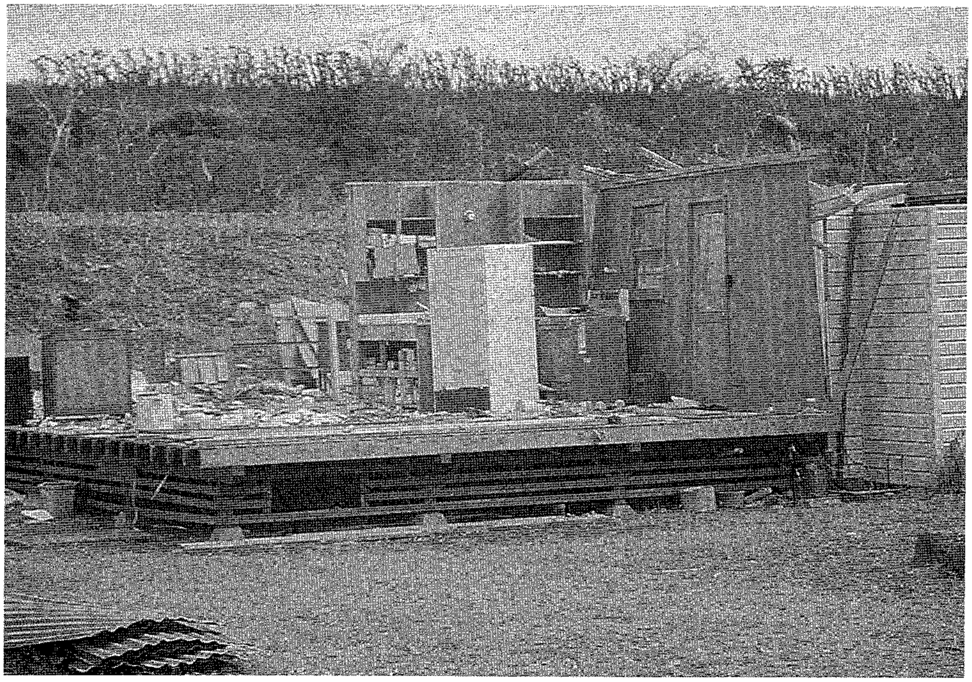

Figure 81. Damaged house showing the vulnerability of single-wall construction.

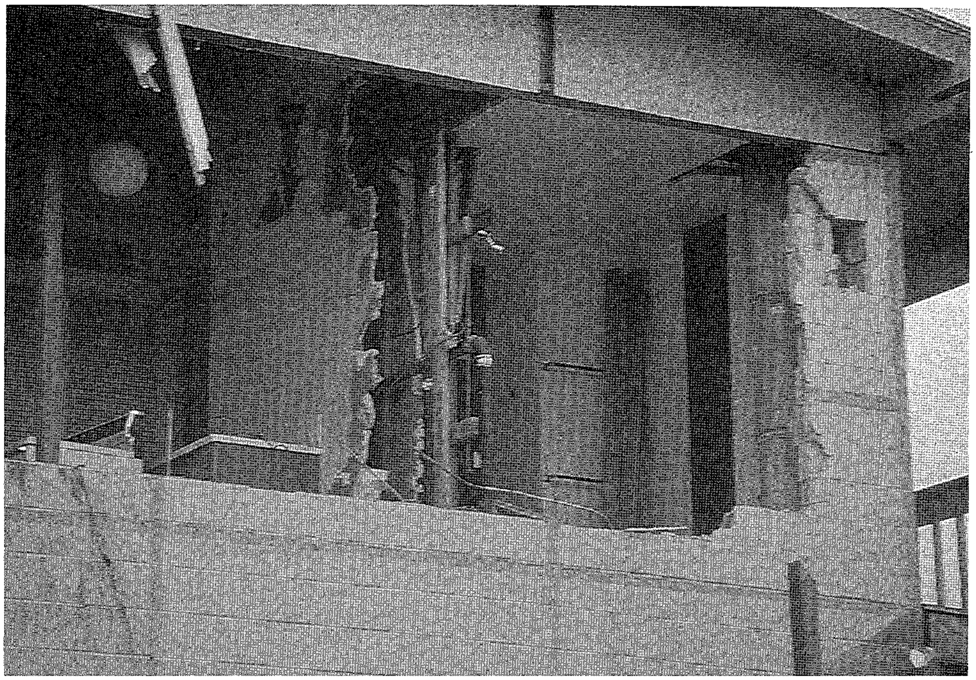

Figure 82. Blown out concrete block end wall that lacked a concrete tie beam and proper reinforcing.

Figure 83. Wood-frame end wall with buckling and tearing of hardboard siding panels.

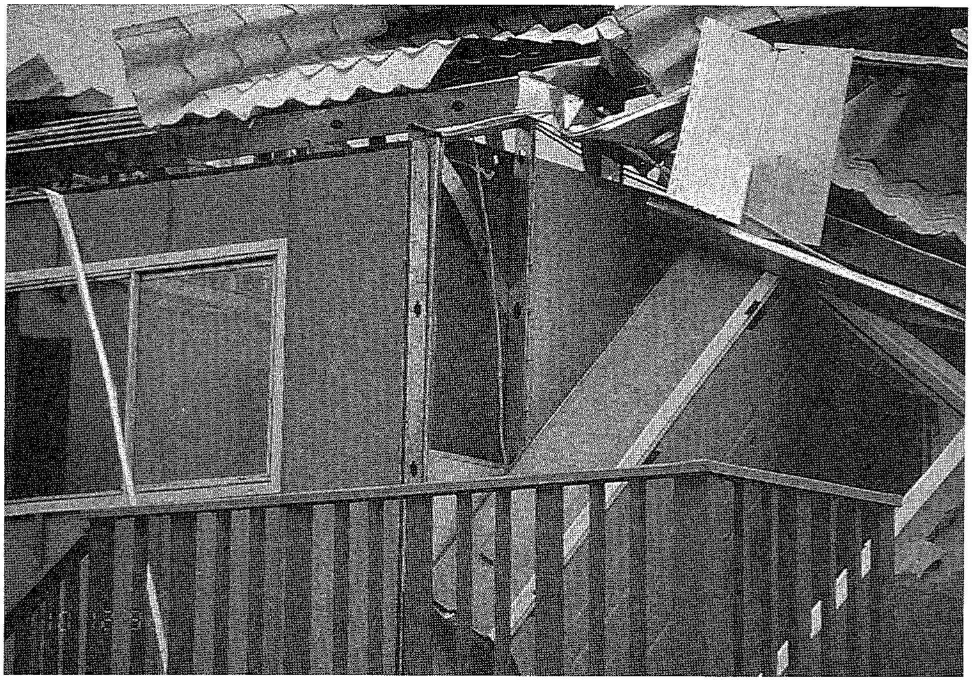

Figure 84. Light-gauge steel framing was also subject to severe damage.

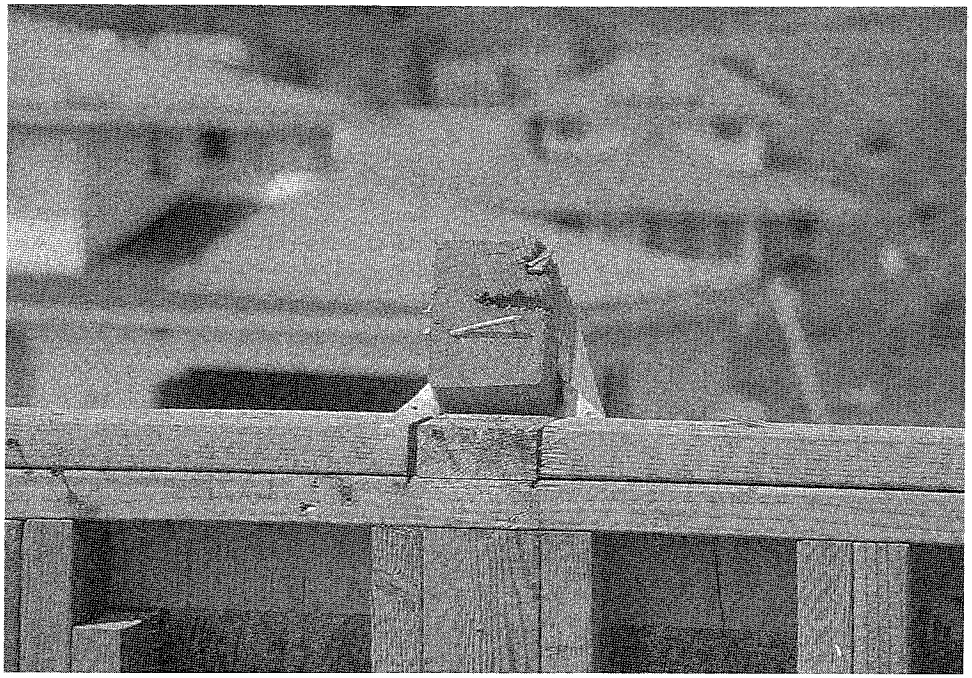

Figure 85. The metal strapping between the first and second story on this home did not provide adequate structural continuity between stories.

Figure 86. The bracket and lag bolts that anchored the wall post to the elevated foundation on this coastal home provided insufficient lateral resistance against the wind loads experienced by the inadequately braced wall.

Foundation Type - The foundation types found in Kauai were also more varied than those found in Florida. As shown in Figure 87, pier foundations of either wood post or concrete masonry units (CMU) were predominant. Post and pier foundations were typical of older homes with single-wall construction, whereas slab-on-grade was more typical of newer homes.

The distribution of damage to the foundations of all homes surveyed is shown in Figure 88. About 97 percent of the surveyed homes were ranked in the lowest category (Level 1) for foundation damage. Though infrequent, foundation-related failures of overturning, uplift, and sliding were observed in post and pier foundations (see Figures 89 through 93). These were generally the result of inadequately designed, installed, or maintained foundations with deficient lateral bracing or load paths to the super-structure. Foundations for coastal homes were often not elevated or otherwise designed to prevent damage from storm surge (Figure 94). Storm surge damage is discussed in detail in a later section. As in Florida, slab-on-grade foundations performed very well when not subject to storm surge.

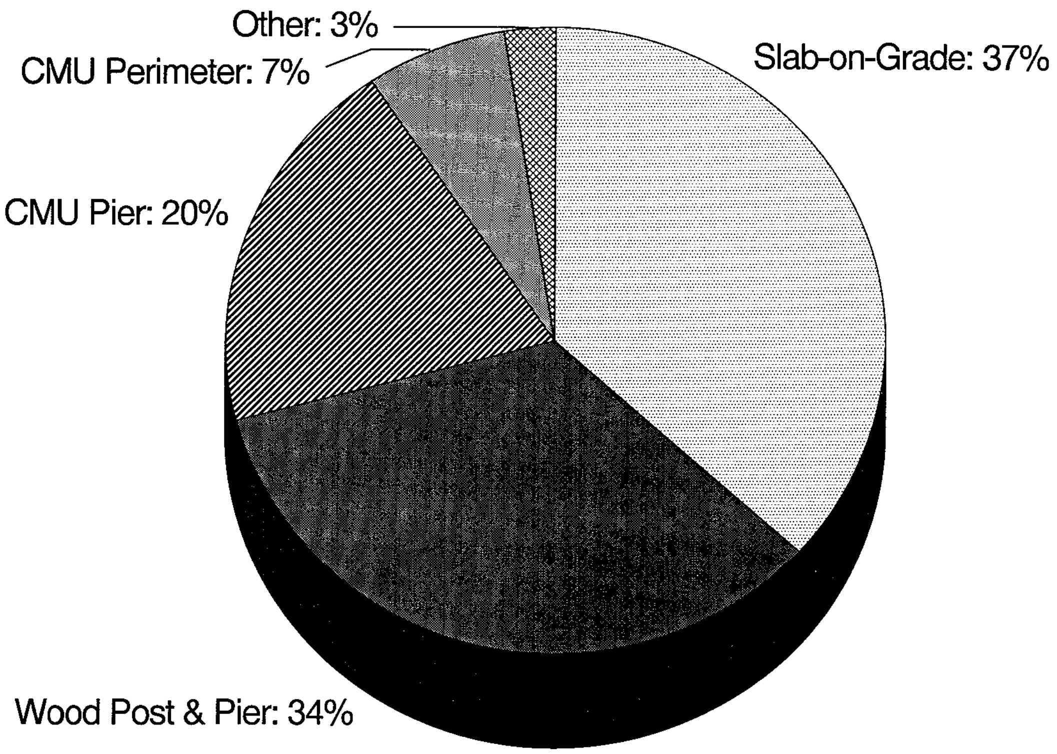

Figure 87. Distribution of foundation types in homes surveyed.

