BUILDING PERFORMANCE: HURRICANE INIKI IN HAWAII

OBSERVATIONS, RECOMMENDATIONS, AND TECHNICAL GUIDANCE

Learning from failure...

...building on success

Teaming To Reduce Future Damages

FEDERAL EMERGENCY MANAGEMENT AGENCY
FEDERAL INSURANCE ADMINISTRATION

IN COOPERATION WITH
THE STATE OF HAWAII OFFICE OF CIVIL DEFENSE
AND KAUAI COUNTY

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Executive Summary

On September 22, 1992, at the request of the Mayor of Kauai County, the Federal Coordinating Officer for the Iniki disaster tasked the Federal Emergency Management Agency's (FEMA's) Federal Insurance Administration (FIA) to assemble a team of experts to assess the performance of buildings. Since the 1970s, FIA has gained valuable experience through an ongoing assessment program that focuses on the performance of buildings that have incurred flood damage. In addition, FIA's National Flood Insurance Program establishes regulations for the reconstruction of substantially damaged buildings in floodplains, regardless of the cause of the damage.

For the Iniki disaster, the team assembled by FIA included FEMA Headquarters and Regional staff, representatives of the State of Hawaii Office of Civil Defense and Kauai County, and Registered Professional Engineers and Architects from both Kauai and Oahu (see Appendix A for complete list). The team was tasked with surveying the performance of primarily residential structures under wind and water forces generated during Hurricane Iniki. The goal of this effort is to provide guidance and offer recommendations for reducing damage from future hurricanes. This goal is best met through learning from both failures and successes of building performance.

During the field assessment, the team investigated primary structural systems, i.e., systems in a building that resist lateral and vertical forces. For all buildings, the performance of exterior architectural systems, such as roofing, windows, and doors was analyzed. The analysis also included the effects of windborne and waterborne debris and the quality of construction and materials. The majority of building types observed were one- and two-story, wood-frame, single-family and multi-family residential structures. However, pre-engineered steel commercial and industrial buildings, as well as resort hotels and condominiums constructed of reinforced concrete and masonry, were also examined.

WIND FORCES

Noteworthy examples of adequately engineered and constructed buildings were observed in Kauai County. Almost without exception, successful performance resulted from clearly defined and continuous "load transfer paths" from the roof to the foundation. A well-designed load transfer path depends primarily on the proper type, sizing, and attachment of connections between the critical components of a building (for example, between the roof and walls and between the walls and foundation). Where connections, such as hurricane clips and metal straps on wood-frame structures, were adequately sized and correctly applied, buildings performed relatively well.

Incomplete design and construction for load transfer and improper connections, especially between the roof and walls, were found to be the most important factors causing structural failure of buildings due to uplift wind forces. Consistently, a building's structural integrity was compromised through the action of uplift forces on insufficiently designed and connected roof and wall systems. Loss of roof cladding (e.g, shingles), roof sheathing (e.g., plywood), and other building attachments provided a source of airborne projectiles which contributed to the overall damage. In many instances, loss of glazing (e.g., glass doors and windows), either from direct wind pressure or from debris impact, resulted in a breach of the building envelope, subsequent internal pressures, and progressive structural failure.

Much of the damage to structures caused by wind forces resulted from incomplete design, reliance on outdated methods of workmanship, and/or misapplication of various building materials. Many of these problems can be addressed by training and education programs that promote prudent building design and construction practices throughout Kauai County. This is especially true for buildings in bluff and oceanfront areas exposed to accelerated wind forces.

Flood Forces

In coastal floodplains and Coastal High Hazard Areas, the obvious primary cause of building failure was direct wave impact (hydrodynamic forces) on buildings whose lowest floors had been constructed directly on the ground surface. Low-lying, oceanfront buildings, situated somewhat landward of the shoreline and having lowest floors elevated above the flood hazard, fared much better than ground-level buildings immediately adjacent to the shoreline. Waterborne debris such as lava boulders and debris from damaged non-elevated buildings increased damage to adjacent buildings.

Recommendations

Recommendations presented in this report can be summarized as follows :

- Provide adequate means and methods to ensure the structural integrity of a building by constructing properly engineered buildings which consider the continuous load transfer path of a structure from roof to foundation. To ensure the integrity of the structure's load transfer path, metal fasteners ("hurricane clips") and straps must be adequately sized and properly installed.

- Design all architectural elements to resist the same wind forces as the primary structural systems.

- Construct and properly engineer buildings such that they protect, or contain adequately designed, glasswork in exposed areas; adhere to nailing and attachment requirements for roof sheathing, roof cladding, and windows and doors; and provide routine maintenance of building components, including repair and replacement of damaged elements.

- In areas subject to flooding, elevate buildings above predicted flood heights on properly designed and constructed foundations. Minimize the sources of future debris by appropriately designing and locating site improvements such as stone walls.

- Provide a program of training and continuous education to code enforcement officials, plan reviewers, inspectors, supervisors, and others who are charged with implementing the recommendations noted above. Provide companion training and education programs for homeowners, building contractors, and design professionals in the proper construction techniques for mitigation of wind and flood hazards.

- Trade associations, labor associations, etc., should provide continuing education programs for updating their members concerning revisions to Building Codes under which they are performing their trades.

This report includes detailed engineering discussions of building failure modes and successful building performance. It also provides detailed recommendations for enhancing building performance under hurricane and flood conditions.

1.0 Introduction

1.1 Purpose

The purpose of this report is to provide guidance and recommendations for reducing hurricane and flood damage in the future. This purpose is best achieved through learning from successes and failures of building performance. Therefore, this report includes observations of both successes and failures of various building types.

Numerous references to figures are made throughout the text of this report. These figures, primarily photographs, explicitly portray, clarify, or reinforce the technical issues addressed. The figures are presented at the end of each pertinent section. The reader is encouraged to examine these figures while reviewing the report.

This report includes detailed engineering discussions of building failure modes and successful building performance supplemented by graphic examples and illustrated design specifications. It also provides recommendations for enhancing building performance under hurricane conditions and addressing building materials, code compliance, plan review, and construction inspection.

1.2 Background

In the afternoon of September 11, 1992, Hurricane Iniki struck the Island of Kauai, Hawaii, generating high winds and storm surge over a vast area of the island (Figure 1). With wind speeds exceeding those of Hurricanes Iwa (1982) and Dot (1959), Iniki was the strongest and most destructive hurricane to strike the Hawaiian Islands in recent memory.

Although measurements of the storm's wind speeds are subject to continuing analysis, it was evident from the extensive damage observed that wind speeds were

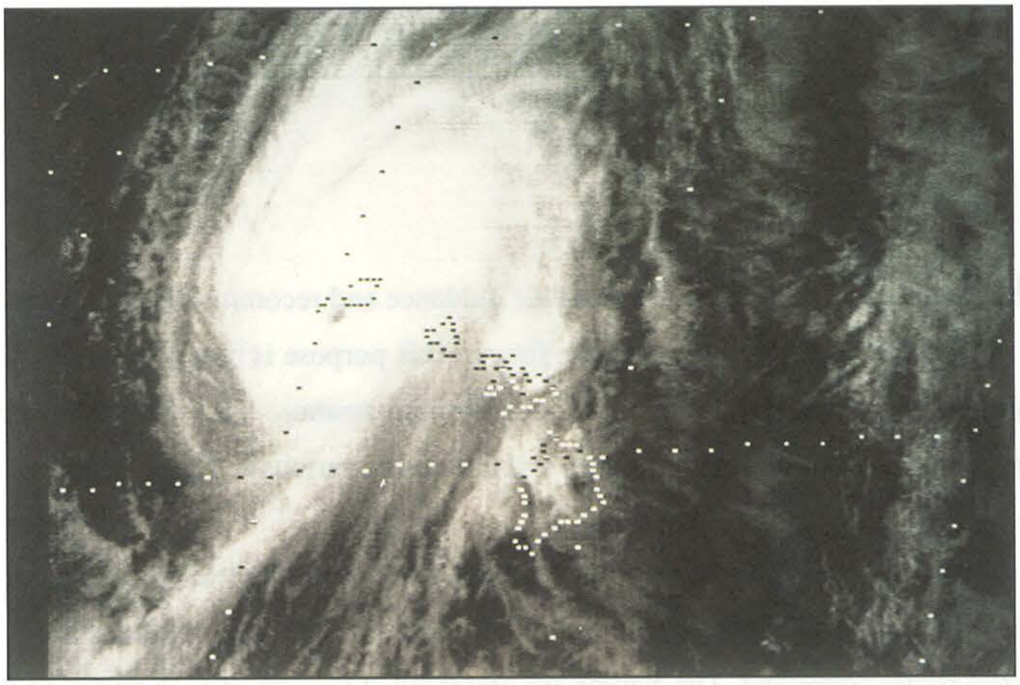


FIGURE 1. *The eye of Hurricane Iniki crossed the Kauai coast just west of Port Allen near Kaumakani just before 4:00p.m. Hawaiian Standard Time on September 11, 1992.*

significant. Preliminary measurements of coastal flooding and deposition of heavy debris considerable distances inland are evidence of the significant storm surge and wave forces associated with the hurricane.

1.3 THE BUILDING PERFORMANCE ASSESSMENT TEAM

On September 22, 1992, following a request from the Mayor of Kauai County, the Federal Coordinating Officer for the Iniki disaster tasked the Federal Insurance Administration (FIA) to assemble a team of experts to assess the performance of buildings. Since the 1970s, FIA has gained valuable experience through an ongoing assessment program that focuses on the performance of buildings that have incurred flood and wind damage. These assessments evaluate and support FIA's administration of the National Flood Insurance Program (NFIP), which includes enforcement of requirements governing the reconstruction of substantially damaged buildings in floodplains, regardless of the cause of the damage.

1.3.1 Team Composition

The team included field-experienced professionals trained in building design and construction and a cadre of technical and policy advisors. Team members that participated in the field surveys were Federal Emergency Management Agency (FEMA) Headquarters and Region IX staff, representatives of the State of Hawaii Civil Defense System and the Kauai County Engineering and Planning Departments, and Registered Professional Engineers and Architects from both Kauai and Oahu (see Appendix A for complete list).

1.3.2 Purpose of the Team

The purpose of the team was to evaluate the effectiveness of past design and construction practices in Kauai County by surveying damage (or lack of damage) caused by Hurricane Iniki. From field assessments of building systems subjected to significant wind and/or water forces, the team sought to diagnose characteristic modes of building system failure and to identify the systems that were successful in resisting those forces. Through this preliminary report and associated training activities, the team also will offer recommendations and guidance on ways to reduce similar damage in the future.

The basis for forming the team, compiling this report, and pursuing further study is the assumption that improved performance of buildings can be attained when:

- observed failure modes can be mitigated using basic and widely recognized practices and standards for new and repair construction;

- observed building successes can be used as evidence to reinforce the use of these practices and standards; and

- Federal, State, and County governments and the private sector work in close cooperation to ensure that repair work and new construction practices will mitigate against future hazards while remaining cost-effective and practical.

1.3.3 Team Activities

During the field assessment, the team investigated primary structural systems, i.e., systems that support a building under lateral and vertical loading conditions. The majority of building types observed were one- and two-story wood-frame structures — single-family residential, multi-family residential, and commercial. However, the team attempted to be comprehensive by assessing a wide range of construction types (including metal-frame pre-engineered commercial and industrial structures and resort hotels and condominiums constructed of reinforced concrete and masonry). These structures were observed in locations experiencing a wide range of wind and flood exposure conditions.

Collectively, the team invested a significant number of man-hours in the site surveys, documentation, assessment of damages, formulation of recommendations, and report production. Documentation of findings made during ground-level and aerial surveys included field notes, photographs, and videotaping.

1.3.4 The "Team" Concept

Participation by State and County governmental officials and locally based consulting Engineers and Architects in the assessment process is critical because it 1) ensures that all State and local Building Code and other requirements are properly interpreted, 2) enhances the likelihood that local construction practices are fully appreciated and understood, 3) helps establish positive relationships between Federal, State, and local governments and the private sector, and 4) encourages recommendations that are realistic, from both economic and technical standpoints.

Under the "team" concept, local government and its citizens become active participants in a positive and forward-looking technical appraisal and planning process which attempts to improve the future performance of buildings. In this way, team recommendations have a much better likelihood of being considered, adopted, and implemented.

1.4 HURRICANE INIKI — STORM CONDITIONS

Hurricane Iniki was a small but intense hurricane as it moved northward across the Island of Kauai during the late afternoon hours of September 11, 1992. The eye of Iniki crossed the Kauai coast just west of Port Allen near Kaumakani just before 4:00 p.m. Hawaiian Standard Time (HST). Iniki left behind a path of destruction, with property damage expected to approach 1.8 billion dollars. On Kauai alone, Iniki destroyed or damaged 14,350 homes. Of that total, 1,421 were destroyed and another 5,152 suffered major damage. Damage on Kauai was widespread, with the most severe damage occurring on the south, east, and north ends of the island. Even with such widespread and severe damage, only three deaths were attributed directly to the storm. The low loss of life can be attributed to ample warning time, an excellent response by the State of Hawaii Office Civil Defense System, the evacuation of all coastal areas, and the high level of awareness created by previous press coverage of Hurricane Andrew in Florida and Typhoon Omar in Guam.

As expected from a hurricane of Iniki's intensity, coastal flooding was significant along the southern shoreline from Kekaha to Poipu Beach. Coastal flood heights were measured along the southern shoreline by the U.S. Army Corps of Engineers (COE), Pacific Ocean Division, under contract to FEMA. Although measurements are preliminary and require verification, they indicate stillwater flood elevations ranging from 10.5 to 12.5 feet above mean lower low water (mllw) at Kekaha to 12.5 to over 20 feet above mllw along Poipu Beach. An independent assessment conducted by the Department of Geology and Geophysics, University of Hawaii, confirms the magnitude and extent of the surge heights and penetration.