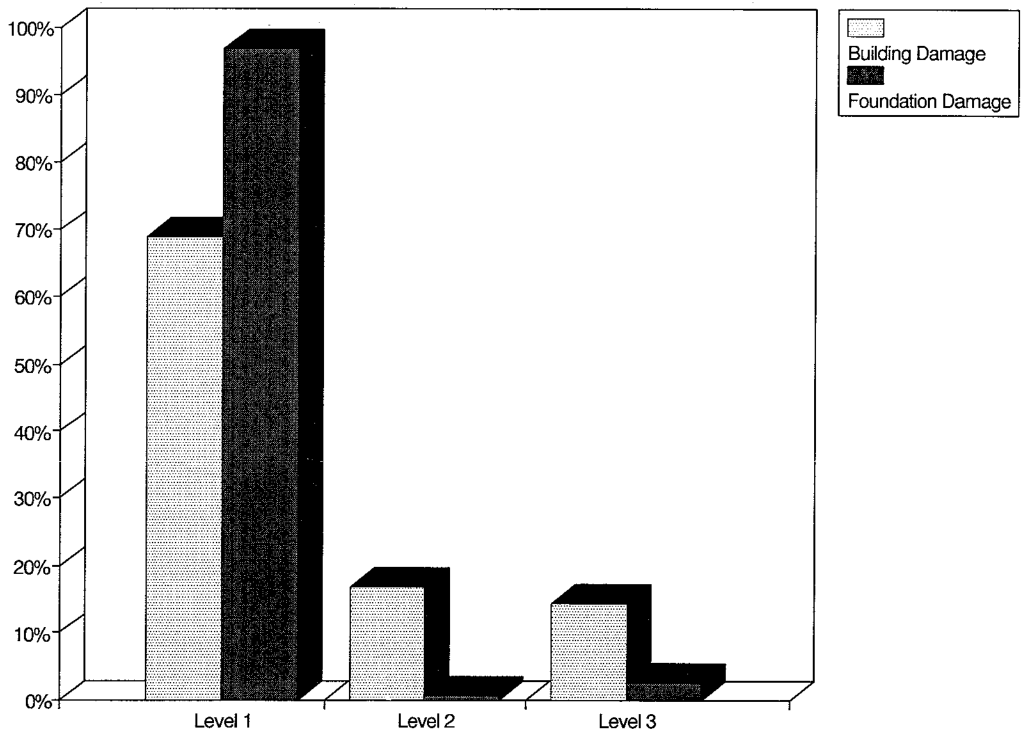

Figure 88. Foundation damage distribution of all homes surveyed.

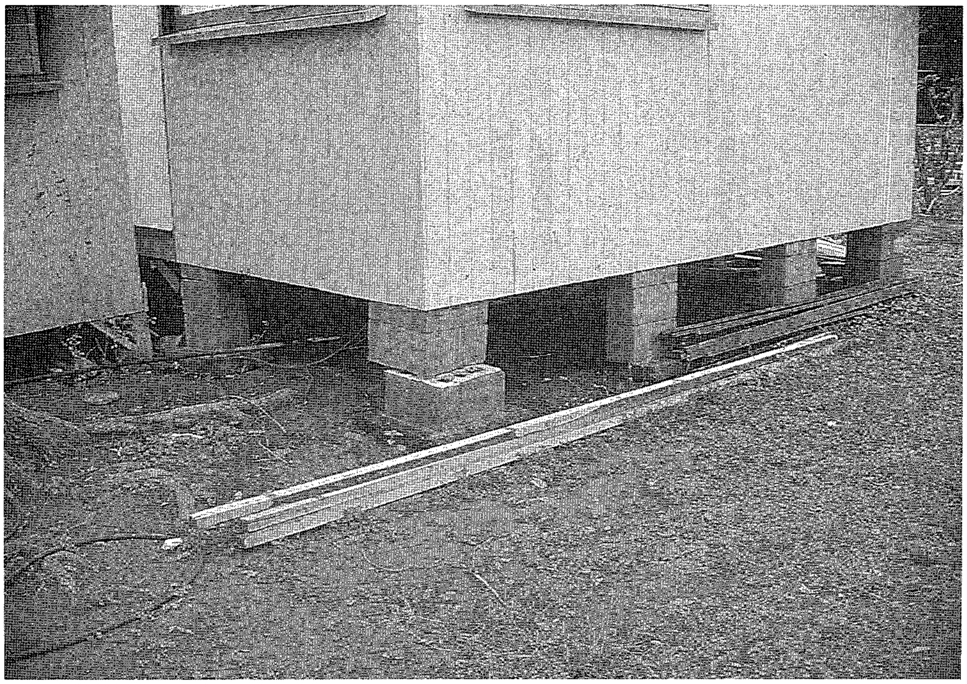

Figure 89. Shear slippage of an unreinforced CMU pier foundation.

Figure 90. Wood post foundation with severe rot and termite damage.

Figure 91. Wood pier foundation shifts under the shear forces created by the wind.

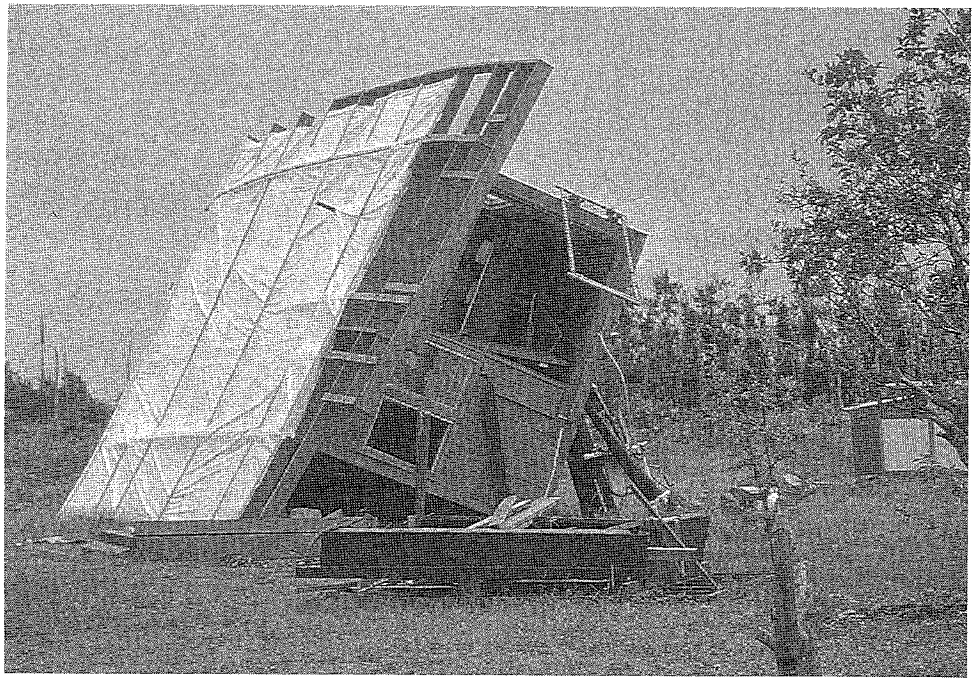

Figure 92. With its large overhangs and lacking connection to a foundation, this small home was lifted and moved several feet from its original location.

Figure 93. This single-wall home lacked continuous load paths to the foundation and failed by overturning.

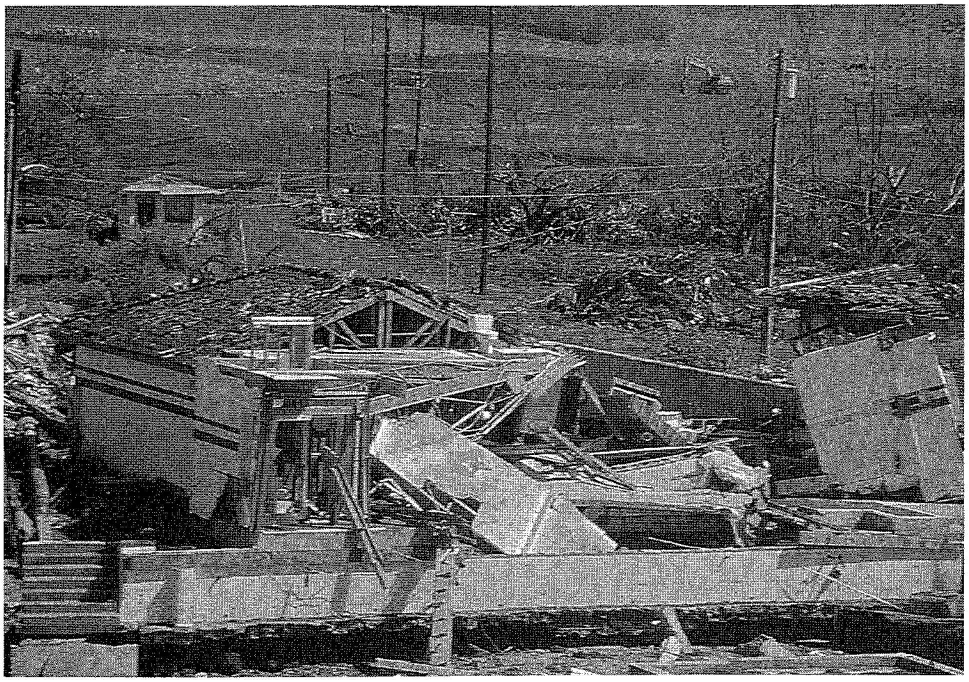

Figure 94. Slab-on-grade foundation survives the storm surge but the remainder of the home was demolished by storm surge. Away from the coastal flood plain, slab-on-grade foundations performed well.

Water Damage - The level of water damage for all homes surveyed is shown in Figure 95. The water damage rating reflects the ability of the structure to maintain a water-proof envelope and protect the building contents during and after a hurricane. Water damage commonly resulted from failure of the roof covering or windows, not necessarily associated with structural damage. The "U" shape of the damage distribution may be attributed to the influence of homes with corrugated metal roofing, which tended to suffer greater roofing loss. As in the Hurricane Andrew assessment, the influence of water damage on the overall building damage was substantial. Nearly 40 percent of the accessible homes experienced a severe level (Level 3) of water damage. Many of the older single-wall homes suffered heavy water damage due to a complete loss of their roof coverings.