A determination of actual wind speeds during Hurricane Iniki proved to be highly variable. This may be due to varying degrees of exposure as a result of ground surface irregularities, the distance between anemometer (a gauge for recording wind velocity) sites, and the potential inaccuracy of anemometers at excessively high winds. Wind speeds were recorded at the Pacific Missile Range Facility at Barking Sands, Lihue Airport, and one other station on the island. The strongest winds were reported from Port Allen eastward, with Makahuena Point reporting east winds at 70 knots (81 mph), with gusts to 105 knots (121 mph) when the power failed. The peak gust at Makahuena Point, which was extracted from the data recorder after the fact, reached 124 knots (143 mph). At Lihue Airport, the strongest sustained wind was southeast at 84 knots (97 mph) at 3:52 p.m. HST and southwest at 78 knots (90 mph) at 5:10 p.m. HST. These wind speeds, however, do not account for higher wind speeds that may have existed along highly exposed ocean promontories such as Makahuena Point or ocean-fronting high bluffs such as at Princeville. Wind speeds can also be amplified above these actual recorded base conditions by channeling through mountain gorges or as a result of the effects of other landforms with extreme topography.

On October 8, 1992, members of the team met with various experts involved in the assessment of the winds generated by Iniki. The team learned that the sustained wind speeds at low altitude were recorded in excess of the 80-mph basic code design (FIGURE 2). However, it is important to understand that the basic wind speed of Hurricane Iniki was not beyond that which a building can be designed for with reasonable likelihood of successful performance.

FIGURE 2. *Hurricane Iniki produced substantial wind speeds at low altitudes in excess of the 80-mph base condition.*

1.5 National Flood Insurance Program Requirements

Currently, Kauai County is participating in the regular phase of the NFIP. County participation in the NFIP makes federally backed and reasonably priced flood insurance available to residents. As a condition of flood insurance availability, the county agreed to and has adopted regulations that meet or exceed NFIP minimum standards. The NFIP standards call for enforcement of prudent construction practices in flood hazard areas. These practices pertain to the construction of new and substantially improved buildings and to the repair of substantially damaged buildings in flood hazard areas as designated on the Flood Insurance Rate Map (FIRM). The cornerstone of the NFIP requirements is that the lowest floors of buildings must be elevated to or above flood heights shown on the FIRM.

The flood hazard designated on the FIRM for southern Kauai is based on a hybrid system of the 100-year tsunami and wave runup recorded from Hurricane Iwa (1982). The 100-year tsunami is the basis for the rest of the State except for Southern Oahu.

Along some oceanfront property such as Poipu Beach (FIGURE 3) and Hanalei (FIGURE 4), Coastal High Hazard Areas have been mapped. These areas are designated as V zones (velocity zones) on the FIRM. A V zone is an area subject to 100-year coastal flooding with waves 3 feet or greater in height. Consequently, additional design considerations are necessary for construction in V zones. Such considerations include use of pile and column foundations, leaving the area under the elevated building open to allow for free passage of velocity flood waters, and ensuring that foundation embedment is sufficient to withstand erosion and localized scour.

Buildings in flood hazard areas that are determined to have been "substantially damaged" during Iniki, for whatever reason (e.g., wind or flood), must be repaired or reconstructed to NFIP standards for new construction. A building is substantially damaged when the cost to fully repair the building equals or exceeds 50 percent of its pre-damaged market value.

1.6 BUILDING CODE REQUIREMENTS FOR WIND HAZARDS

Kauai County was, at the time of the hurricane, using the 1985 version of the Uniform Building Code (UBC). The UBC, in Chapter 23, "General Design Requirements," requires that buildings be "designed and constructed to resist the wind effects determined in accordance with the requirements of this section," this section being Section 2311, which deals with wind design. However, an exception is granted earlier in the Code, in Section 2303, "Design Methods," which states "Unless otherwise required by the building official, buildings or portions thereof which are constructed in accordance with the conventional framing requirements specified in Chapter 25 of this code shall be deemed to meet the requirements of this section." Chapter 25 of the 1985

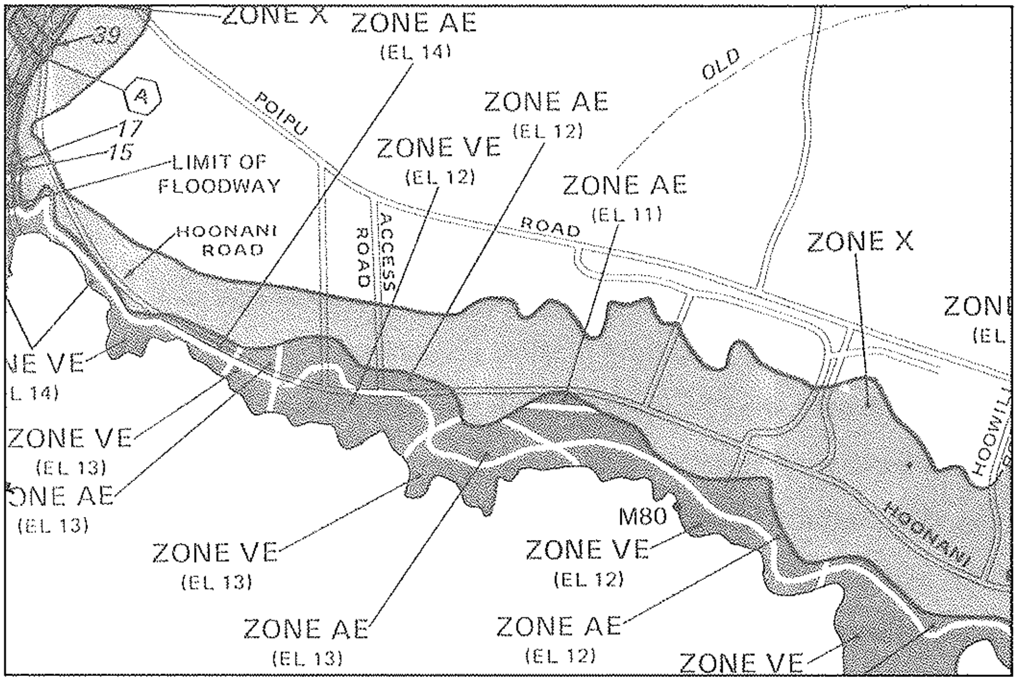


FIGURE 3. *Portion of Flood Insurance Rate Map (FIRM) for Kauai County covering the Poipu Beach area. Note predicted 100-year flood heights of 12 to 14 feet above mean sea level.*

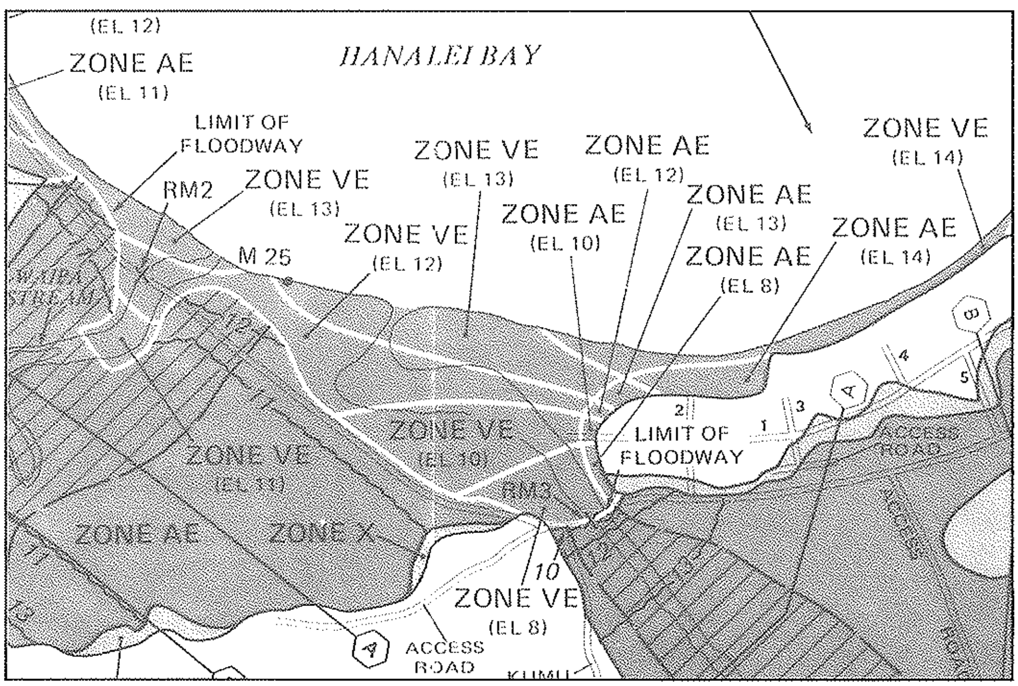


FIGURE 4. *Various flood hazard zones, including velocity (V) Coastal High Hazard zones, on the Kauai County FIRM (Hanalei example).*

UBC contains provisions which implicitly address the quality and design of wood members and their fastenings.

On December 7, 1992, Kauai County adopted Appendix Section 2518 of Chapter 25 of the 1991 UBC, which specifically addresses design and construction of light-frame timber buildings in high-wind areas. Appendix Section 2518 applies to regular-shaped buildings which have roof structural members spanning 32 feet or less, are not more than three stories in height, are of conventional light-frame construction, and are located in areas with a basic wind speed from 80 through 110 miles per hour. This appendix addresses shortcomings in design and construction practices due to reliance on implicit provisions in the 1985 UBC. Appendix Section 2518 of the 1991 UBC is very explicit in its requirements and contains graphical presentations not contained in older versions of the Code. Compliance with Appendix Section 2518 will help reduce wind-related damages in the future, and the County is to be commended for this prudent action.

2.0 Observations Of Flood Damage And Coastal Floodplain Construction

The team surveyed two areas on the island that experienced coastal flooding: Kekaha and Poipu Beach.

2.1 Kekaha

A general examination of flood damage was performed in the Town of Kekaha. The majority of flood damages sustained were to older, single-family, wood-frame structures, probably constructed during the 1920s to 1940s. While flood damages in Kekaha were minor compared to those in Poipu, and only a limited number of homes actually incurred flooding, two important observations were made.

1. Damage to all but a few buildings was relatively minor, i.e., simple inundation with limited or no structural damage. The reduced flood damage resulted from the following:

   —Buildings were located a considerable distance (100-150 feet) from the shoreline. This buffer area allowed for dissipation of wave energy, which greatly reduced exposure of buildings to hydrodynamic forces.

   —Coastal flooding at Kekaha was less severe than flood heights at Poipu Beach. The COE preliminary estimates of flooding, based on surveyed sediment lines inside buildings (stillwater elevations) and debris lines on the ground, ranged from 10.5 to 12.5 feet mllw in the Kekaha area.

   —The lowest floors of some buildings were elevated above the ground surface. While the elevation was only 2 to 3 feet above grade on a crawlspace foundation, it was sufficient in this area to prevent water from entering several homes (Figure 5).

FIGURE 5. *Flood damage to this coastal house in Kekaha was minimized because the house is elevated 2 to 3 feet off the ground and is located a considerable distance from the shoreline.*

2. The vast majority, if not all, of the flood damage might have been prevented if the buildings had been elevated to or above the flood heights shown on the County's FIRM. Since these buildings are quite old, it is to be expected that they would not have been elevated above anticipated flood levels. Interestingly, as mentioned above, the lowest floors of some of the buildings had coincidently been elevated some 2 to 3 feet above the ground surface when the buildings were constructed. These buildings appeared to have suffered little to no damage from flood waters.

Clearly, the flood damage sustained, and the flood damage prevented, in Kekaha reinforce the importance of properly elevating new and substantially improved construction above predicted flood levels in this and other flood hazard areas.

2.2 POIPU BEACH

A detailed damage survey was conducted in the section of Poipu Beach between Spouting Horn Park and Poipu Beach Park. The primary focus of this survey was single-family residential structures. Due to security and public safety issues, some damaged hotels and condominiums were not evaluated in great depth. However, with the permission of on-site security personnel, safe access was gained to other hotels and condominiums. From the resulting site analyses, observations and basic recommendations were made that are universally applicable to resort-type, multi-unit facilities.

As in Kekaha, the COE surveyed stillwater elevations and debris lines throughout the Poipu Beach area. Preliminary results indicated highly variable, but severe, coastal flooding, ranging from approximately 13.5 to over 20 feet mllw. When combined with breaking waves of significant height, the coastal flooding generated by Hurricane Iniki along Poipu Beach was a very serious hazard. Areas such as Poipu Beach that have been identified by FEMA as Coastal High Hazard Areas require prudent design considerations, including both siting of buildings on lots and specific design and construction guidelines.

Coastal flooding in the section from Spouting Horn Park to Poipu Beach Park was severe and widespread, resulting in substantial damage to an estimated 60 or more single-family, detached residences (FIGURE 6). Several condominiums and hotels fronting the ocean also sustained significant flood damage to their lowest (ground level) units. Table 1 provides a preliminary inventory of damaged buildings for particular segments. The damage was caused by direct wave impact on buildings that were constructed without adequate consideration of the potential flood hazard. Additional damage was caused by debris impact. This debris included lava rocks, trees, detached pieces of buildings, and in some cases entire buildings that rammed adjacent structures (FIGURE 7).

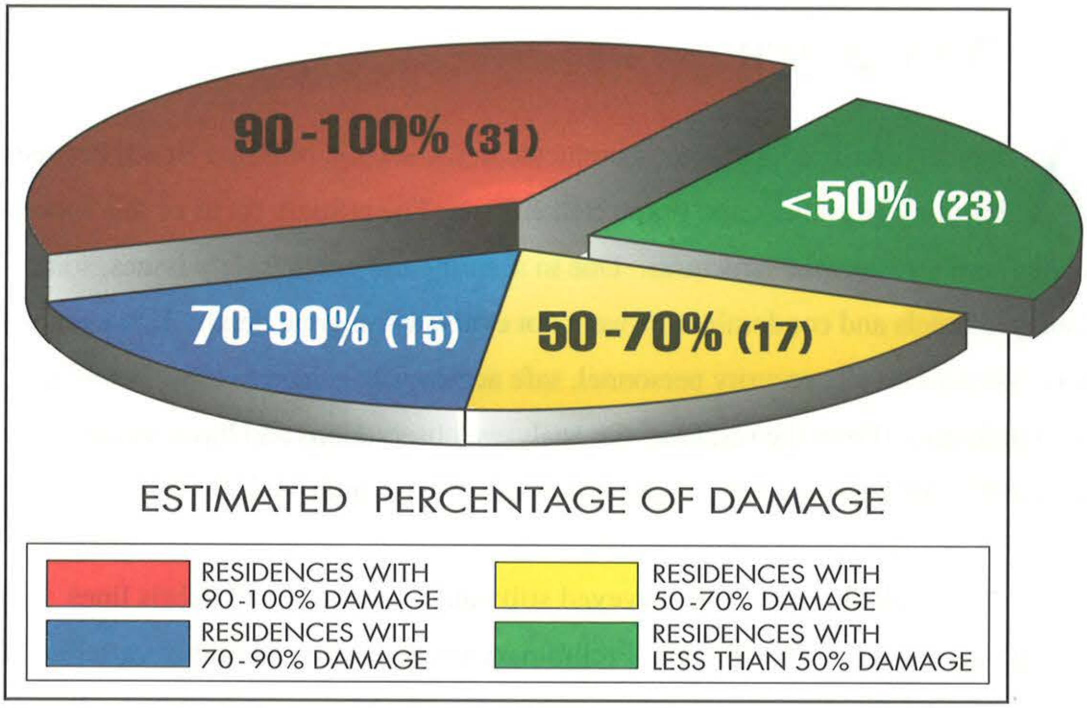


FIGURE 6. *Results of preliminary field inventory of damaged residential buildings — Poipu Beach Park to Spouting Horn Park. Numbers in parentheses are building counts.*

TABLE 1

RESIDENTIAL BUILDINGS SUBSTANTIALLY DAMAGED* BY FLOODING AT POIPU BEACH

Spouting Horn Park to Lawai-Amio Intersection	8
Lawai-Amio Intersection to the Kuhio Shores	17
Hoona Road Poipu Beach	18
Poipu Beach to Pee Road	20
Total	63

* Damage estimates are approximations based on field observations. Precise damage valuations will require detailed estimates and appraisals.

NOTE: Use of commercial names as notable landmarks is for locational purposes only.

FIGURE 7. *Waterborne debris resulted in significant damage to non-elevated buildings along Poipu Beach.*

Flood damage at Poipu Beach was the result of one primary and three secondary factors:

1. Lack of Elevation. Almost without exception, the lowest floors of buildings were constructed directly on the ground (FIGURE 8). Because the lowest horizontal structural members of buildings were not elevated to or above predicted flood heights, all (or large sections) of the buildings' walls were directly impacted by significant hydrodynamic and debris impact forces.

Three types of failure modes were observed:

- Where buildings rested on piers with very shallow poured footings and precast concrete foundations ("tofu" blocks) with insufficient or no (i.e., gravity) connections between support posts and foundation, they were literally floated off their foundations by buoyant forces as the waters rose (FIGURE 9). In some instances, these "floaters" were carried considerable

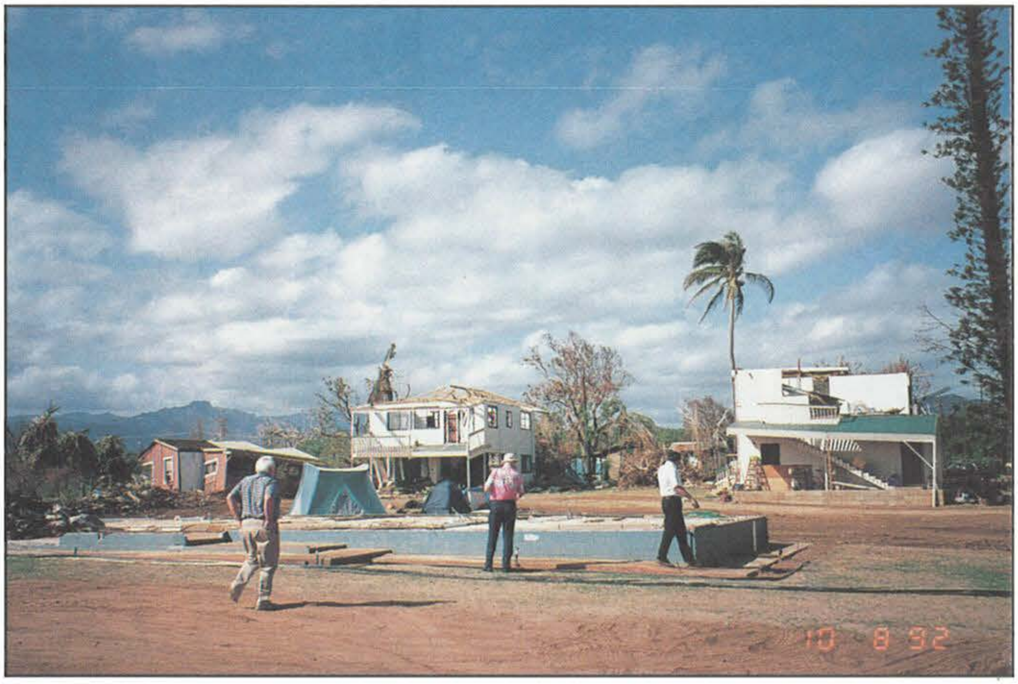


FIGURE 8. *Typical example of residential construction along Poipu Beach that was destroyed because it was not elevated above the flood hazard.*

FIGURE 9. *Non-elevated house at Poipu Beach that floated off its foundation and was transported well inland.*

distance inland. In others, they were pinned against trees or other stable objects and then destroyed by waves (FIGURE 10). There was clear evidence that in some instances these buoyed buildings crashed into other buildings, causing further damage (FIGURE 11).

- In most instances where the bottom sill plate was fastened to the grade slab, the building was partially or entirely dislodged from its foundation. Either the wooden sill plate failed at the anchor bolts (FIGURE 12) or the vertical members (studs) were dislodged from the sill plate (FIGURE 13).
- Where the vertical members were not torn from the foundation, the walls were dislocated and the building's interior destroyed (FIGURE 14).

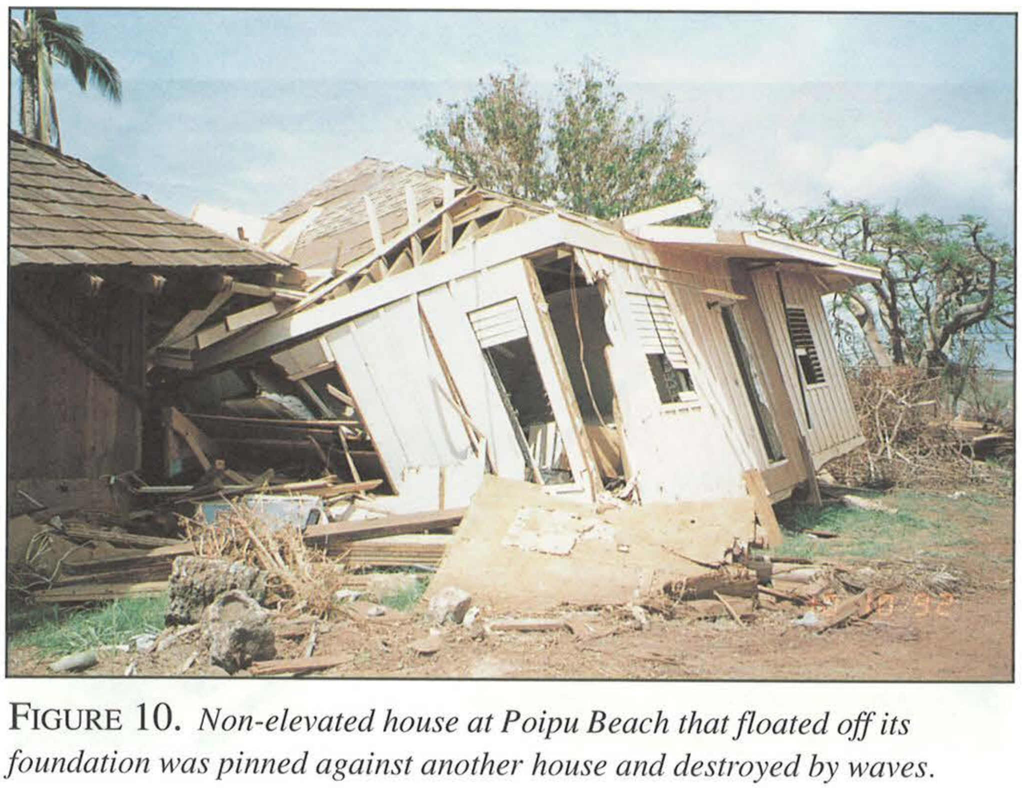


FIGURE 10. *Non-elevated house at Poipu Beach that floated off its foundation was pinned against another house and destroyed by waves.*

FIGURE 11. *Non-elevated building at Poipu Beach that rammed and increased damage to an adjacent building.*

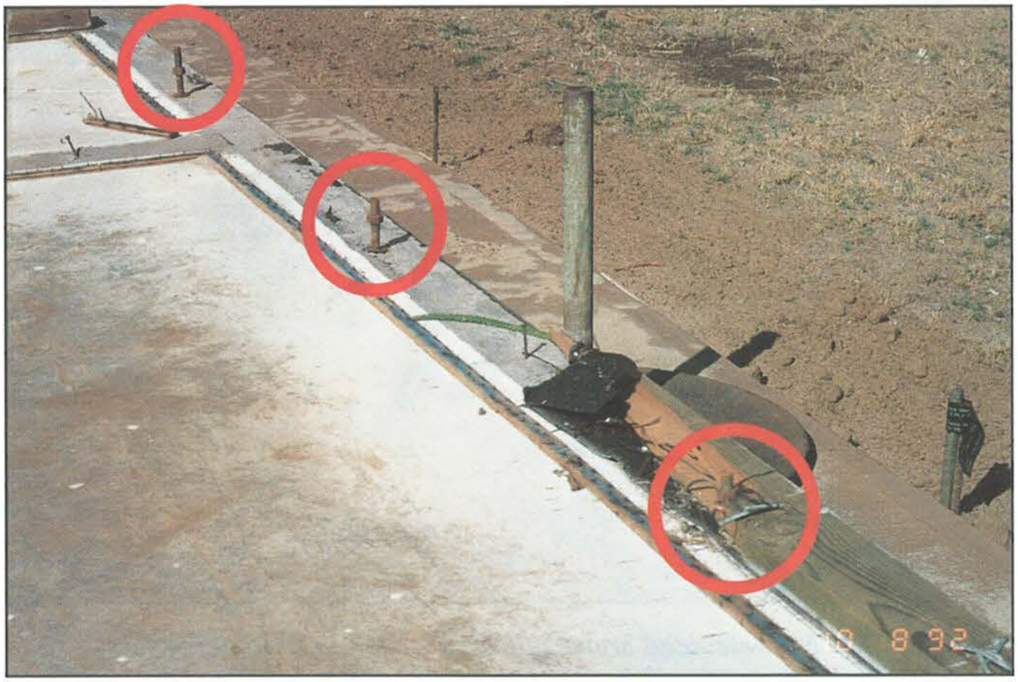


FIGURE 12. *Non-elevated building at Poipu Beach destroyed by coastal flooding. Sill plate ripped from anchor bolts.*

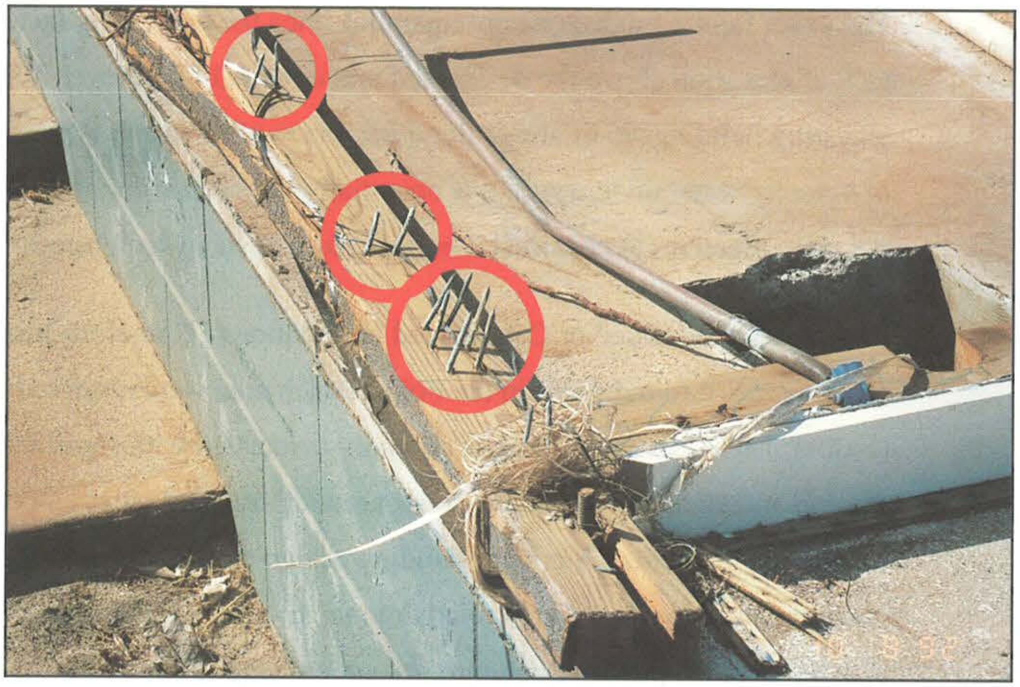


FIGURE 13. *Non-elevated building at Poipu Beach destroyed by coastal flooding. Vertical members ripped from sill plate.*

FIGURE 14. *Interior of non-elevated building at Poipu Beach destroyed by coastal flooding.*

The exact failure mode is inconsequential since the overriding factor was lack of elevation above the designated and/or actual flood level. Without elevating buildings to or above flood heights to allow for the free passage of velocity water underneath, it is essentially impossible (or at the least not cost-effective) to construct a building to withstand such forces.

2. Improperly Embedded or Constructed Foundations. Numerous instances of undermined foundations in the Poipu Beach area were observed (FIGURE 15). Coastal flooding is typically associated with significant erosion and localized or conical scour around posts and other embedded foundation elements. A critical building design consideration is the embedment of the foundation relative to the erosion depth caused by such storms. If piers, posts, or columns are not embedded deep into unconsolidated sediment or securely connected to natural lava rock deposits, the foundation of even a properly elevated building can be undermined and the building destroyed (FIGURE 16).