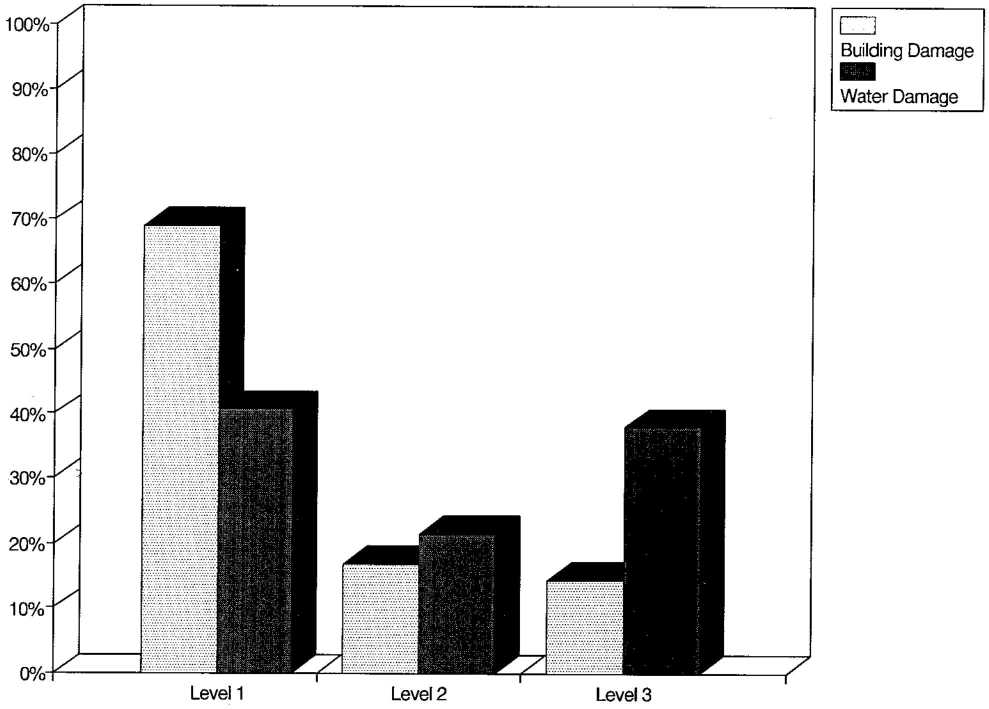

Figure 95. Distribution of water damage to all homes surveyed.

Roof Covering - The survival of roof coverings is one of the most important factors (along with windows) in mitigating widespread water damage to homes during and after a hurricane. Kauai differed from Florida in that a higher proportion of the homes had metal roofing, particularly single-wall homes, and a lower proportion had composition shingles (Figure 96). Figure 97 shows the distribution of roof covering damage relative to overall roof damage. About 64 percent of the homes surveyed experienced high levels (Levels 2 and 3) of roof covering damage.

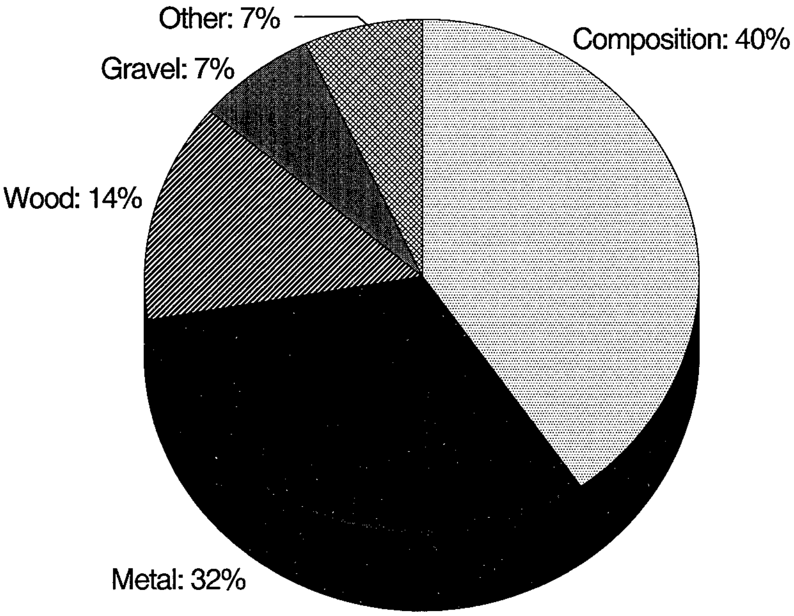

Figure 96. Distribution of roof covering materials.

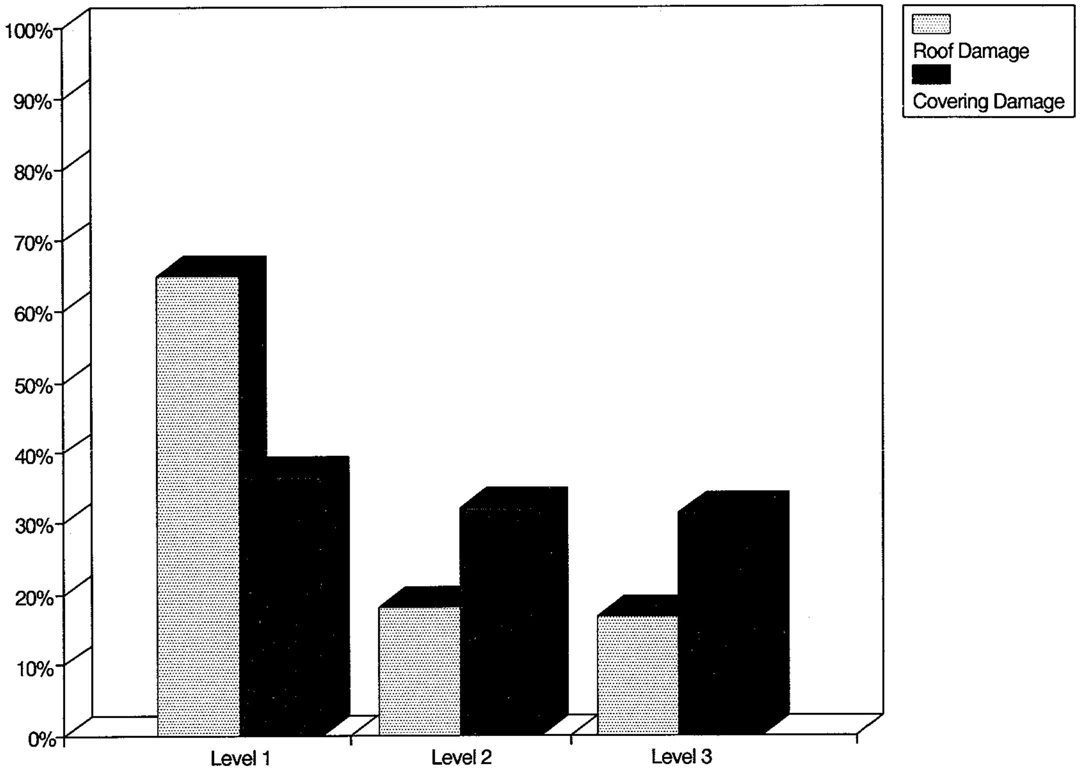

Figure 97. Distribution of roof covering damage and overall roof damage for all homes surveyed.

Generally, composition shingle roofs appeared to withstand the winds better than corrugated metal roofs, and most were rated in the lower roofing damage category. This is partly attributed to the fact that shingle roof systems were wood sheathed, which remained fastened better than the corrugated metal. Therefore, homes with shingle roofing generally maintained some degree of protection from water, as well as structural integrity from the plywood sheathing even though they sustained damage to the roofing. Another factor is that many of the metal roofs were located on the southern coast and may have been subject to higher wind loads on average. Wood shake roofs, where used, appeared to have performed well. Figures 98 through 100 provide some examples of roof covering damages.

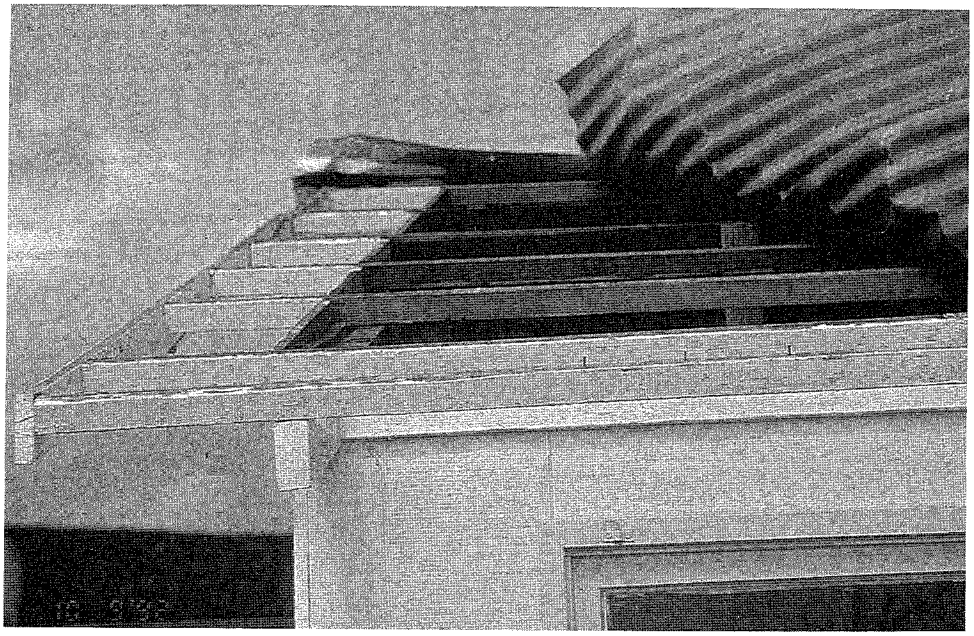

Figure 98. Steel roofing torn from the roof of a single-wall home. The wood purlins often went with the roofing.

Figure 99. Typical damage to composition roof shingles.

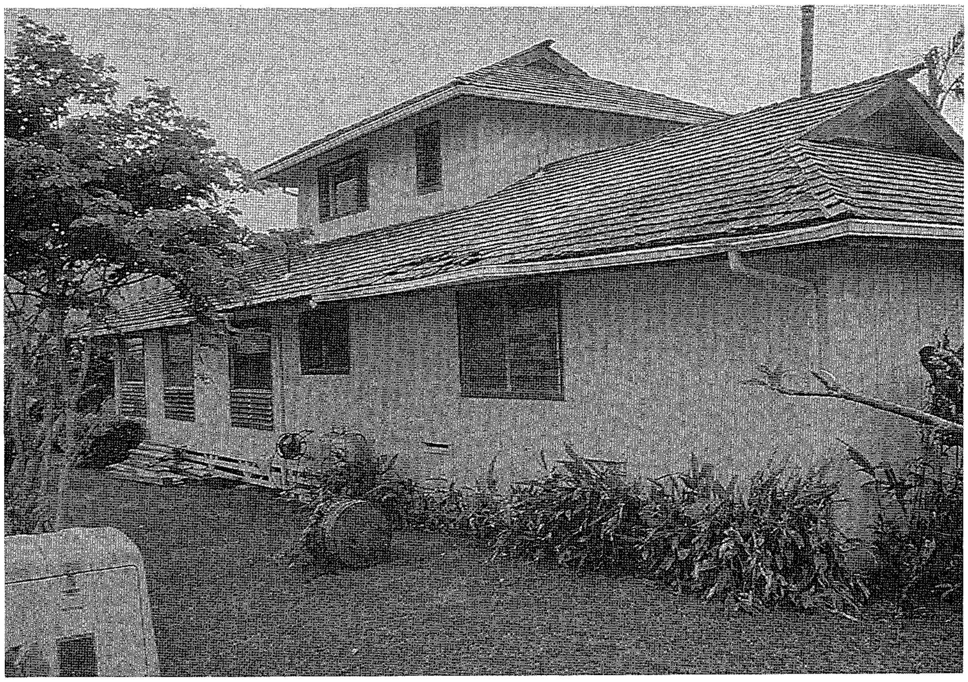

Figure 100. Wood shake roofs performed relatively well.