3. Lava Rock and Other Debris. From detailed field observations, it can be concluded that low (2- to 4-foot-high) landscaping lava rock walls offer little flood protection even when they are not destroyed. In many cases, lava rock walls failed in part or completely (FIGURE 17), generating a significant amount of large projectiles which caused additional damage to buildings landward and/or to neighboring buildings (FIGURE 18). Design professionals should reconsider the suitability of oceanfront lava rock walls seaward of buildings. Other debris also acted to batter buildings. This debris was generated primarily from buildings destroyed during the storm. Building debris can be significantly reduced if new construction is built with consideration of the flood hazard design criteria.

FIGURE 15. *Foundation at Poipu Beach undermined by erosion.*

FIGURE 16. *Undermining of shallow pier foundation at Poipu Beach due to lack of sufficient embedment below erosion depth.*

FIGURE 17. *Breakup of grouted lava rock walls at Poipu Beach generated waterborne projectiles.*

FIGURE 18. *Waterborne lava rock projectiles at Poipu Beach increased damage to non-elevated buildings.*

4. Distance from Shoreline. Buildings sited extremely close to the shoreline (within 10 to 40 feet) in many cases were completely destroyed (entirely dislodged from foundations). In comparison, buildings placed on the back portion of ocean-front lots and buildings on the second inland tier of lots suffered less damage. While relative location of a building to the shoreline is important, damage at Poipu Beach is related much more to the lack of elevation.

The Poipu area includes hotels and condominiums with ground-level units. The team observed numerous instances in which hotel and condominium ground-level units had been rendered uninhabitable by wave impact. While ground-level units may be attractive from a resort and recreational perspective, they represent imprudent design and construction practices in Coastal High Hazard Areas. Construction of new and repair of substantially damaged condominiums and hotels must be done in compliance with floodplain management provisions in the Kauai County Zoning Ordinance. Resort management firms and insurance companies would significantly reduce their financial liabilities associated with damages and business interruptions resulting from future disasters by designing new and substantially improved construction in such a way that the floors of the lowest units are above flood levels and the areas underneath are kept free of obstructions to allow uninterrupted flow of high-velocity floodwaters and waves. Such construction practices have become commonplace throughout the mainland United States without compromising architectural standards or revenue considerations.

2.3 Conclusions

Where foundations of multi-story or split-level residential buildings were not undermined, the lower areas were significantly damaged, but the upper levels suffered less damage (Figure 19). For condominiums and hotels with engineered foundations and shear-wall construction, the architectural components of the ground-level units were completely gutted by wave forces (Figure 20), while second-story units experienced no flood damage. These examples further attest to the prudence of elevating buildings above the flood hazard.

Poipu Beach, Kekaha and other areas of the County are subject to coastal flooding from hurricanes and tsunamis. In these areas, future damage can be significantly reduced by elevating the lowest horizontal structural member (i.e., the floor system) of buildings above predicted or anticipated flood levels. For designing new construction and repairing substantially damaged buildings, flood levels indicated on the Kauai County FIRM or produced by Hurricane Iniki (whichever are greater) should be used. Alternatively, Kauai County could consider adding a freeboard of approximately 3 feet on the flood elevation requirements designated along the south shore on the existing FIRM.

In addition, the horizontal structural members supporting the lowest floor must bear on piles or columns to allow velocity waters to freely pass beneath the lowest floor of buildings. These foundations must also be affixed securely to resistant lava rock or be sufficiently embedded in unconsolidated sediment to withstand the erosion and localized scour caused by hurricane-induced waves. While foundation types and construction materials may differ for condominiums or hotels, the basic minimum elevation and foundation-embedment and/or anchoring principles apply. Proper implementation of these basic design standards, which are required under the NFIP, will considerably reduce future hurricane and tsunami flood damages in Kauai County.

For non-elevated buildings, a clear relationship was observed between severity of flood damage sustained and distance from the shoreline. Thus, in conjunction with NFIP

FIGURE 19. *Non-elevated buildings at Poipu Beach. Lower area gutted; upper area suffered much less flood damage. Note transported lava rock debris, which can cause additional damage.*

FIGURE 20. *Typical non-elevated condominium or hotel. Interiors of lower units destroyed; upper units suffered considerably less flood damage. Elevating a building's lowest floor and keeping lower areas clear to allow passage of velocity water can significantly reduce future flood damage.*

floodplain construction standards, damage to future construction in areas subject to coastal flooding could be reduced by locating buildings as far back from the shoreline as is feasible or acceptable.

In many areas along Poipu Beach, the flood elevations and inland flood penetration produced by Hurricane Iniki surpassed those shown on the existing FIRM. The FIRM is based on a hybrid system that considers 100-year tsunamis and wave runup recorded from Hurricane Iwa (1982). In light of the magnitude of the flood elevations associated with Hurricane Iniki, FEMA should incorporate those elevations into a reevaluation of the flood hazard along the south shore of Kauai County and other counties in Hawaii and, if warranted, revise the FIRMs accordingly.

3.0 Observations Of Wind Damage And Successful Building Performance Under Wind Loading Conditions

3.1 Field Sites

The team surveyed the island in a comprehensive manner for wind damage. Field sites included the following:

- Princeville, for examples of contemporary (post-1974) single-family and multi-unit, heavy- and light-timber, one- and two-story wood-frame construction in exposed areas subject to amplified wind speeds and not subject to flood damage.

- Hanalei, for examples of both contemporary and older, traditional Hawaiian construction, which coincidently is located in a flood hazard area but suffered no flooding of significance.

- Anahola, Wailua, Kapaa, and Lihue, for examples of a mixture of contemporary, light wood-frame construction, traditional homes, and commercial establishments.

- Nawiliwili Harbor and other sites, for examples of commercial/industrial metal-frame warehouse construction.

- Kekaha and Hanapepe and vicinity, for examples of both older construction and a new subdivision containing light wood-frame construction.

3.2 Observations Of Building Performance Under Wind Loading

Observations of the impact of wind forces included various building types damaged at the above sites, as well as buildings that incurred little or no damage. The discussion of observations presented in the following subsections addresses the following:

- Modes of failure and examples of inappropriately designed and constructed structural systems.
- Modes of successful performance and examples of properly designed and constructed structural and roofing systems, as well as noteworthy architectural detailing and construction craftsmanship.
- Roof sheathing (e.g., plywood) and roof cladding (e.g., shingles) and their methods of attachment.
- Architectural features, such as the amount, type, installation, and protection of glazing (windows and glass doors), and roofing configurations, such as large overhanging, steep, or offset roof lines.
- Windborne debris and its role in causing damage.
- Quality of construction and workmanship.
- Deterioration (e.g., rotting, rusting) and its role in contributing to damage.

3.3 Diagnostic Modes Of Structural Failure

The most pervasive type of failure to primary structural systems was caused by uplift forces on roof systems that were incompletely or inadequately connected to walls.

Primary structural systems are those that frame the building to resist applied forces. In residential applications, these systems are made up almost entirely of the exterior and interior loadbearing and non-loadbearing walls, the roof and floor systems, and the foundation. The integrity of the overall structure depends not only on the strength and deflection performance of these components, but also on adequate designs of the connections between the components.

In the majority of cases on Kauai, when properly engineered and constructed residential units were built to define the continuous load transfer path, their performance under the storm conditions was significantly improved. Where there was construction that evidenced a breakdown in the load transfer path, damage extent ranged from considerable to total, depending on the configuration, type of construction involved, and the exposure to both flood and wind loads.

One- and two-story wood light-frame buildings were the most severely damaged type of construction. Building failure was primarily a result of 1) wind overload to roof systems caused by uplift forces, and 2) wall failure from direct wind pressure on interior and exterior walls which lost top support once all or part of the roof was lost. Simply stated, the roof system is a key component that provides stability by supporting the tops of exterior and interior loadbearing walls and exterior non-loadbearing walls of the building. Geometric stability of the wall system is generally dependent on the roof as a top lateral support. Buildings whose walls did not fail even after the loss of the roof may have been geometrically stabilized by the interior partition walls, such as in the smaller residences with numerous interior walls. Once the roof is partially or fully lost, the ability of the walls to withstand wind pressure is greatly diminished (Figure 21).

FIGURE 21. *Once the roof system is compromised, the ability of the wood-frame exterior walls to withstand external wind pressure is greatly diminished.*

The roof framing systems observed were typically composed of prefabricated trusses or job-site-assembled timber rafters or trusses. Four key failure points in the loss of these roof systems were consistently observed:

- Inadequate design.
- Reliance on simplistic and inadequate nailing procedures to construct the roof structures (FIGURES 22, 23, and 24).
- Reliance on simplistic nailing procedures to connect the roof structure to the wall system (FIGURE 25).

FIGURE 22. *Roof rafter construction with simple nailing or toenailing failed under uplift forces. Note two nails used to connect each rafter to hip beam.*

FIGURE 23. *Toenailing of ridge beam to gable-end support. Roof failure from uplift.*

FIGURE 24. *Toenailing of rafter to ridge beam. Roof failure from uplift.*

FIGURE 25. *Toenailing of roof rafters to wall system. At this critical connection, toenailing does not provide the load transfer path necessary to withstand uplift forces.*

- Improperly sized, designed, or connected metal straps, fasteners, or hangers used to construct roof systems and/or connect roof and wall systems (FIGURE 26).

The simplistic nailing procedures (generally toenailing) used to construct roof systems such as rafter tie-ins to the ridge beam or rafter attachments at stud wall sides or corners were not adequate to withstand significant wind loading. This is especially true in exposed areas along coastlines or other areas subjected to terrain-amplification of wind speed and subsequent forces. Simple toenailing of rafters and wood trusses to stud walls was a regularly observed failure point. Such toenailing did not provide the

FIGURE 26. *Example of improperly sized and placed metal fastener, which led to roof failure from wind uplift forces.*

complete load path to distribute the uplift and lateral loads from the roof to the walls and therefore should be eliminated as an accepted practice.

Shortcomings in design and construction practices such as toenailing were technically allowed due to reliance on implicit provisions in the 1985 UBC. Appendix Section 2518 of the 1991 UBC is very explicit in its requirements and contains graphical presentations not contained in older versions of the Code. For new and repair construction, much of the structural damage observed due to wind forces can be prevented if provisions in Appendix Section 2518 are correctly implemented.

Metal straps, anchors, or mechanical fasteners used on buildings that suffered roof and other structural damage were typically not sized, designed, or attached properly or lacked the proper coating (hot-dipped galvanizing) necessary for highly corrosive marine environments. Corrosion results in a loss of section and a loss of material strength, and the clips, anchors, and fasteners fail at loads below the design load. The use of metal connectors or hurricane clips in and of itself does not necessarily result in successful building performance.

In one noteworthy failure that characterizes this problem, light-gage metal straps were nailed to the top of a vertical post, bent upward in an L-shape, and nailed to one side of a horizontal roof beam (FIGURE 27). Instead, a heavy-gage metal strap used continuously in an over-the-top or collar fashion and securely nailed on either side of the vertical post would have been the proper connection and would have provided an acceptable complete load path between the roof and the wall system. Graphic examples of proper load path connectors such as this are contained in Appendix Section 2518 of the 1991 UBC.

A second type of roof system observed was prefabricated (factory-made) light-wood trusses with plywood sheathing. Trusses themselves performed relatively well under wind loads (FIGURE 28). However, because connected trusses and sheathing

FIGURE 27. *Undersized and improperly attached metal fasteners led to roof damage from uplift forces.*

FIGURE 28. *Individual prefabricated wood roof trusses performed relatively well.*

formed the horizontal diaphragm of the building system, truss systems tended to become unstable and failed to varying degrees when the sheathing was lost (FIGURE 29). This amplified failures due to the inadequate load transfer mechanism between truss and wall systems, as previously described (FIGURE 30).

Gabled roof structures were invariably more failure-prone (FIGURE 31). Hip roofs (FIGURE 32) generally performed better than gabled-end roofs, clearstory roofs (offset roof peak), and other steeply pitched roof systems . The geometric discontinuity in these roof lines made the roofs susceptible to high localized wind-induced external pressure on eaves and soffits (FIGURE 33).

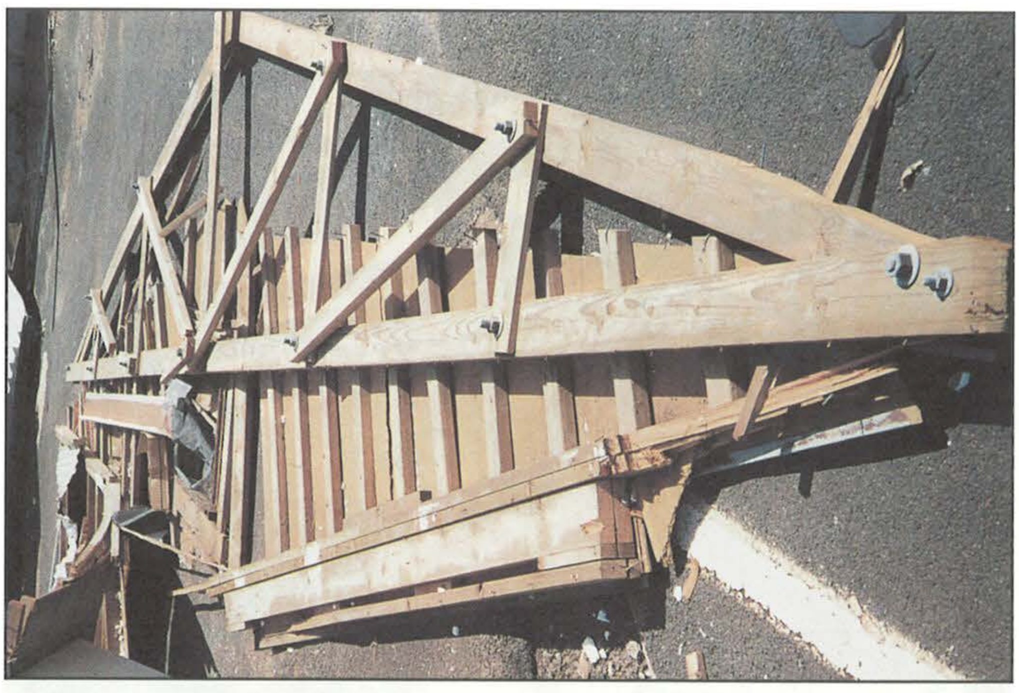


FIGURE 29. *Gable-end roof failure due to loss of roof sheathing and lack of gable bracing.*

FIGURE 30. *Improper connection (toenailing) between roof trusses and wall systems. When roof sheathing was blown off by wind, unbridged trusses failed, as did the exterior wall.*

FIGURE 31. *Gable-end roof designs tended to be more failure-prone.*

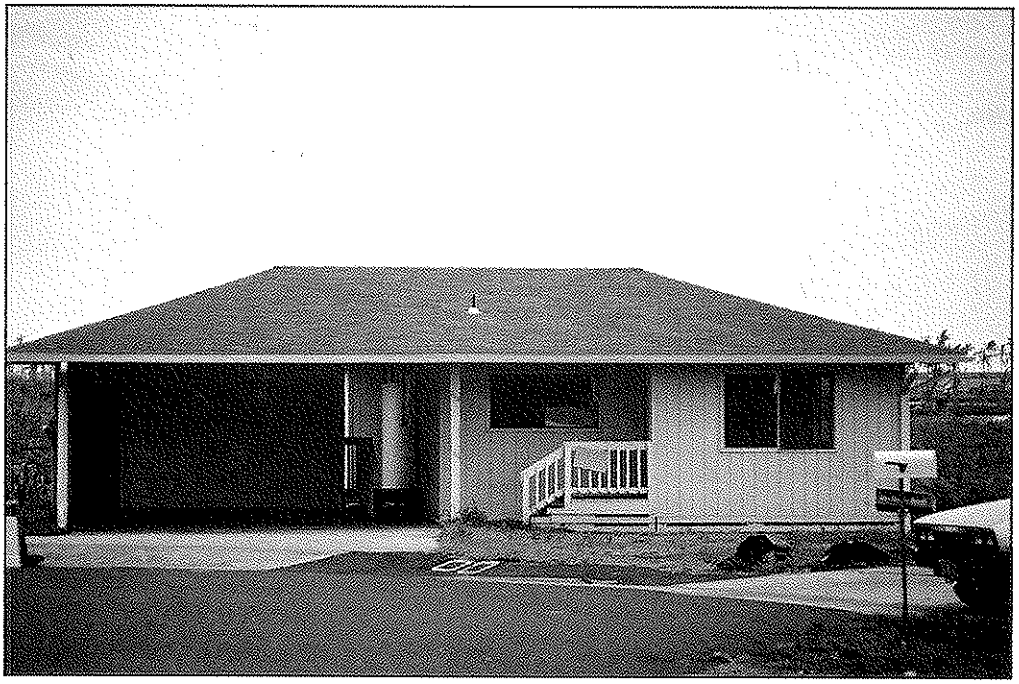


FIGURE 32. *Low-pitched hip roofs are aerodynamically superior and generally performed better than steeply pitched gable-end roofs.*

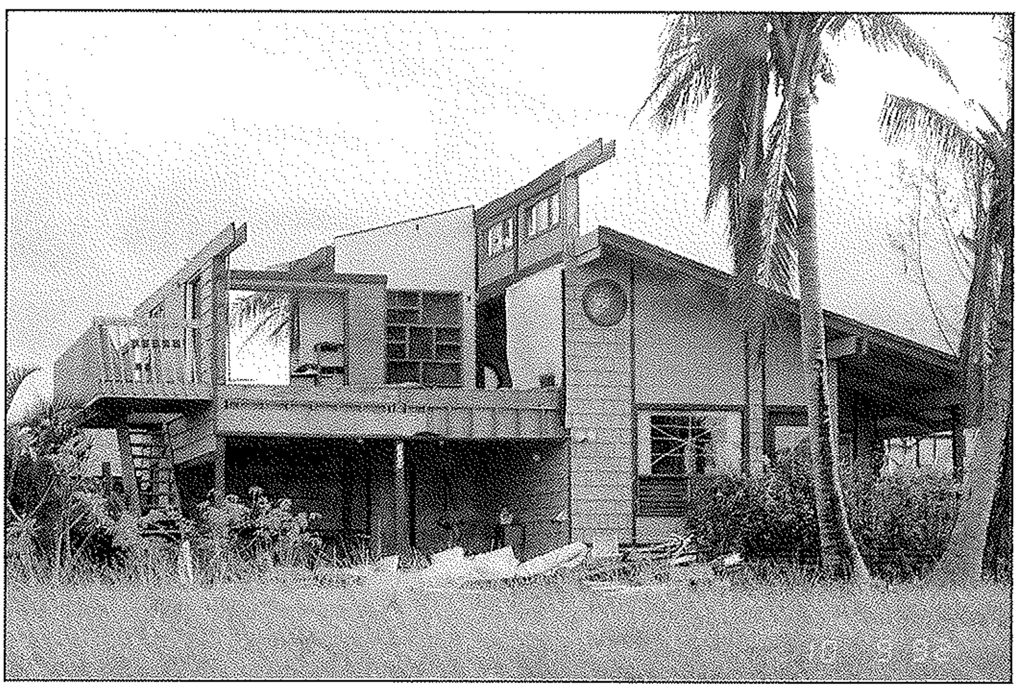


FIGURE 33. *Offset roof peak provides geometric discontinuity and results in greater localized wind-induced pressure, which can lead to roof and then wall failure.*

Roof overhangs or soffits 3.0 feet long or less, with adequate venting, suffered comparatively less damage from wind forces. Overhangs exceeding 3.0 feet in many instances failed to resist the uplift forces and were the source of progressive roof structure failure (FIGURE 34). Much of this failure was due to inadequate installation, lack of proper engineered enclosure of extended soffits, lack of tie-back from rafters to wall, and improper sheathing and venting.

In summary, incomplete design for load transfer (either improper roof construction or improper connection between the roof and wall systems) was found to be the most pervasive cause of structural failure of buildings due to wind loads.

FIGURE 34. *Excessive roof overhang and poor connections in many instances led to roof failure.*

3.4 Diagnostic Modes Of Successful Structural Performance

Noteworthy examples of properly engineered and constructed buildings were observed in Kauai County, both tract development houses and individual custom-built houses. Almost without exception, successful performance resulted from adequately designed and clearly defined continuous load transfer paths. Where connections, such as hurricane clips and metal straps, were correctly applied, buildings performed relatively well (Figure 35).

Examples of proper building design and construction were noted in two new subdivision developments in Kauai County. Both contained modestly sized, single-story, light wood-frame construction.

The following key design and construction factors led, at least in part, to successful performance of homes at these sites:

- Creation of a continuous load transfer path through the use of proper connections between the roof and the wall, and between the walls and the foundation (Figure 36).

- Use of roof designs that are more aerodynamically stable. Both subdivisions were characterized by hip roofs with low angles and modest overhangs.

- Proper attachment of roof cladding to roof sheathing. Properly nailed common fiberglass composition shingles were used and performed adequately.

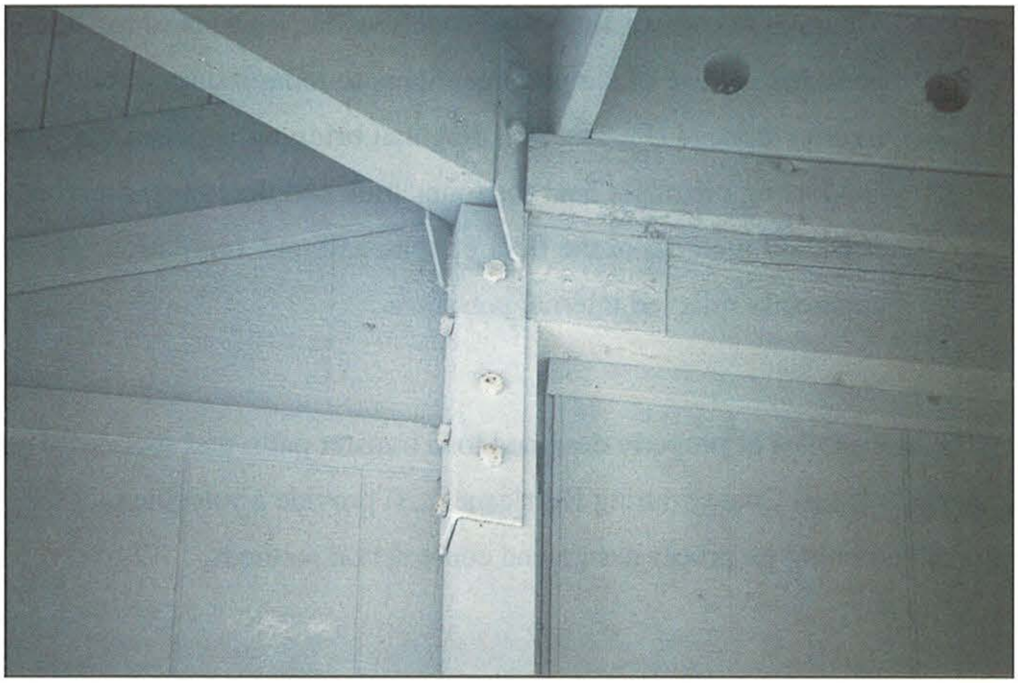


FIGURE 35. *Example of very successful heavy-gauge metal fastener connecting roof and wall systems. Note the over the top application and the number and size of lag bolts used for attachment.*

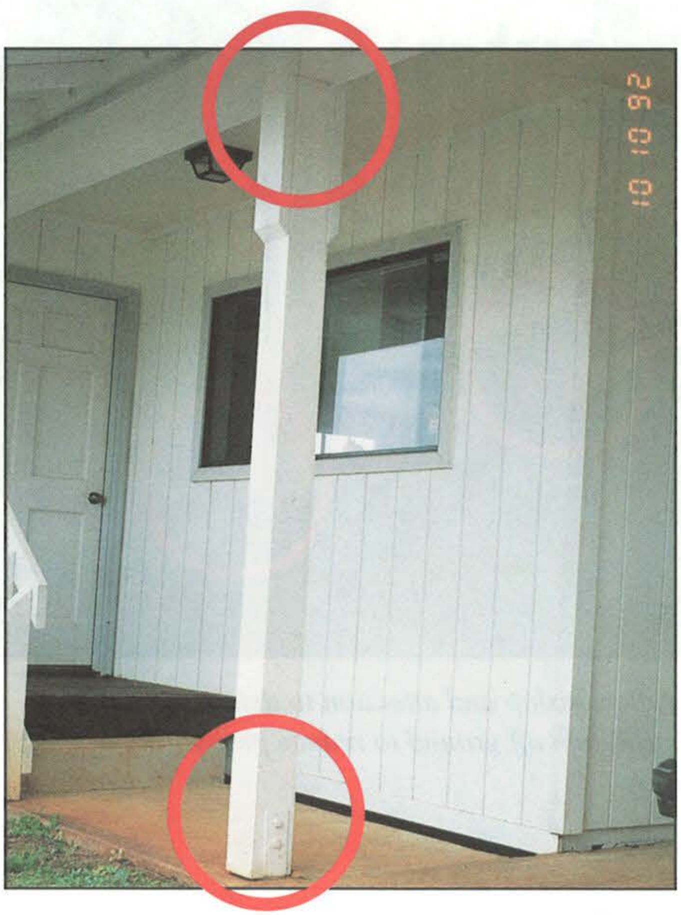


FIGURE 36.
Wood splice or strap provides a secure connection between wall and roof systems. Bolted metal anchor provides secure connection between vertical member and foundation. This is a fine example of a continuous load path.

- Attention to construction details and sensible workmanship. Examples included the use of simple procedures to reduce susceptibility to termite damage (FIGURE 37), diagonal bridging between the vertical supporting members near the foundation and the lowest horizontal structural member of the floor system, and roof ventilation, which apparently relieved internal pressures.

These examples of properly designed load transfer paths and successful building performance in Kauai County during Hurricane Iniki provide a valuable tool for education and training on proper design and construction methods.

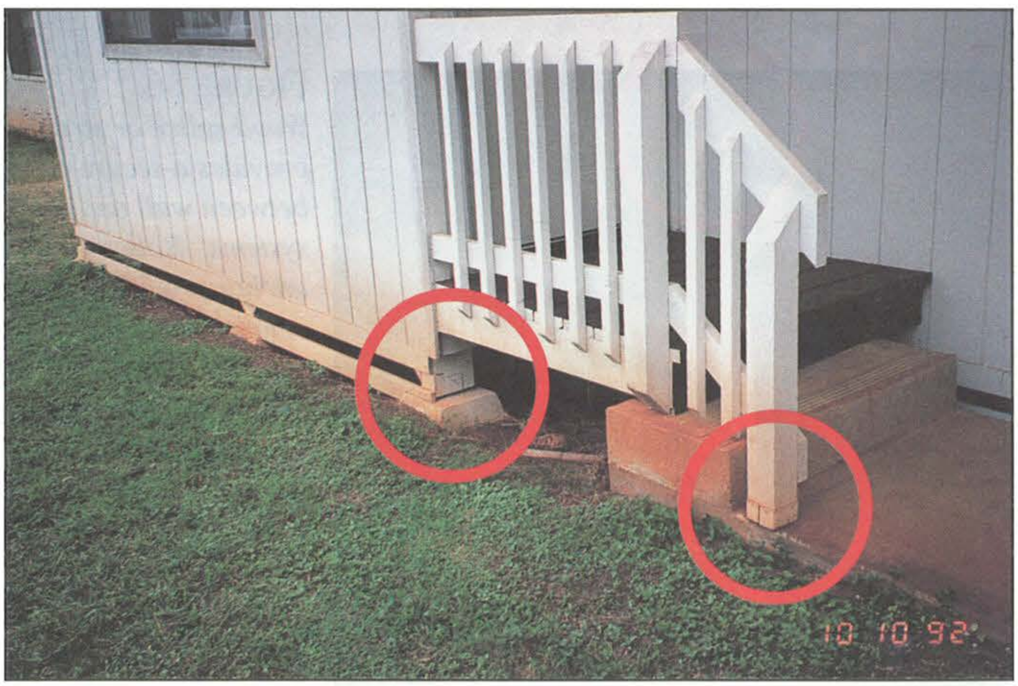


FIGURE 37. *Sensitive craftsmanship and attention to detail: Vertical preservative-treated posts 1/4 inch off ground to reduce probability of termite infestation and decay.*

3.5 Roof Sheathing

Loss of roof sheathing (e.g., plywood) was a consistently observed failure mode. The primary cause of sheathing loss was the lack of adequate nailing of the sheathing to the structural underpinnings of the roof system (e.g., rafters, trusses, and purlins) (Figures 38-40). Frequently observed evidence of inadequate attachment including excessive space between staples or nails; lack of staples or nails where sheathing rested on rafters, trusses, or purlins; and failure of staples or nails to strike rafters, trusses, or purlins. In addition, excessive corrosion of inadequately protected nails and staples was observed. Where inadequate nailing or excessive corrosion occurred, high winds were often able to peel the sheathing from the roof structure.