Projectile Damage - As with Hurricane Andrew, projectile damage and associated window damage was a serious issue. The distributions of window damage and projectile damage are shown in Figures 101 and 102, respectively. About three-quarters of the surveyed homes were rated in the lowest category (Level 1) for both window and projectile damage.

Unprotected windows are vulnerable to projectile damage as shown in Figure 103. In this case, a built-up tar and gravel roof on an upwind building became a launching pad for the gravel that broke every window in this home. In Figure 104, a piece of wood pierced the roof of this home, completely severing the hip joint of a truss. The house in Figure 105 was struck by a roof dislodged from a neighboring home. A particularly serious source of projectiles was corrugated metal roofing, which frequently appeared on the landscape. Unsecured propane fuel tanks also became projectiles in the high winds.

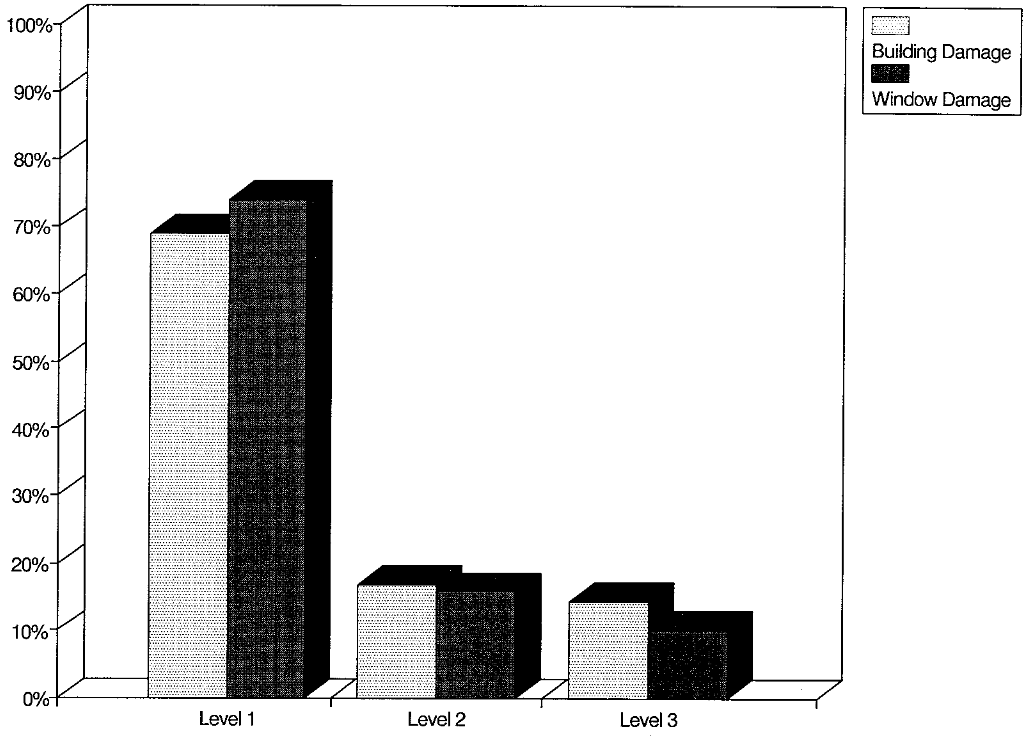

Figure 101. Distribution of window damage for all homes surveyed.

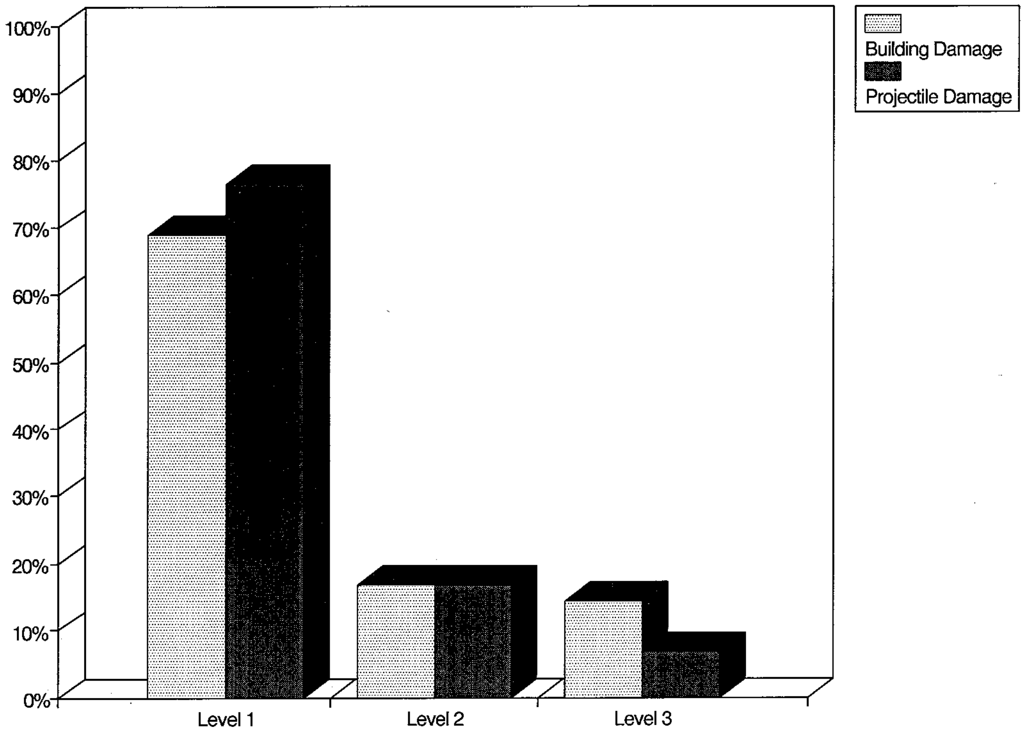

Figure 102. Distribution of projectile damage for all homes surveyed.

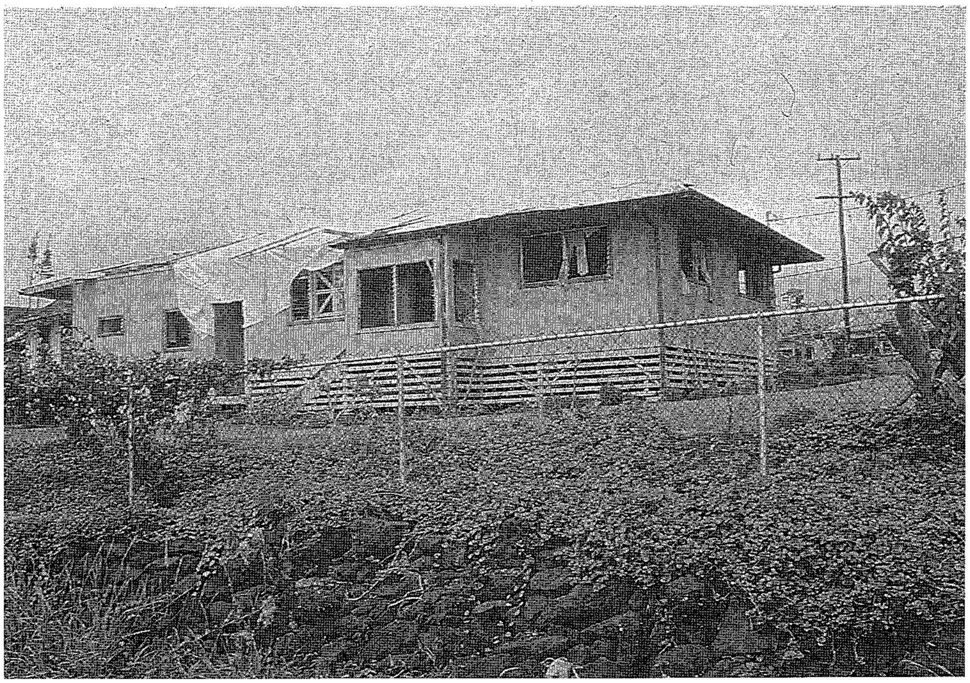

Figure 103. Shattered windows from gravel originating from a neighboring tar and gravel roof.

Figure 104. A wood projectile penetrates roof framing materials.

Figure 105. This home was struck by the roof blown off a neighboring home.

Topographic Wind Effects - One of the unique conditions on Kauai were failures apparently associated with topographical wind effects. Frequently homes were built on the edge of plateaus at the crest of a slope where localized high winds developed (Figure 106). The homes at the crest of the slope were commonly destroyed, whereas homes just behind them suffered less direct wind damage but some degree of projectile damage. This condition is shown in Figures 107 and 108. Neither the UBC-88 or ASCE 7-88 procedure for calculating wind loads accounts for the effects of topography on near-ground wind speeds.

Storm Surge - Kauai lacked natural or manmade measures to protect against storm surge. Many buildings along the southern coast of Kauai were destroyed or severely damaged. The relatively few homes in the storm surge area were severely damaged either by water or by massive structural damage from the impact of the storm surge. Some types of construction appeared to perform better than others, as shown in Figure 109. In one home, sliding glass doors and large openings gave way, which reduced the forces by allowing water to pass through. The adjacent structure was devastated and caused some damage to the surviving building. Both were on unelevated foundations and constructed with wood framing.

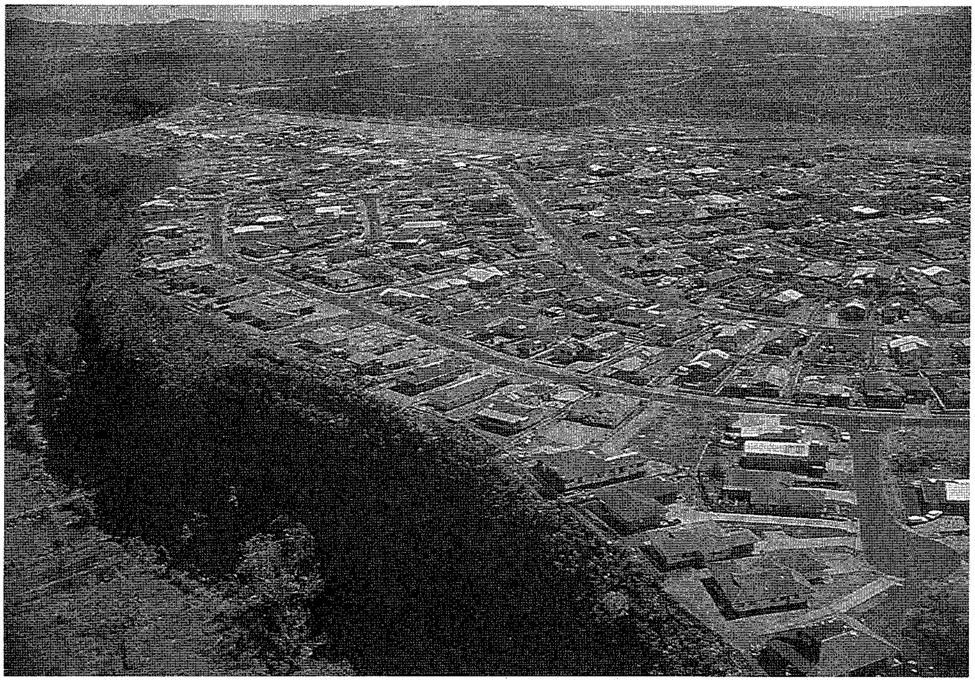

Figure 106. Construction on a coastal plateau.

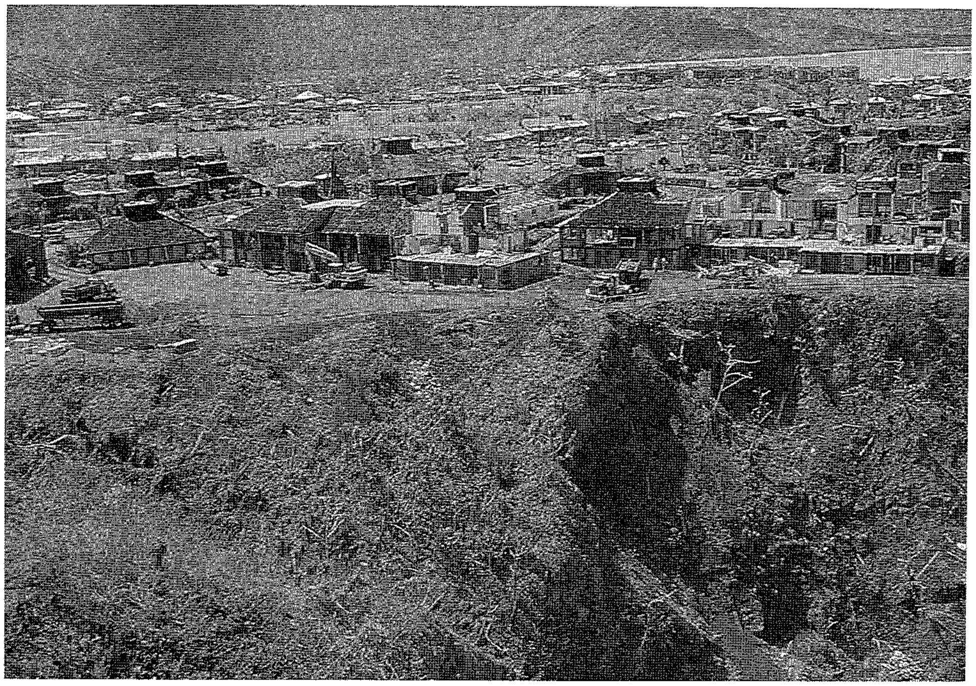

Figure 107. Residences located at the top of a slope on the shoreline of Kauai.

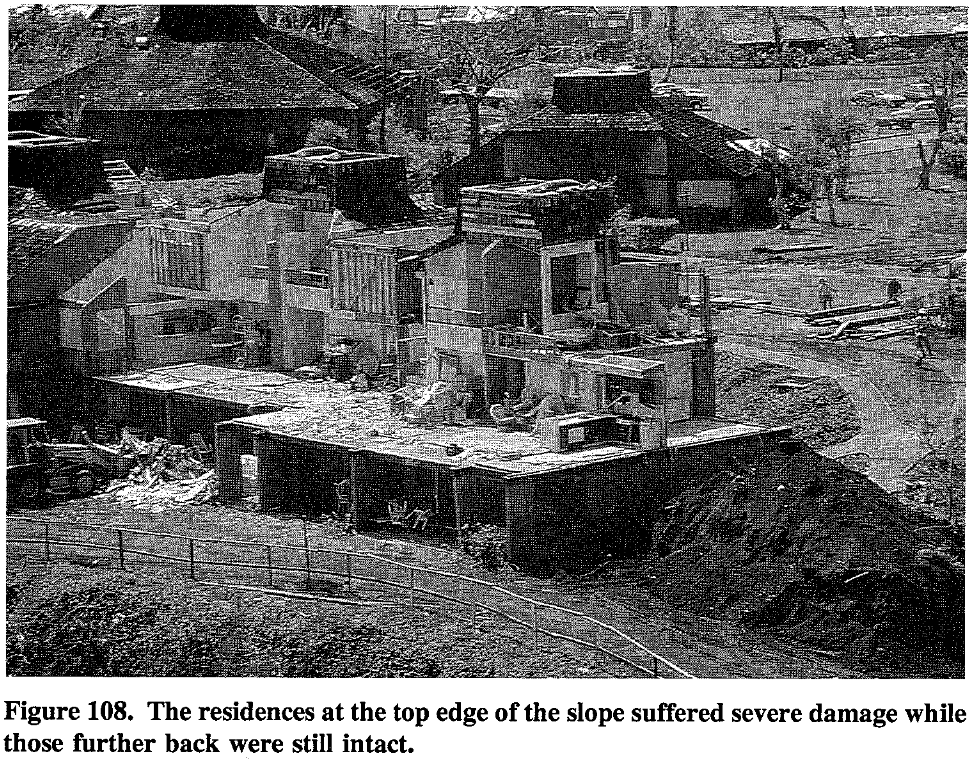

Figure 108. The residences at the top edge of the slope suffered severe damage while those further back were still intact.

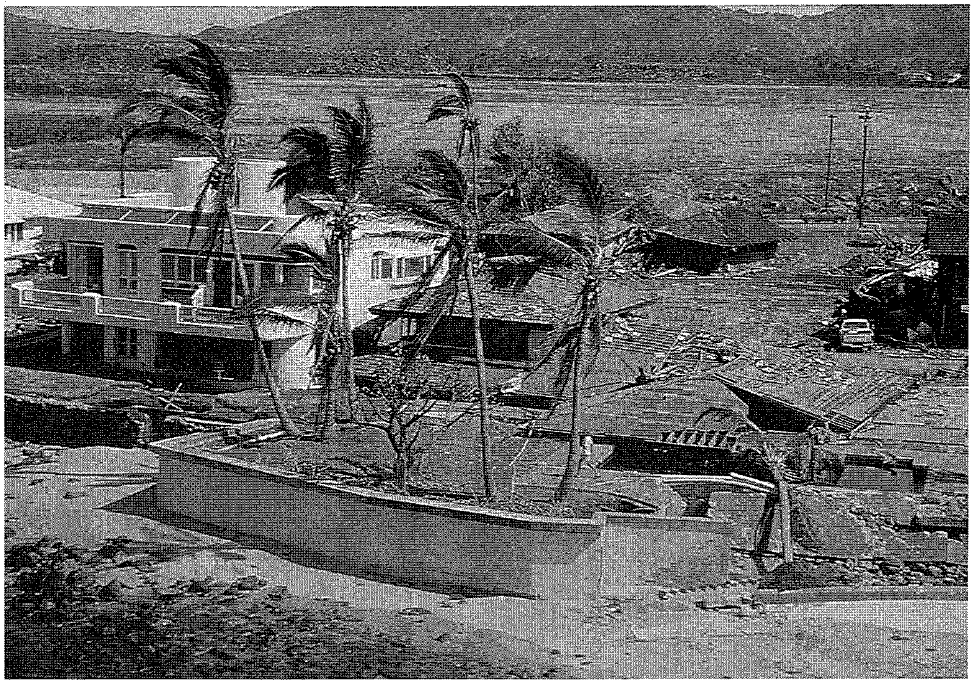

Figure 109. Storm surge damage to adjacent unelevated homes. The home on the left allowed the storm surge to pass through the lower level, which reduced the surge pressure on the structure.

SUMMARY AND CONCLUSIONS - HURRICANE INIKI

Hurricane Iniki provided a demanding test of construction practices and housing characteristics on the island of Kauai. Although Hurricane Iniki was less severe than Hurricane Andrew, components of homes generally failed in a manner similar to that found in Florida. The housing conditions on Kauai varied widely, and many of the homes were constructed with practices unique to the Hawaiian Islands.

Similar to the Florida damage assessment, the most costly aspect of the overall damages was related to widespread water damage. In most cases, the basic structures were left standing. When significant structural damage occurred, it was usually associated with the roof system. Structural and water damages were primarily related to problems with window protection, roof coverings, and roof sheathing attachment (corrugated metal and plywood). For older Kauaiian homes, in particular, there is additional concern for the lack of adequate continuous vertical load paths. There is also a heightened awareness needed for the specific hazards of storm surge and topographical wind effects.

The following conclusions are drawn from this investigation through statistical evaluation and field observations in Kauai:

1. Hurricane Iniki produced winds in excess of the design wind speed established by the 1988 Uniform Building Code (UBC-88) and ASCE 7-88. For those homes directly on the coast, storm surge damage was serious. Basic coastal construction practices, such as

elevating foundations, were not consistently followed. Storm shelters provided satisfactory protection to the population of Kauai during the hurricane.

2. As covered in the damage survey analysis, the topical conclusions regarding the wind damage are:

   a. Two-story homes suffered greater damage than single-story homes, especially in coastal areas and on the crest of steep slopes.

   b. Homes with gable roofs appeared to be more susceptible to damage than their hip-roof counterparts. Loss of roof sheathing was a major problem due to inadequate fastening relative to the materials used (plywood and corrugated metal). About 38 percent of the sampled homes lost one or more sheathing panels, particularly corrugated metal. Framing problems commonly related to field built trusses and purlin connections also contributed to structural damage in roof systems. Vertical load paths (e.g., hurricane straps) were deficient in the roof systems of some older homes.

   c. Though infrequent, failures were found in all types of walls, including conventional wood-frame, single-wall, heavy timber, masonry, and light-gauge steel framing. About 88 percent of the homes surveyed were ranked in the lowest category (Level 1) for wall damage. Observed failures were often related to inadequate continuous load paths, connections, or topographic wind effects.

   d. About 97 percent of the surveyed homes were rated in the lowest category (Level 1) of foundation damage. Post or pier foundations, common to the older single-wall homes, were more susceptible to sliding and collapse, and the supported structure was more susceptible to uplift and overturning. In coastal storm surge areas, elevated foundations and breakaway construction methods were not applied consistently.

   e. Failures in the water-resistant envelope (primarily windows and roof coverings) greatly increased water damage, which was the greatest factor in the amount of overall damage. Severe water damage was documented in 40 percent of the homes surveyed.

   f. High levels (Levels 2 and 3) of roof covering damage were experienced by 64 percent of the surveyed homes. In particular, metal roofing was often stripped from the roofs, sometimes with the purlins attached.

   g. Projectile damages were not as prevalent as those experienced in Florida, in part because of the lower density of housing and less severe winds. Consequently, most homes experienced minimal (Level 1) window damage. However, cases of severe projectile damage were observed. The worst examples of projectile damage were found in homes down-wind from those destroyed by severe topographical wind effects or homes with tar and gravel roofs. Window failures also contributed to structural damage through the effects of internal pressurization.

3. The UBC-88 contains numerous provisions for hurricane resistant design of homes. In the widely varied housing types observed, the application of these measures was not consistent and was often lacking. Older homes of indigenous, island construction were generally not in compliance with the UBC and some suffered severe damage.

4. Topography appears to have had a significant effect on near ground wind speeds and related damage to homes located at the crests of slopes along the coast. Topographic wind effects are not accounted for by either UBC-88 or ASCE 7-88.