Figure 38. *Improper attachment of sheathing to purlins. Note wide spacing, shallow penetration, misalignment, and corrosion of staples.*

FIGURE 39.
Improper nailing design and schedule for purlin-to-rafter attachment. Note infrequency of nails for large surface area. Nowhere is the plywood sheathing directly nailed to the rafter system.

FIGURE 40. *Loss of roof sheathing due to improper nailing design and schedule.*

Once sheathing was lost, damage was increased by rainwater. Stripped sheathing was also a source of airborne projectiles which caused additional damage to adjacent buildings. Sheathing loss was particularly troublesome because sheathing composed a significant part of the building envelope. Sheathing loss often led to progressive roof structure failure. This in turn led to a loss of support for the tops of both interior and exterior walls. In many cases, this led to major structural damage and even total loss.

Loss of sheathing was especially critical where roof structures (rafter or truss systems) were engineered. In these instances, the roof structure relied on the plywood to provide rigidity to the roof diaphragm. Once the sheathing was peeled from the purlins or trusses, the roof structure became unstable and highly susceptible to damage (FIGURE 41).

Adequate roof rafter connections and use of truss bridging, proper roof system-wide lateral bracing, adequate cross-bracing at gable end trusses, and stiffening of the gable ends were observed to have provided additional structural roof support and supplemented the sheathing diaphragm for structural support.

Corrugated metal roofing is the predominant type of roof covering in Kauai County. In most cases it is used on small 800- to 1200-square-foot rectangular wood-frame "single wall" structures that typify the traditional architecture style in Hawaii. Failure of this roofing material occurred at points of attachment to underlying rafter systems (FIGURE 42). Such damage was attributed to improper fastening procedures and, in some instances, to rusting of metal panels at nailing locations, or to significant corrosion of the nails.

Usually, however, loss of corrugated metal roofs did not lead to further structural failure of buildings because 1) the metal sheets were simply coverings and do not serve to act as as a stiffening for the roof diaphragm to provide structural stability to the walls and 2) the buildings on which these roofs are usually found are inherently stable as a result of their small plan size, rectangular shape, and numerous interior partition walls. Thus, loss of corrugated metal roofs, with the exception allowing some internal wind pressure, did not significantly decrease the structural integrity of these traditional-style buildings.

FIGURE 41. *Total roof failure due to loss of sheathing.*

FIGURE 42. *Failure of corrugated metal roof at attachment points. These small, geometrically stable, "single wall," rectangular structures with numerous interior partition walls often remained structurally intact after loss of metal coverings.*

Loss of corrugated metal roofing was nonetheless a significant problem because of the resulting rainwater damage and the generation of windborne projectiles (FIGURE 43). Thus, considerable effort should be given to teaching building contractors, and especially homeowners, the proper fastening of corrugated metal roofing to the underlying rafters and purlins.

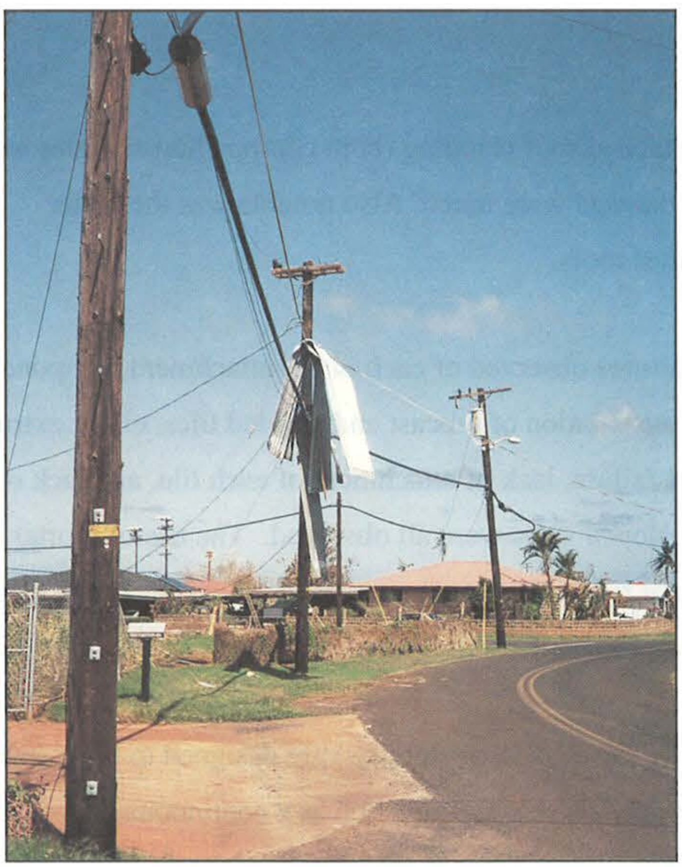


FIGURE 43.
Metal roof loss generates large airborne projectiles, which often cause additional damage.

3.6 ROOF CLADDING

Damage to roof covering or cladding such as extruded concrete and clay tiles, wood shakes, fiberglass composition shingles, and underlayment material was extensive at most field sites. While many structures escaped very costly structural frame damage, most structures suffered some degree of roofing damage. Damage to roof cladding permitted further damage to building interiors from high-velocity winds and rain, particularly since the common practice is to support concrete tile and wood shake roofing on spaced wood strips rather than complete roof sheathing.

Close observation revealed that attachment procedures (stapling or nailing) for cladding types were deficient at many locations (FIGURE 44). Rarely was material failure caused solely by wind pressure. It was observed that less damage occurred to roofs where either staples or nails were sized and installed to generally accepted standards of construction practice. In some instances, individual tiles were observed that had not been nailed (FIGURE 45).

Examples of properly attached roof cladding (both composition shingles and extruded tiles) with little or no damage were noted. Also notable was the better performance of cladding on flatter roofs.

In general, there were failures observed of each of the attachment components that were integral to the proper installation of precast and molded tiles, either extruded concrete or clay. Underlayment failure, lack of attachment of each tile, and lack of mortar pads on ridge and steep-sloped sides were all observed. The use of mortar pads to provide improved adherence of roof tiles is not generally practiced in Kauai County. However, mortar has been shown to significantly improve adherence of the roof tiles.

Roof cladding materials (tiles, shakes, or shingles) are designed to work together to form a secure attachment to underlayment and function as a continuous skin. Loss of

FIGURE 44. *Loss of roof cladding due to failure at attachment points. Notice that many staple crowns have corroded away on staples used to attach wood shake roofing to plywood roof sheathing.*

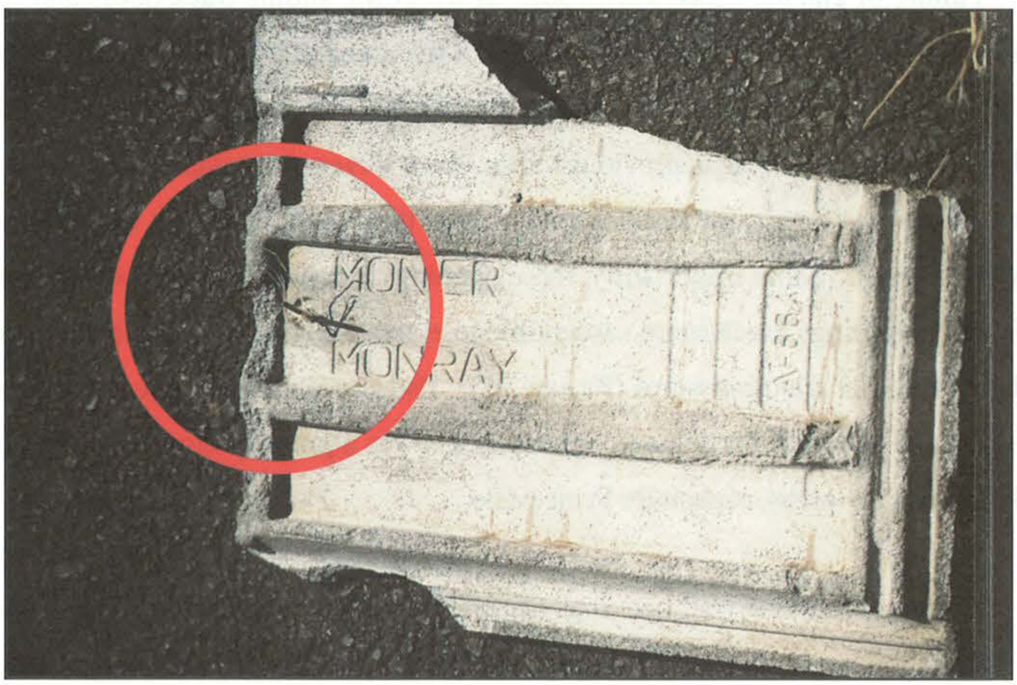


FIGURE 45. *Heavy concrete tile attached at one point with undersized nail. It was also observed that neighboring tiles had not been nailed.*

one piece allows wind to effectively penetrate under and lift the next piece. This explains the chain-reaction failure mode of shakes and tiles once debris impact or improper attachment allowed wind to remove the first few pieces of cladding (FIGURE 46).

3.7 GLAZING AND TRANSPARENT OPENINGS

Openings in exterior walls and roofs receive the various door, window, and venting systems necessary to complete, fully functioning architecture. The observed failures of the door and window "inserts" were typical of those that occur during high-wind events. These failures resulted in a breach of the building's envelope and allowed wind to directly enter the interior of the building. This resulted in an uncontrolled buildup of internal pressure that overloaded the building's structural components. While most glazing should be protected prior to significant storms, all other opening components should have performed acceptably without additional reinforcing.

Failure of glazing (glasswork), such as windows, sliding track doors,and hinged doors, contributed to a significant percentage of the damage to buildings. Moreover, once glazing components and doors failed (FIGURE 47), the structural integrity of the building was compromised as previously described. Given an entrance path for uncontrolled wind forces, the interior components then become subject to wind and rainwater damage. More importantly, these openings, coupled with the penetration of wind, make buildings much more susceptible to extensive structural damage due to rapid buildup of internal wind pressures (FIGURE 48). The larger the area that is compromised, the greater the potential for damage. This process was a primary mode of failure of buildings in many areas, especially Princeville.

Failure of exterior wall openings occurred in two ways: 1) shattering of glazing from projectile impact (FIGURE 47) and 2) implosion or explosion of glazing due to the combination of wind pressure and improper installation (FIGURE 49).

FIGURE 46. *Roof cladding system composed of interdependent elements. Failure of one tile led to failure of adjacent tiles in a "chain reaction" effect.*

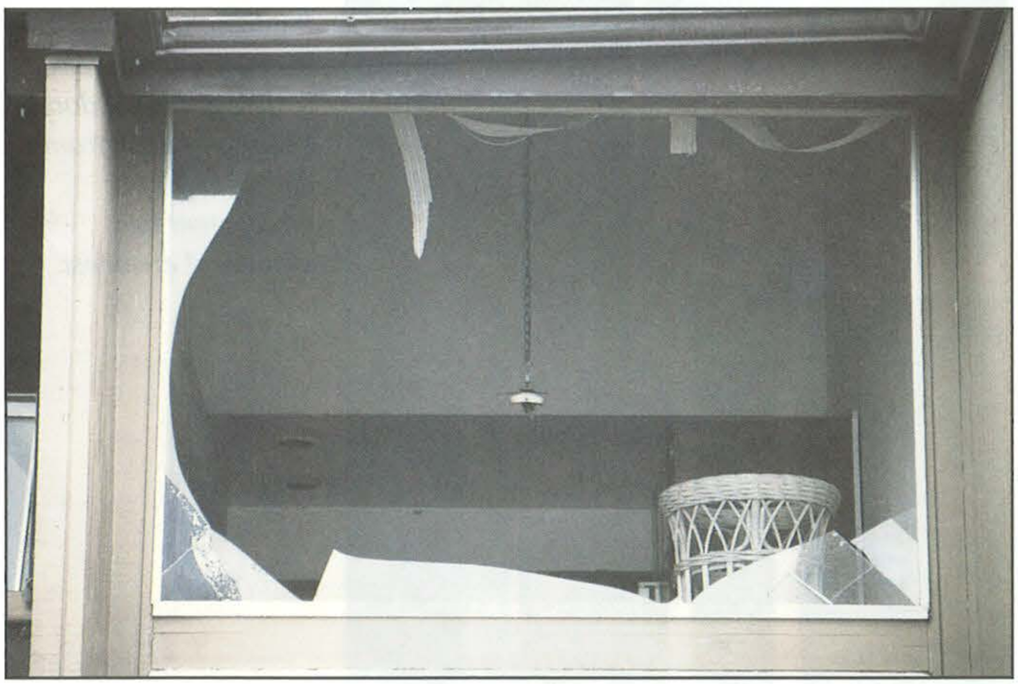


FIGURE 47. *Glazing broken by windborne debris or direct wind pressure.*

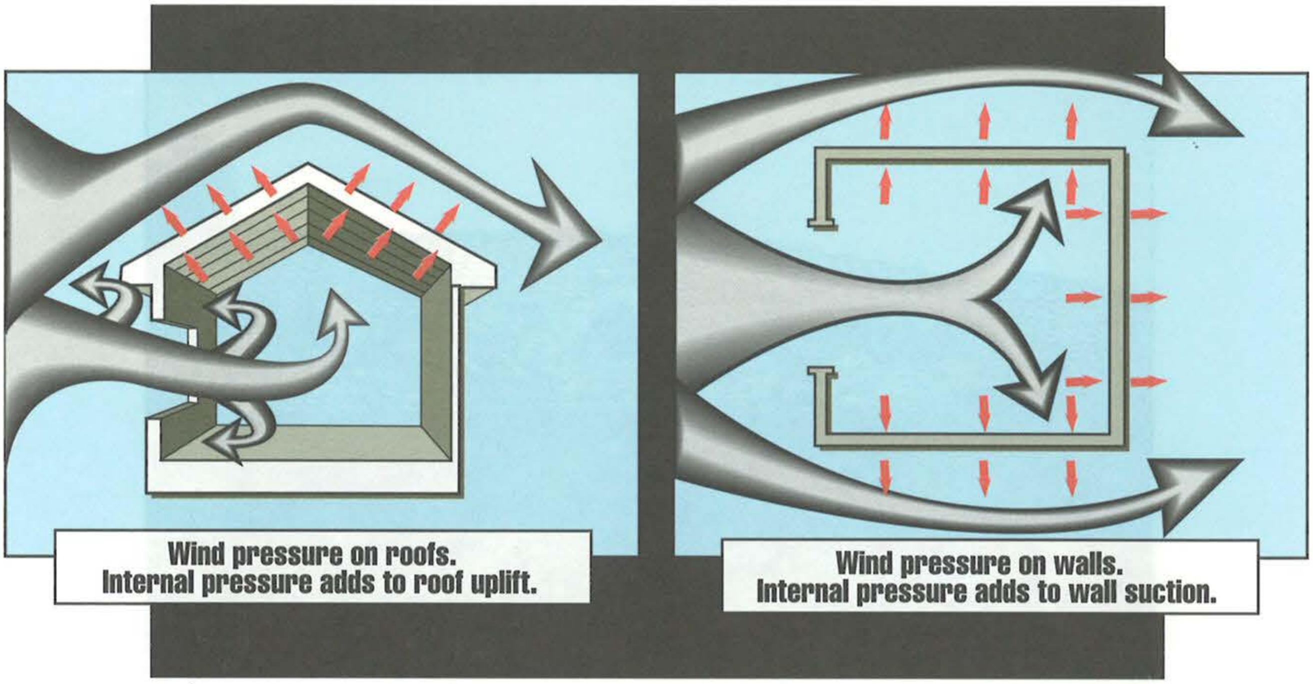


FIGURE 48. *Loss of opening protection allows wind entry and increases internal exposure.*