FINAL CONCLUSIONS

The primary goal of this study is to provide an impartial assessment of the damage to single-family homes caused by Hurricanes Andrew and Iniki. To this end, over 500 homes in Florida and 160 homes in Kauai were subjected to a detailed damage assessment of housing characteristics and damages. Many other homes, including those damaged in Louisiana by Hurricane Andrew, were also observed to capture unique aspects of the housing populations and the damages sustained.

The assessed homes were subject to some of the most severe winds of Hurricanes Andrew and Iniki. The winds in these events exceeded the design specifications of all U.S. building codes and standards. Widespread water damage was the most costly factor in the damages for both South Florida and Kauai where 65 percent and 40 percent of the surveyed homes, respectively, suffered severe water damage to their interiors. Significant structural damage (e.g., a collapsed roof) occurred in less than 20 percent of the sampled homes affected by the worst winds of both hurricanes.

The analysis of hurricane damage to single-family homes in this study reveals three characteristics of a typical home that have the greatest influence on the overall resistance to hurricane damage:

- Opening protection (windows and doors)
- Roof coverings
- Roof sheathing attachment

It is recognized that the hurricane resistance of a home is dependent on all components of the system. However, the three characteristics above were consistently found to be the weakest links in the assessed homes. Improvements in these characteristics will have the greatest impact on limiting the damage to single-family homes under hurricane conditions.

Window and door damages contribute substantially to increased levels of water damage as well as to a greater potential for structural damage through internal pressurization. Internal pressurization from wind entering a breached opening can effectively double the wind loads on structural components such as roof sheathing. In the Florida survey, 64 percent of the accessible homes experienced damage to at least one window. In most homes surveyed, it was apparent that little regard was given to proper window protection. It is likely that a simple but effectively applied plywood covering would have provided the needed protection in most cases.

Damage to roof coverings contributed heavily to the high levels of water damage experienced. In Florida, 77 percent of the homes were judged to have sustained a high level of damage to the roof coverings. Roof covering problems were most commonly associated with conventional composition shingles and, in Kauai, corrugated metal roofing as well. These materials were not designed to withstand the conditions experienced in Hurricanes Andrew and Iniki, although composition shingles are the most widely used and affordable roofing materials in most areas of the United States.

Most structural damage in Florida, Louisiana, and Kauai was related to roof systems. Roof structural problems were most evident in gable-roof homes, which experienced significantly greater damages than hip-roof homes. Considering only single-story homes in the Florida survey, about 33 percent of the gable roofs were rated in the highest level of roof damage (e.g., one or more severely stressed gables and several missing sheathing panels). Only 6 percent of the hip roofs received this rating. Since gable-roof homes comprise about 80 percent of the houses surveyed in Florida, they provide a focal point for analyzing the detailed structural problems in homes.

While gable roofs are more susceptible to damage, the basic problem in most cases was inadequate attachment of roof sheathing at the gable ends. Roof sheathing is a critical component that locks all other roof members together to form a structural system. The significance of roof sheathing is best illustrated in the Florida survey where almost 25 percent of all assessed homes experienced the loss or damage of one or more panels of roof sheathing, commonly starting at the gable end.

Walls and foundations contributed to only a small portion of the overall structural damages. The performance of wood-frame walls depended on the integrity of the roof system to a much greater degree than reinforced concrete and block walls. As a result, wood-frame walls observed in Florida case study homes exhibited more susceptibility to wind damage. Of the limited number of wood-frame walls observed, damage was often related to deficient connections, particularly at the corner top plate joint—even when the roofs were still intact. Use of non-structural siding and tall, steep roofs also contributed to damage of the wood-frame walls observed.

RECOMMENDATIONS

The levels of damages experienced in Florida, Louisiana, and Kauai were caused by several intertwined factors. The principle factors or causes relevant to the damages discussed in this report are:

- Construction (workmanship, inspection, and building code requirements)
- Design (aesthetic and structural elements)
- Building products and materials (performance standards and building code requirements)
- Preparedness (home owner awareness, preparation, maintenance, and training)
- Acceptable risk policy (with respect to probable extreme wind speeds and storm surge in coastal areas)

While some of these factors may be viewed as more significant than others in influencing the level of damage from hurricanes, they all have the potential to seriously affect the cost of housing as well as the protection of property in hurricane-prone areas. The most beneficial policies for the public at large will require a rational balance between the cost and the degree of protection afforded to homes. Meanwhile, the protection of lives should retain its essential function through distinct measures related to hurricane forecasting, evacuation, and storm shelters.

With the above factors in mind, the following recommendations are suggested in accordance with the observations and analyses conducted in this investigation:

1. Improved compliance to wind-resistant construction practices is needed. Multidisciplined efforts to assure compliance to existing wind-resistant building code measures should be prioritized above all other corrective alternatives. This effort includes establishing adequate training and accountability for all participants in the building process.

2. Improvements in building code requirements related to hurricane resistance are recommended according to the findings in this report. Careful examination of building codes should focus on major contributors to damage (structural and water) identified in this report, including roofing, roof sheathing attachment, and window protection. Each proposed modification should be carefully considered for its relative cost vs. benefit before implementation. Affordable housing should be maintained through rational amendments to building codes. One possible approach involves a differentiation between houses with higher risk characteristics that may require special engineering, and those with lower risk qualities which can be more effectively administered and constructed through easily understood, cost-effective prescriptive provisions.

3. Programs to inform and train owners in effective measures to prepare their homes for impending storms should be instituted in hurricane-prone areas. All residents and property owners should be accountable for basic preparatory actions. Evacuation procedures and storm shelters should continue to receive high priority.

4. Research efforts to improve the technical understanding of extreme wind events and near-ground wind effects on buildings should be prioritized. Wind engineering design procedures should include the effects of topography and projectiles.

5. Industry involvement in the investigation and development of cost-effective, wind-resistant construction methods and materials should be encouraged, particularly in the areas of roof coverings, window protection, and structural connections.

6. Standardized procedures for assessing and reporting damage in future hurricanes and other natural disasters should be developed and improved. The objective techniques used in this investigation should be considered in such an effort. Multivariate analysis techniques should be considered to improve the explanatory power within the damage database.

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Appendix A
TASKS

This emergency damage assessment involved the performance of several tasks, which are listed chronologically as follows:

1. Review of preliminary observations and case studies of hurricane damage area in South Florida.*

2. Pre-survey gathering of information related to:

   - estimated regions of impact
   - review of preliminary damage estimates
   - determining accessibility and authorization to enter damage areas
   - other post-disaster conditions such as crime and humanitarian relief activities

3. Organize survey teams and support equipment

4. Develop a survey methodology that addresses:

   - requirements for significant sample size
   - representative sampling methods
   - identification of important parameters to accurately record field data
   - grading method for levels of damage to various components of a home
   - hurricane damage assessment forms

5. Standardize the grading strategies and damage assessment among all survey teams by comparatively assessing several homes in Florida.

6. From the best available map sources, determine a selection of houses (or streets) to survey within defined damage zones in Florida, Louisiana, and Kauai. (Adjustments to the sampling methodology were implemented in Louisiana and Kauai because of the diverse conditions and less geographically structured housing population.)

7. Recode the field survey sheet information into a digital format to perform database and statistical operations. Analyze the coded field data and collective observations to investigate relationships of building and storm characteristics to the level of damage observed.

8. Search current literature pertaining to the hurricane events.

9. Evaluate applicable building codes and wind design standards.

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*Edward M. Laatsch, P.E. "Preliminary Hurricane Andrew Notes—Site Visits on August 27, 28, and 29, 1992," September 3, 1992.

Appendix B
TERMINOLOGY

Basic wind speed:	Design wind speed; fastest-mile wind speed at 10 m (32.8 ft) above ground level in flat open country (exposure Category C) with a 50-year return period.
Bernoulli effects:	The fluid dynamics of flowing wind that create high and low pressure regions around the different geometries of a structure, arrangement of buildings, or topographic features.
Building damage level:	Overall assessment of the condition of an entire building relative to superficial, structural, and water damages; based on the collective damage level ratings of all assessment categories on the survey form.
Building envelope:	The shell of a building that protects the interior from weather damage, including roof, walls, windows, and doors.
Chi-square test:	A common statistical test, which, in this report, is used to determine if significant differences in damage exist for various house characteristics.
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.
Components:	Structural elements that are directly loaded by the wind and transfer the loads to the main wind force resisting system of the building; includes sheathing, studs, and trusses.
Concrete block and stucco (CBS):	A wall construction system common to the southern United States comprised of a stucco finish over block or concrete masonry units (CMU).
Continuous load path:	Structural elements and connections that transmit vertical and horizontal loads from the roof to the foundation.
Damage level:	Rating of the amount of damage to a particular element or group of elements of a house relative to the maximum potential damage; 1=low, 2=medium, 3=high.
Design:	The structural and aesthetic qualities of a building governed by details generally determined before construction.

Diaphragm action:	The structural stability provided by an extended, two-dimensional building element such as roof, ceiling, and floor assemblies. Diaphragms provide lateral support (bracing), load distribution, and structural continuity between other elements of a structure.
Eave overhang:	Horizontal extension of the roof beyond the building wall perimeter, as opposed to a rake overhang along the sloping edge of a gable roof.
End wall:	Exterior wall oriented perpendicular to the roof ridge or long axis of a building.
Exposure:	A designation representing the characteristics of ground surface conditions upwind of a building or measurement device that influence the magnitude of ground-level winds.
Eye wall:	Inner boundary of maximum winds circulating around the center or "eye" of a hurricane.
Failure mode:	A description of the method or type of failure experienced by a structure.
Fastest-mile wind speed:	The maximum wind speed averaged over the time required for a "mile" of wind to pass a point; exposure and elevation of the measurement site must be considered.
First wind:	Winds experienced in the leading edge of a hurricane before the eye passes over.
Hip roof:	A roof framing method that provides a sloped roof down to the supporting walls along all sides of the building.
Gable end:	The triangular part of the end wall of a gable roof.
Gable roof:	A roof framing method that provides a sloped roof down to two side walls, and triangular shaped ends that are a vertical extension of the end walls.
Horizontal load path:	Structural elements and connections that transmit loads acting in a horizontal direction.
Hurricane:	A tropical cyclone with a maximum sustained wind speed of 74 mph or greater.
Internal pressure:	The negative (outward) pressure acting on the interior surfaces of a building enclosure as a result of wind entering through openings on the windward side.

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.
Leeward wall:	The wall that faces away from the wind (opposite of windward wall).
Main Wind Force Resisting System (MWFRS):	An assemblage of structural elements that provides support for components and cladding directly loaded by the wind. Examples include rigid and braced frames, roof and floor diaphragms, and shear walls.
Maximum gust wind speed:	The maximum wind speed averaged for 2 to 5 second periods during a complete wind event, often reported in the media; exposure and elevation of the measurement site must be considered.
Maximum sustained wind speed:	The maximum wind speed averaged for 1-minute periods during a complete wind event.
Near-ground wind effects:	The highly variable behavior of wind near the ground as a result of ground surface characteristics and the complex and dynamic nature of extreme winds.
Overhang:	A horizontal projection of a roof, floor, or other architectural feature beyond the perimeter of the underlying structure.
Performance requirements:	Provisions of a building code specifying a level of required performance but providing flexibility in the means of complying. Engineering procedures are generally used for determining structural details to meet the performance requirement based on a wind speed.
Preparedness:	Temporary or permanent measures taken by a property owner to prepare a building and premises for a hurricane impact in advance or during the period of a hurricane warning.
Prescriptive requirements:	Provisions of a building code that prescribe specific construction methods or materials that are allowable. Examples include nail spacing for roof sheathing, rebar sizes, and location of hurricane straps.
Projectile:	Wind driven debris that becomes an additional hazard to humans and buildings during extreme wind events.
Rake Overhang:	Sloped edge of a roof that extends beyond the gable end.

Return period:	A prediction of the average time between design events of like magnitude or greater; usually determined by applying statistical models to available data.
Secondary bracing:	Lateral bracing of structural elements provided in addition to the support provided by diaphragm action.
Second wind:	Winds experienced on the tailing side of a hurricane after the eye passes over; generally in the opposite direction of first winds.
Shear wall:	An interior or exterior wall designed to resist racking, which provides lateral support to adjoining wall, ceiling, or roof assemblies.
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.
Single-wall:	A type of rudimentary wood construction found in regions with temperate climates such as Kauai; similar to construction practices used in agricultural buildings.
Storm surge:	Wind-driven tides and waves that impact coastal areas during a hurricane landfall.
Tributary area:	The area of a building surface (wall, floor, or roof) that contributes to the load being considered on a particular element.
Uplift:	Wind load acting upward on a structure; forces are a result of Bernoulli effect from wind flow over and around the building shell.
Windward wall:	Wall that faces into the wind (opposite of leeward wall)
Workmanship:	The quality imparted to a building in the process of construction, includes the elements of craftsmanship beyond that literally required in a building code.

Appendix C
ASSUMPTIONS AND FORMULAS FOR COMPARISON OF WIND DESIGN PROCEDURES

Assumptions for Florida (ASCE 7-88 vs. SFBC) and Kauai (ASCE 7-88 vs. UBC)

- enclosed building condition (partial internal pressures are considered for all but two-story MWFRS)†
- roof pitch of 22.6° (5:12)
- building dimensions: one-story (28'W x 40'L x 16'H)
  two-story (28'W x 48'L x 25'H)
- basic design wind speed: 120 mph for SFBC (as dictated by the code)
  110 mph for ASCE 7-88 (Florida)
  80 mph for ASCE 7-88 and UBC (Kauai)
- where applicable, tributary areas are: 16 sq. ft. roofs
  10 sq. ft. walls

The following wind design equations were used:

- SFBC (1991 Edition):
  Velocity Pressure (p) = $.00256 * V^2 * (h/30)^{2/7}$, where
  V = wind speed (mph, fastest-mile)
  h = building height
  Design Wind Load = p * shape factor * use factor
- UBC (1988 Edition):
  Design Wind Load = $C_e * C_q * Q_s * I$, where
  C_e = height, exposure, and gust correction factor
  C_q = pressure coefficient
  Q_s = wind stagnation pressure (psi)
  I = importance factor

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†This critical assumption is commonly made for the wind load analysis of homes. However, homes not systematically designed (or managed) to protect against failures of the building envelop were not "enclosed" after Hurricanes Andrew and Iniki. The alternative of assuming a partially enclosed or "open" building greatly increases the theoretical wind loading on a building and its components.

- ASCE 7-88:

  Velocity Pressure (q) = .00256 * $K_z(I*V)^2$, where
  K_z = velocity pressure exposure coefficient at height z
  I = importance factor
  V = wind speed (mph, fastest-mile)
  for buildings less than 60 feet the **Design Wind Load (p)** = $qG_hC_p - q_h(GC_{pi})$
  for MWFRS and **Design Wind Load (p)** = $Q[(GC_p)-(GC_{pi})]$
  for components and cladding where,

  q, q_h = velocity pressure at height z (psi)
  C_p = external pressure coefficient
  G_h = gust response factor
  GC_p & GC_{pi} = product of exterior or internal pressure coefficient and gust response factor

Appendix D
SUMMARY OF DAMAGE ASSESSMENT DATA

Commentary for Tables D-1 through D-8

The data in the following tables summarize the detailed information recorded for each of the homes surveyed in this study. The tabulated data is specific to wind damage only. Many of the descriptive statistics presented in the report are derived directly from this information. A detailed tabulation of the data for each home, as recorded on the individual damage survey forms, is available through the U.S. Department of Housing and Urban Development.

Tables D-1 and D-2 summarize the house characteristics and damages, respectively, found in the main Florida damage survey which used a random selection process. Tables D-3 and D-4 summarize the information found in case studies of wind damaged communities in Florida having high percentages of wood-frame wall construction (concrete block homes are included in the summary statistics). Tables D-5 and D-6 also summarize the case study data, but only for those homes which contained wood-frame construction on one or more stories. Tables D-7 and D-8 summarize the house characteristics and damages, respectively, for the Kauai damage survey. The nature of damage in the rural areas of Louisiana, were not conducive to data acquisition, tabulation, and analysis.

In some cases, tabulated percentages may be presented as a percentage of only those homes (or components) which received a rating by the assessor ("not specified" entries are ignored). This manipulation is necessary and accurate when the "not specified" (NS) entries are a result of the tabulation procedure. For example, in Table D-2 there are 374 NS entries for second-story wall damage, which is a result of the large number of single-story homes in the sample. Some NS entries are the result of the particular house component being inaccessible. This was common for unoccupied homes, which had tarpaulins covering the roof or were posted against trespassing. If the number of NS entries is not large compared to the total sample size, the percentages may be reported in terms of "accessible" homes. Ignoring the NS entries and recalculating the percentages based only on those homes with responsive entries should be used with extreme caution as the resulting percentages could easily be misleading.

Table D-1
FLORIDA SURVEY SUMMARY OF CHARACTERISTICS

STORIES			**EXPOSURE**			**ROOF TYPE**		
One	373	80%	Open, Inland	28	6%	Gable	376	81%
One-and-a-Half	10	2%	Suburban	437	94%	Shed	2	0%
Two	82	18%	On Water	1	0%	Hip	62	13%
Three	1	0%	Open Coastal	0	0%	Flat	5	1%
						Gable-on-Hip	21	5%
ROOF PITCH			**ROOF FRAMING**			**ROOF SHEATHING**		
Low	148	32%	Wood Rafter	58	12%	Plywood	331	71%
Medium	292	63%	Wood Truss	344	74%	Board	20	4%
High	5	1%	Steel Truss	1	0%	OSB	21	5%
Not Specified	21	5%	Not Specified	63	14%	Not Specified	94	20%
ROOFING			**EXTERIOR WALL SIDING**			**2ND STORY WALL SHEATHING**		
Composition	289	62%	Woodlap	12	3%	Plywood	5	1%
Wood Shingle	1	0%	Plywood	2	0%	OSB	3	1%
Flat Clay	60	13%	Brick	9	2%	Not Specified	458	98%
Barrel Clay	13	3%	Stucco	439	94%			
Built-Up	32	7%	Stone Veneer	1	0%			
Not Specified	71	15%	Not Specified	3	1%			
1ST STORY WALL FRAMING			**2ND STORY WALL FRAMING**			**INTERIOR WALL MATERIALS**		
CMU	464	100%	CMU	74	16%	Wood Stud	124	27%
Wood	2	0%	Wood	19	4%	Steel Stud	115	25%
			Not Specified	373	80%	CMU	1	0%
						Not Specified	226	48%
INTERIOR FINISH MATERIALS			**2ND STORY FLOOR FRAMING**			**FOUNDATION TYPE**		
Gypsum	270	58%	Wood Joist	3	1%	Slab-on-Grade	466	100%
Plaster	50	11%	Engineered Joist	67	14%			
Not Specified	146	31%	Concrete	1	0%			
			Not Specified	395	85%			

Table D-2
FLORIDA SURVEY SUMMARY OF DAMAGE RATINGS

	DAMAGE LEVELS							
	One-Third or Less		One-Third to Two-Thirds		Two-Thirds or More		Not Specified	
OVERALL CONDITION								
Building Damage	100	21%	168	36%	141	30%	57	12%
Roof Damage	114	24%	165	35%	106	23%	81	17%
Wall Damage	446	96%	5	1%	2	0%	13	3%
Foundation Damage	454	97%	0	0%	1	0%	11	2%
Projectile Damage	325	70%	78	17%	37	8%	26	6%
Porch/Balcony Damage	332	71%	58	12%	36	8%	40	9%
Water Damage	45	10%	63	14%	201	43%	157	34%
ROOF CONDITION								
Roofing	84	18%	106	23%	170	36%	106	23%
Sheathing	267	57%	56	12%	28	6%	115	25%
Rafters/Trusses	344	74%	23	5%	14	3%	85	18%
Soffit/Facia	306	66%	90	19%	40	9%	30	6%
Roof-Wall Connection	398	85%	28	6%	10	2%	30	6%
Gable End	296	64%	48	10%	34	7%	88	19%
EXTERIOR WALL CONDITION								
1st Story	455	98%	4	1%	2	0%	5	1%
2nd Story	92	20%	0	0%	0	0%	374	80%
3rd Story	3	1%	0	0%	0	0%	463	99%
Veneer/Siding	324	70%	5	1%	0	0%	137	29%
Sheathing	51	11%	0	0%	0	0%	415	89%
Wall-Floor Connection	415	89%	0	0%	0	0%	51	11%
FENESTRATION								
Windows	156	33%	123	26%	158	34%	29	6%
Doors	332	71%	78	17%	25	5%	31	7%
INTERIOR WALL/CEILING CONDITION								
1st Floor	79	17%	64	14%	169	36%	154	33%
2nd Floor	6	1%	3	1%	57	12%	400	86%
3rd Floor	0	0%	0	0%	2	0%	464	100%
FLOOR CONDITION								
Framing	58	12%	0	0%	0	0%	408	88%
Sheathing	29	6%	0	0%	0	0%	437	94%

Table D-3
SUMMARY OF CHARACTERISTICS FOR ALL FLORIDA CASE STUDY HOMES

STORIES			**EXPOSURE**			**ROOF TYPE**		
One	43	78%	Open, Inland	2	4%	Gable	45	82%
One-and-a-Half	3	5%	Suburban	53	96%	Hip	3	5%
Two	9	16%				Gable-on-Hip	7	13%
Total	**55**							
ROOF PITCH			**ROOF FRAMING**			**ROOF SHEATHING**		
Low	7	13%	Wood Rafter	9	16%	Plywood	40	73%
Medium	42	76%	Wood Truss	41	75%	OSB	10	18%
High	6	11%	Not Specified	5	9%	Not Specified	5	9%
ROOFING			**EXTERIOR WALL SIDING**			**1ST STORY WALL SHEATHING**		
Composition	54	98%	Wood/Hardboard	21	38%	Plywood	13	24%
Not Specified	1	2%	Brick	1	2%	Not Specified	42	76%
			Stucco	21	38%			
			Hardwood	8	15%			
			Not Specified	4	7%			
1ST STORY WALL FRAMING			**2ND STORY WALL FRAMING**			**INTERIOR WALL MATERIALS**		
CMU	27	49%	Wood	9	16%	Wood Stud	13	24%
Wood	26	47%	Not Specified	46	84%	Steel Stud	8	15%
Not Specified	2	4%				Not Specified	34	62%
INTERIOR FINISH MATERIALS			**2ND STORY FLOOR FRAMING**			**FOUNDATION TYPE**		
Gypsum	32	58%	Wood Joist	5	9%	Slab-on-Grade	55	100%
Not Specified	23	42%	Not Specified	50	91%			
ROOF-WALL CONNECTION			**WALL-FLOOR CONNECTION**			**FOUNDATION CONNECTION**		
Toe Nails only	1	2%	Nail/Strap	1	2%	Nail only	4	7%
Toe Nails and Straps	16	29%	Not Specified	54	98%	Not Specified	51	93%
Straps only	4	7%						
Not Specified	34	62%						