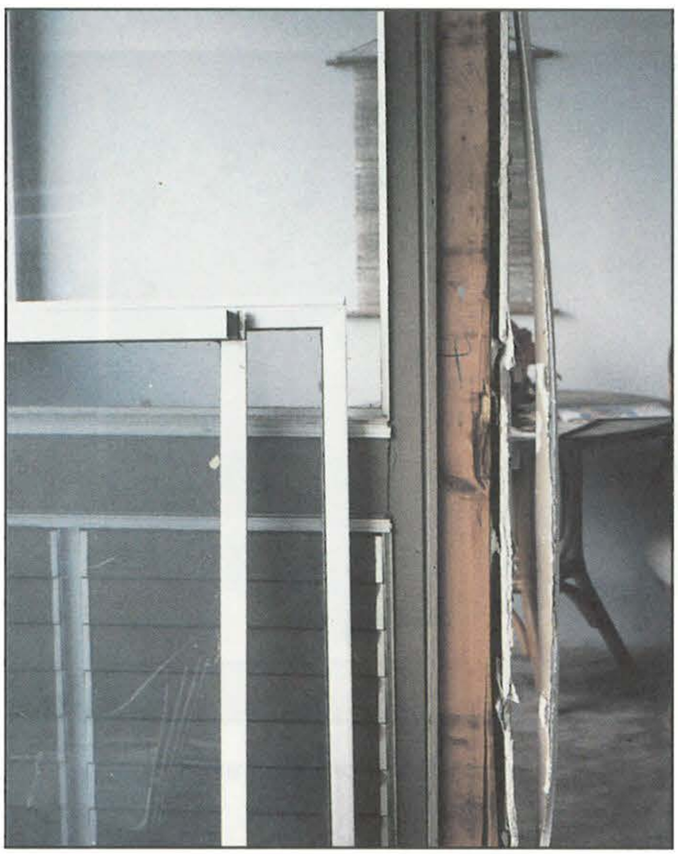


FIGURE 49. *Implosion of transparent shatter-resistant sliding door. Failure of door frame due to improper attachment to structural elements.*

Improper installation, for example, inappropriate attachment of window frames to the structural elements of the wall (FIGURE 50), and weak connections of expansive sliding doors (FIGURE 51), were consistently observed causes of the failure of glazing units. Where shatter-resistant material was used, failure was frequently observed where the material remained intact, but the unit, as a whole, was displaced inward by wind pressure (FIGURE 52) due to bowing and subsequent failure at the perimeter connections.

Open exposure of frangible (glass) windows and doors during high winds is problematic. Obviously, transparent components, including glazing, are fundamental and necessary architectural features of all residential structures. Yet, the use of glasswork over large, exposed surface areas without adequate protection significantly increases the potential for internal damage, and even seriously jeopardizes the performance of

FIGURE 50.
Improper attachment of window unit. Note only one connection (nailing) point between unit and wall structure at the single shim.

FIGURE 51. *Improper connection of sliding glass door. Track attached with only three screws in vertical member. Sliding track on floor attached with caulk only.*

FIGURE 52. *Gable-end window unit as a whole was displaced inward by wind pressure. Apparently, this allowed wind entry, increased interior pressure, and caused roof uplift.*

structures exposed to high wind loads and flying debris (FIGURE 53). Without the use of in-place working shutter systems (FIGURE 54), emergency protection such as securely fastened plywood, or non-frangible transparent materials, survival of glasswork from flying debris becomes random chance.

Furthermore, glasswork should be properly designed according to the same criteria used for the structure itself. Properly designed glasswork provides a factor of safety from failure due to direct wind pressures.

FIGURE 53. *Extensive use of glazing on windward side can significantly compromise a building's envelope and lead to roof failure.*

FIGURE 54.
In-place protective devices for glazing reduced the occurrence of building envelope failures.

3.8 WINDBORNE DEBRIS

The primary sources of windborne debris, probably in decreasing order of prevalence, were improperly installed roof cladding (e.g., shingles, tiles, and shakes), structural failure of roof systems and thus wall systems, and improperly installed roof sheathing (e.g., plywood). Although windborne debris caused some damage to exterior siding from direct impact (FIGURE 55), by far its primary effect was in the shattering of unprotected glazing such as windows and glass doors.

Thus in hurricanes such as Iniki, the modes of building failure are interconnected: Loss of roofing due to improper structural attachment or improper installation contributed to the number of windborne projectiles; this in turn significantly increased

3.9 DETERIORATION

Weakening of structural components, sheathing, and cladding was caused by insect (termite) infestation and weatherization (rotting and rusting). This reduction in strength acted to increase damage. Several procedures could have been used to mitigate hurricane damage due to previously weakened wood and metal building material:

- Use of proper building material, such as chemical-pressure-treated lumber, to reduce insect infestation, or corrosion-resistant fasteners to reduce attachment failures due to weakened fasteners.
- Use of pre-painted wood and metal and periodic maintenance to reduce open-weather deterioration.
- Application of sensible construction practices that reduce the probability of deterioration. For example, taking care that no part of a wood foundation system comes into contact with the soil (FIGURE 37).
- Inspection and replacement of damaged elements.

3.10 PRE-ENGINEERED STEEL WAREHOUSES

Several pre-engineered steel warehouses at Nawiliwili Harbor, as well as other structured steel structures were analyzed. Warehouse failure typically included loss of light-gage metal sheet cladding (FIGURE 56) and, in several cases, failure of main structural members (FIGURE 57). Obvious points of failure included sill-to-concrete-foundation attachments (FIGURES 58 and 59) and rusting at attachment points.

FIGURE 55.
Windborne debris impact can puncture building and allow buildup of internal wind pressure.

the potential for compromise of windows and doors and failure of neighboring buildings; this in turn further increased the number of windborne projectiles.

As discussed in Section 4.0, the team observed that properly engineered and constructed architectural and structural components, attention to detail in attachment of roof cladding and sheathing, and proper design and protection of glazing components significantly reduced damages caused by windborne projectiles.

FIGURE 56. *Steel warehouse failure commonly was due to loss of light-gauge metal sheet cladding.*

FIGURE 57. *Steel warehouse failure was also due to failure of structural steel members.*

FIGURE 58. *Failure of steel warehouse due to age and weatherization and insufficient anchorage to resist uplift.*

FIGURE 59. *Steel warehouse, sill-to-concrete-foundation failure at anchoring points.*

Because these structures are generally pre-engineered by manufacturers, and referred to in performance language in the UBC, a detailed discussion of design considerations and failure modes is beyond the scope of this report. For further details refer to a report currently being prepared by the Structural Engineers Association of Hawaii.

4.0 Recommendations

There were noteworthy examples of buildings properly designed and constructed in compliance with current Codes that suffered little to no damage. However, there was also overwhelming field evidence to suggest the existence of certain deficiencies in past design and construction practices in Kauai County permitted under older versions of the Code. Much was learned from these deficiencies and associated building failures. Likewise, much was learned from some fine examples of properly designed and constructed buildings that suffered little to no damage. In the wake of Hurricane Iniki, during repair/ retrofit activities and new construction in Kauai County, it is important that lessons learned be applied in a positive, forward-looking manner.

Therefore, the following recommendations are offered by the Building Performance Assessment Team. Consideration of these recommendations should be viewed as a shared responsibility, with leadership provided by Kauai County and assistance provided by Federal and State Governments and the private sector. Adoption of these recommendations, whether in part or in full, will require certain changes in administrative practices by the Kauai County government; others will require changes in the way that structures are designed and constructed by people in the building industry. Many of the recommendations can be accomplished through basic training and education with minimal increase in construction costs.

4.1 Floodplain Management And Flood Damage

- The single most important mitigating action to reduce future flood damages would be to properly administer NFIP requirements for new construction and the repair of buildings substantially damaged by Hurricane Iniki. These requirements are presently contained in the Floodplain Management provisions of the Kauai County Zoning Ordinance.

- In accordance with NFIP requirements and the Kauai County Zoning Ordinance, all new construction and repair of substantially damaged buildings in Coastal High Hazard Areas along Poipu Beach, Hanalei, and other areas (in addition to all riverine flood hazard areas designated on the FIRM) must be elevated above anticipated flood heights (FIGURE 60) and constructed with proper foundations (FIGURES 61-76).

- For future construction in coastal flood hazard areas, special consideration should be given to the depth of structure foundations relative to the maximum potential depth of erosion that will be caused by flood waters. Piers, posts, and columns should be embedded deep into unconsolidated sediment or, preferably, socketed into the natural lava rock deposits so that the foundation will not be undermined. (FIGURES 60, 62-65, 68-73, 75, and 76).