Table D-4
SUMMARY OF DAMAGE RATINGS FOR ALL FLORIDA CASE STUDY HOMES

	DAMAGE LEVELS							
	One-Third or Less		One-Third to Two-Thirds		Two-Thirds or More		Not Specified	
OVERALL CONDITION								
Building Damage	19	35%	19	35%	16	29%	1	2%
Roof Damage	26	47%	16	29%	12	22%	1	2%
Wall Damage	47	85%	7	13%	1	2%	0	0%
Foundation Damage	55	100%	0	0%	0	0%	0	0%
Projectile Damage	42	76%	10	18%	1	2%	2	4%
Porch/Balcony Damage	33	60%	2	4%	7	13%	13	24%
Water Damage	11	20%	8	15%	28	51%	8	15%
ROOF CONDITION								
Roofing	20	36%	15	27%	18	33%	2	4%
Sheathing	29	13%	13	24%	10	18%	3	5%
Rafters/Trusses	38	69%	10	18%	3	5%	4	7%
Soffit/Facia	37	67%	10	18%	4	7%	4	7%
Roof-Wall Connection	41	75%	4	7%	2	4%	8	15%
Gable End	34	62%	8	15%	8	15%	5	9%
EXTERIOR WALL CONDITION								
1st Story	48	87%	4	7%	0	0%	3	5%
2nd Story	4	7%	1	2%	2	4%	48	87%
Veneer/Siding	45	82%	4	7%	0	0%	6	11%
Sheathing	38	69%	3	5%	0	0%	14	25%
Wall-Floor Connection	44	80%	1	2%	0	0%	10	18%
FENESTRATION								
Windows	28	51%	16	29%	4	7%	7	13%
Doors	37	67%	7	13%	3	5%	8	15%
INTERIOR WALL/CEILING CONDITION								
1st Floor	4	7%	9	16%	21	38%	21	38%
2nd Floor	0	0%	1	2%	6	11%	48	87%
FLOOR CONDITION								
Framing	7	13%	0	0%	0	0%	48	87%
Sheathing	4	7%	2	4%	0	0%	49	89%

Table D-5
SUMMARY OF CHARACTERISTICS FOR WOOD-FRAME FLORIDA CASE STUDY HOMES*

STORIES			**EXPOSURE**			**ROOF TYPE**		
One	24	71%	Suburban	34	100%	Gable	28	82%
One-and-a-Half	1	3%				Hip	3	9%
Two	9	26%				Gable-on-Hip	3	9%
Total	**34**							
ROOF PITCH			**ROOF FRAMING**			**ROOF SHEATHING**		
Low	0	0%	Wood Rafter	8	24%	Plywood	30	88%
Medium	28	82%	Wood Truss	25	74%	OSB	3	9%
High	6	18%	Not Specified	1	3%	Not Specified	1	3%
ROOFING			**EXTERIOR WALL SIDING**			**1ST STORY WALL SHEATHING**		
Composition	34	100%	Wood/Hardboard	27	79%	Plywood	13	38%
			Brick	1	3%	Not Specified	21	62%
			Stucco	6	18%			
1ST STORY WALL FRAMING			**2ND STORY WALL FRAMING**			**INTERIOR WALL MATERIALS**		
CMU	8	24%	Wood	9	26%	Wood Stud	8	24%
Wood	26	76%	Not Specified	25	74%	Steel Stud	6	18%
						Not Specified	20	59%
INTERIOR FINISH MATERIALS			**2ND STORY FLOOR FRAMING**			**FOUNDATION TYPE**		
Gypsum	20	59%	Wood Joist	5	15%	Slab-on-Grade	34	100%
Not Specified	14	41%	Not Specified	29	85%			
ROOF-WALL CONNECTION			**WALL-FLOOR CONNECTION**			**FOUNDATION CONNECTION**		
Toe Nails only	1	3%	Nail/Strap	1	3%	Nail only	4	12%
Toe Nails and Straps	11	32%	Not Specified	33	97%	Not Specified	30	88%
Straps only	3	9%						
Not Specified	19	56%						

*Includes CBS construction only when two-story and the second story is wood frame.

Table D-6
SUMMARY OF DAMAGE RATINGS FOR WOOD-FRAME FLORIDA CASE STUDY HOMES*

	DAMAGE LEVELS							
	One-Third or Less		One-Third to Two-Thirds		Two-Thirds or More		Not Specified	
OVERALL CONDITION								
Building Damage	12	35%	13	38%	9	26%	0	0%
Roof Damage	17	50%	11	32%	6	18%	0	0%
Wall Damage	28	82%	6	18%	0	0%	0	0%
Foundation Damage	34	100%	0	0%	0	0%	0	0%
Projectile Damage	29	85%	5	15%	0	0%	0	0%
Porch/Balcony Damage	22	73%	2	7%	6	20%	4	12%
Water Damage	6	19%	4	13%	22	69%	2	6%
ROOF CONDITION								
Roofing	14	41%	7	21%	13	38%	0	0%
Sheathing	19	56%	9	26%	6	18%	0	0%
Rafters/Trusses	26	76%	5	15%	2	6%	1	3%
Soffit/Facia	24	71%	6	18%	3	9%	1	3%
Roof-Wall Connection	29	85%	2	6%	2	6%	1	3%
Gable End	23	68%	7	21%	3	9%	1	3%
EXTERIOR WALL CONDITION								
1st Story	30	88%	3	9%	0	0%	1	3%
2nd Story	57%	12%	1	14%	2	29%	27	79%
Veneer/Siding	31	91%	2	6%	0	0%	1	3%
Sheathing	29	85%	2	6%	0	0%	3	9%
Wall-Floor Connection	31	91%	1	3%	0	0%	2	6%
FENESTRATION								
Windows	22	65%	8	24%	3	9%	1	3%
Doors	27	79%	5	15%	1	3%	1	3%
INTERIOR WALL/CEILING CONDITION								
1st Floor	3	9%	5	15%	15	44%	11	32%
2nd Floor	0	0%	1	3%	6	18%	27	79%
FLOOR CONDITION								
Framing	7	21%	0	0%	0	0%	27	79%
Sheathing	4	12%	2	6%	0	0%	28	82%

*Includes CBS construction only when 2-story and the second story is wood frame.

Table D-7
KAUAI SURVEY SUMMARY OF HOME CHARACTERISTICS

STORIES			**EXPOSURE**			**ROOF TYPE**		
One	129	80%	Open, Inland	10	6%	Gable	78	48%
One-and-a-Half	2	1%	Suburban	139	86%	Shed	5	3%
Two	29	18%	On Water	6	4%	Hip	60	37%
Three	1	1%	Open, Coastal	1	1%	Gable-on-Hip	14	9%
			Not Specified	5	3%	Other	3	2%
Total	**161**					Not Specified	1	1%
ROOF PITCH			**ROOF FRAMING**			**ROOF SHEATHING**		
Low	19	12%	Wood Rafter	44	27%	Plywood	92	57%
Medium	125	78%	Wood Truss	102	63%	Board	9	6%
High	4	2%	Other	7	4%	Other	2	1%
Not Specified	13	8%	Not Specified	8	5%	Metal	50	31%
						Not Specified	8	5%
ROOFING			**EXTERIOR WALL SIDING**			**EXTERIOR WALL SHEATHING**		
Composition	63	39%	Wood Lap	18	11%	Plywood	67	42%
Metal	52	32%	Plywood	65	40%	Board	62	39%
Wood Shingle	22	14%	Stucco	7	4%	OSB	1	1%
Flat Clay	4	2%	Vinyl/Aluminum	18	11%	Other	7	3%
Barrel Clay	6	4%	Board	35	22%	Not Specified	24	15%
Gravel	11	7%	Other	16	10%			
Not Specified	2	1%	Not Specified	2	1%			
1ST STORY WALL FRAMING			**INTERIOR WALL MATERIAL**			**INTERIOR FINISH MATERIALS**		
CMU	8	5%	Wood Stud	104	65%	Gypsum	56	35%
Single Wall	68	42%	Steel Stud	2	1%	Other	4	2%
Conventional Wood	78	48%	Not Specified	55	34%	Not Specified	101	63%
Other	3	2%						
Not Specified	5	3%						
1ST STORY FLOOR FRAMING			**2ND STORY FLOOR FRAMING**			**FOUNDATION TYPE**		
Wood Joist	88	55%	Wood Joist	26	16%	Slab-on-Grade	57	35%
Engineered Joist	3	2%	Engineered Joist	1	1%	CMU Pier	31	19%
Not Specified	70	43%	Not Specified	134	83%	CMU Perimeter	11	7%
						Wood Pile	4	2%
						Wood Post & Pier	55	34%
						Not Specified	3	2%
ROOF-WALL CONNECTION			**WALL-FLOOR CONNECTION**			**FOUNDATION CONNECTION**		
Toe Nails only	19	12%	Nail only	11	7%	Bolt	4	2%
Toe Nails and Straps	11	7%	Nail and Strap	2	1%	Nail only	7	4%
Other	2	1%	Bolt	2	1%	Other	4	2%
Not Specified	129	80%	Not Specified	146	91%	Not Specified	146	91%

Table D-8
KAUAI SURVEY SUMMARY OF DAMAGE RATINGS

	DAMAGE LEVELS							
	One-Third or Less		One-Third to Two-Thirds		Two-Thirds or More		Not Specified	
OVERALL CONDITION								
Building Damage	111	69%	27	17%	23	14%	0	0%
Roof Damage	106	66%	28	17%	27	17%	0	0%
Wall Damage	142	88%	9	6%	9	6%	1	1%
Foundation Damage	156	97%	1	1%	4	2%	0	0%
Projectile Damage	122	76%	28	17%	11	7%	0	0%
Porch/Balcony Damage	105	65%	18	11%	27	17%	11	7%
Water Damage	60	37%	31	19%	56	35%	14	9%
ROOF CONDITION								
Roofing	58	36%	50	31%	52	32%	1	1%
Sheathing	87	54%	26	16%	27	17%	21	13%
Rafters/Trusses	127	79%	12	7%	18	11%	4	2%
Soffit/Facia	121	75%	17	11%	17	11%	6	4%
Roof-Wall Connection	29	18%	1	1%	6	4%	125	78%
Gable End	57	35%	2	1%	6	4%	96	60%
EXTERIOR WALL CONDITION								
1st Story	148	92%	1	1%	9	6%	3	2%
2nd Story	22	14%	1	1%	4	2%	134	83%
3rd Story	1	1%	0	0%	0	0%	160	99%
Veneer/Siding	138	86%	7	4%	8	5%	8	5%
Sheathing	65	40%	3	2%	5	3%	88	55%
Wall-Floor Connection	17	11%	0	0%	3	2%	141	88%
FENESTRATION								
Windows	117	73%	25	16%	16	10%	3	2%
Doors	137	85%	7	4%	6	4%	11	7%
INTERIOR WALL/CEILING CONDITION								
1st Floor	46	29%	23	14%	28	17%	64	40%
2nd Floor	6	4%	2	1%	5	3%	148	92%
3rd Floor	0	0%	0	0%	1	1%	160	99%
FLOOR CONDITION								
Framing	70	43%	0	0%	4	2%	87	54%
Sheathing	43	27%	0	0%	4	2%	114	71%

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