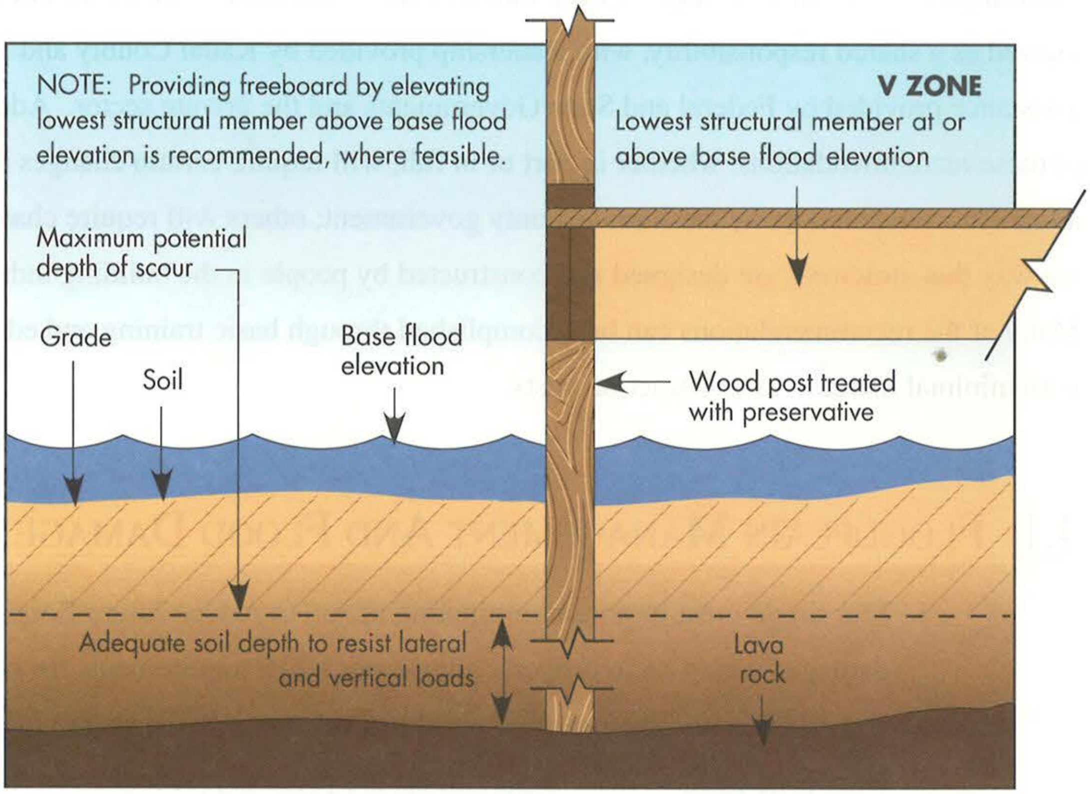


FIGURE 60. *NFIP requirements for elevated foundations in V zones.*

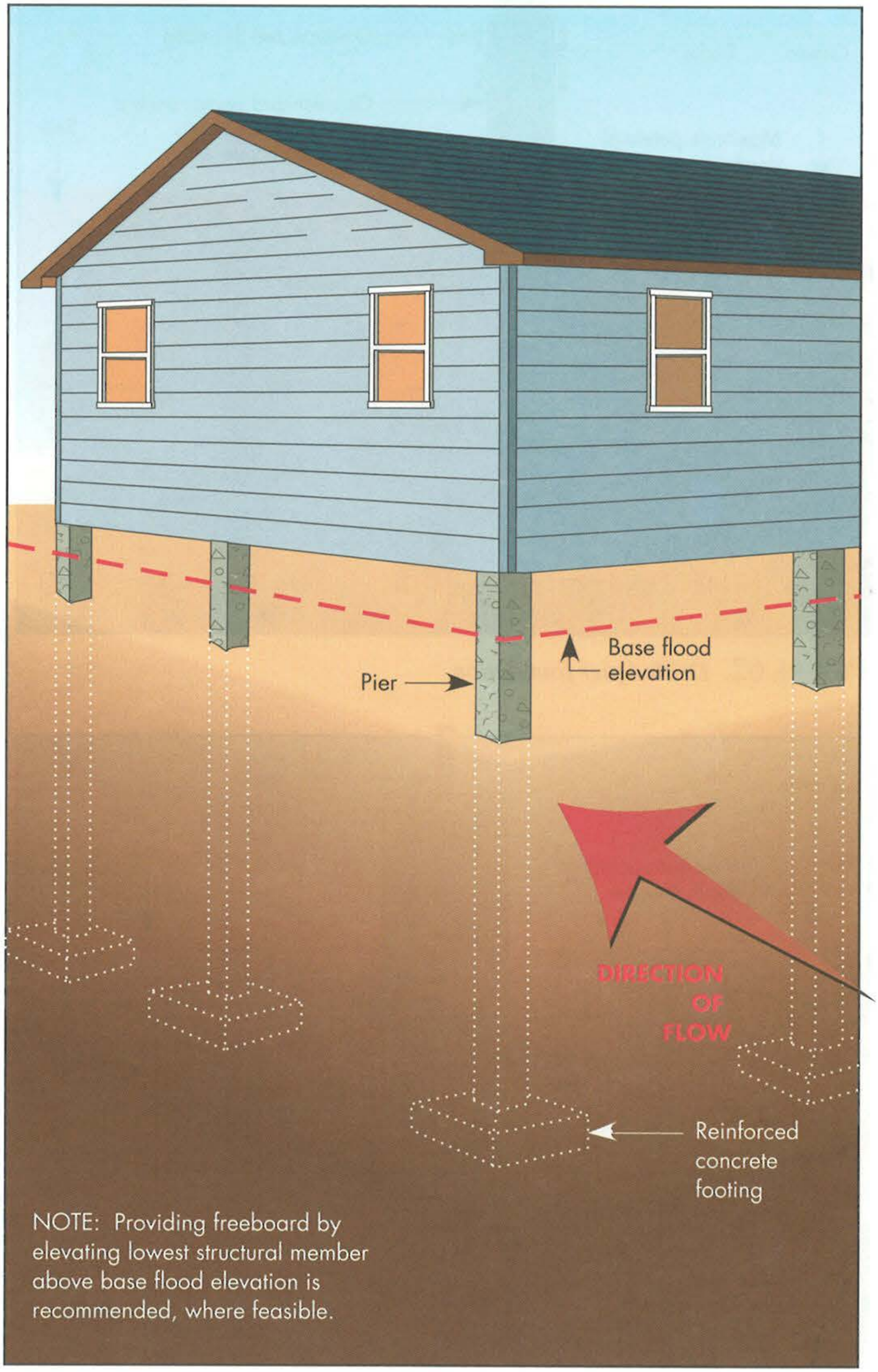


FIGURE 61. *One method of support for piers is a reinforced concrete footing.*

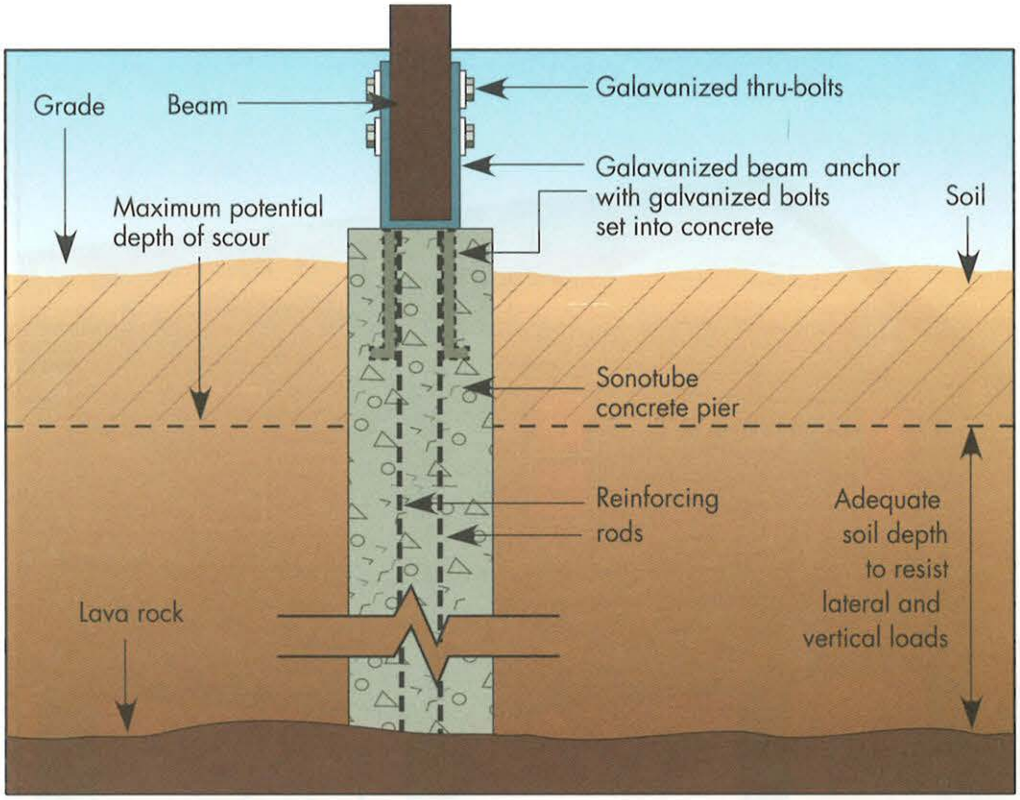


FIGURE 62. *Drilled pier foundation.*

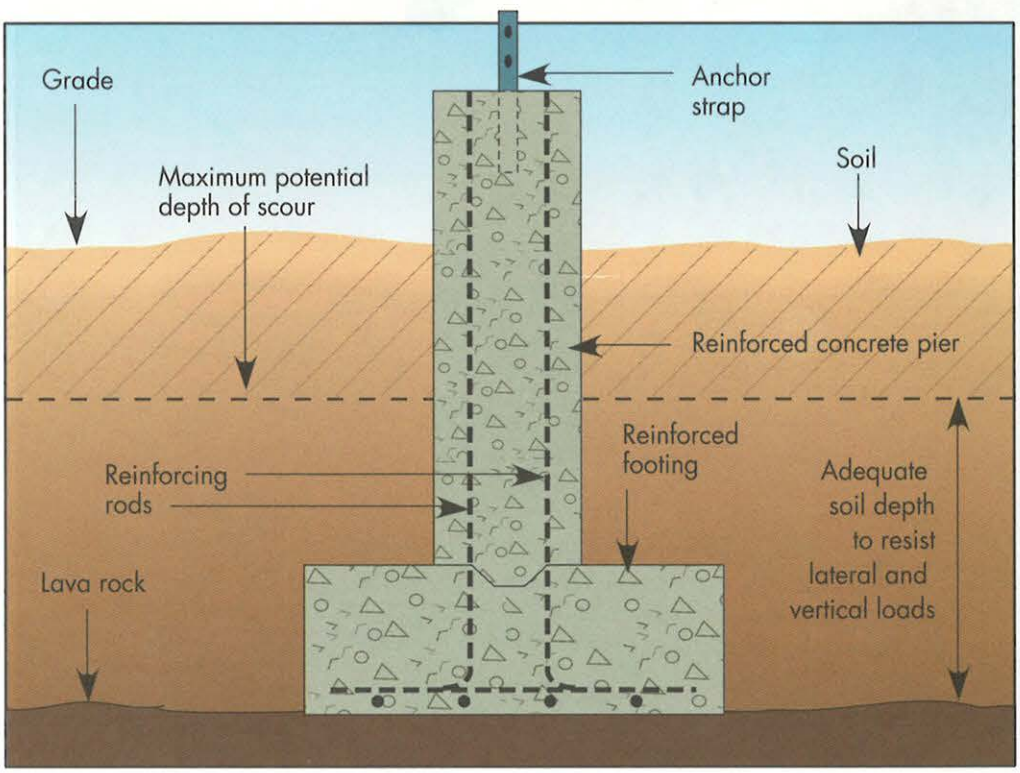


FIGURE 63. *Reinforced concrete pier.*

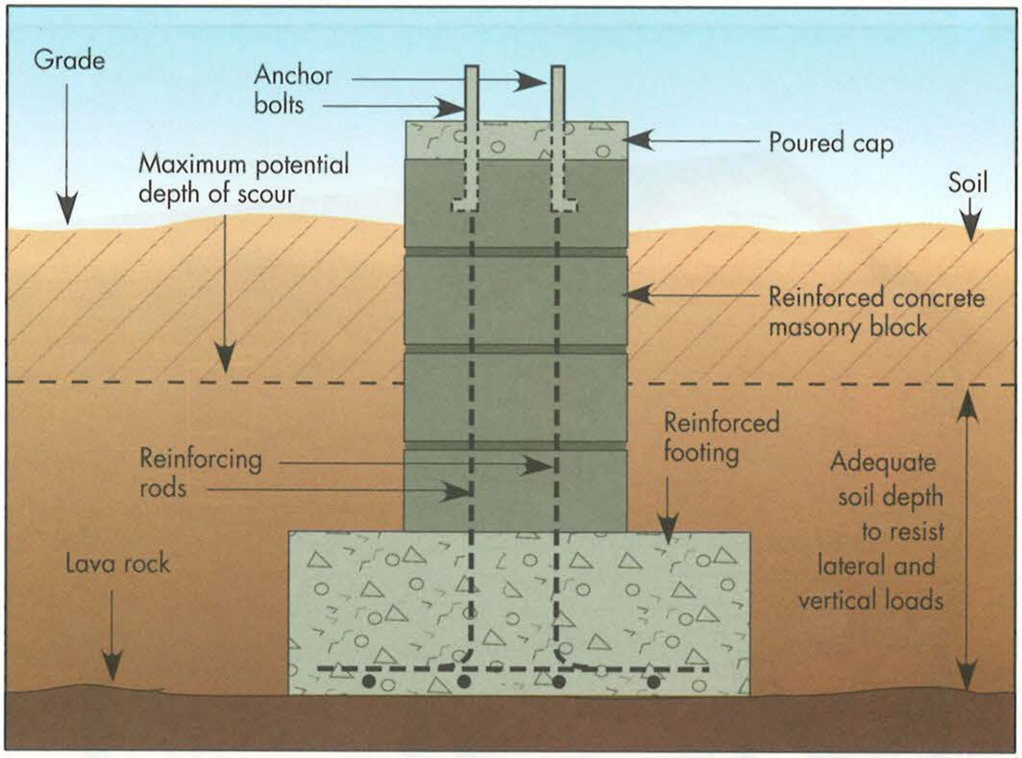


FIGURE 64. *Reinforced concrete masonry pier.*

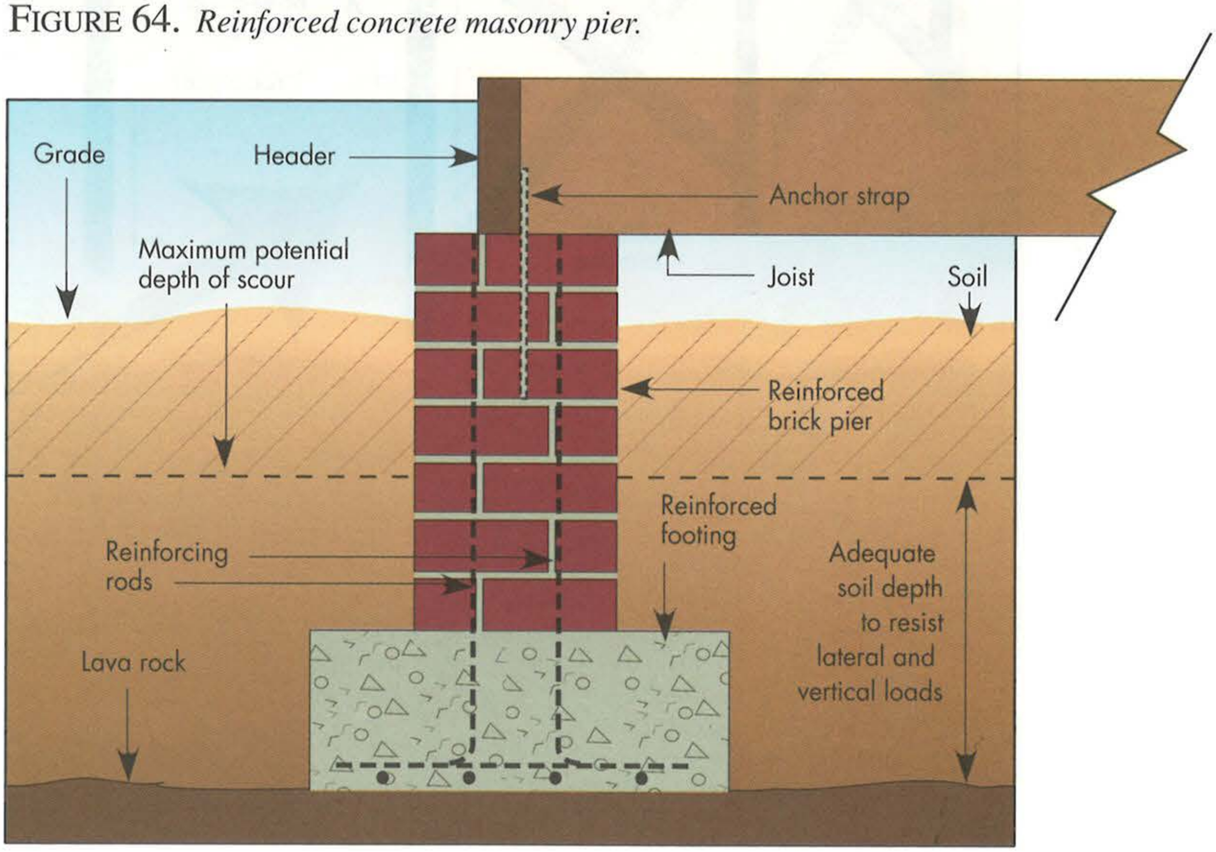


FIGURE 65. *Reinforced brick pier.*

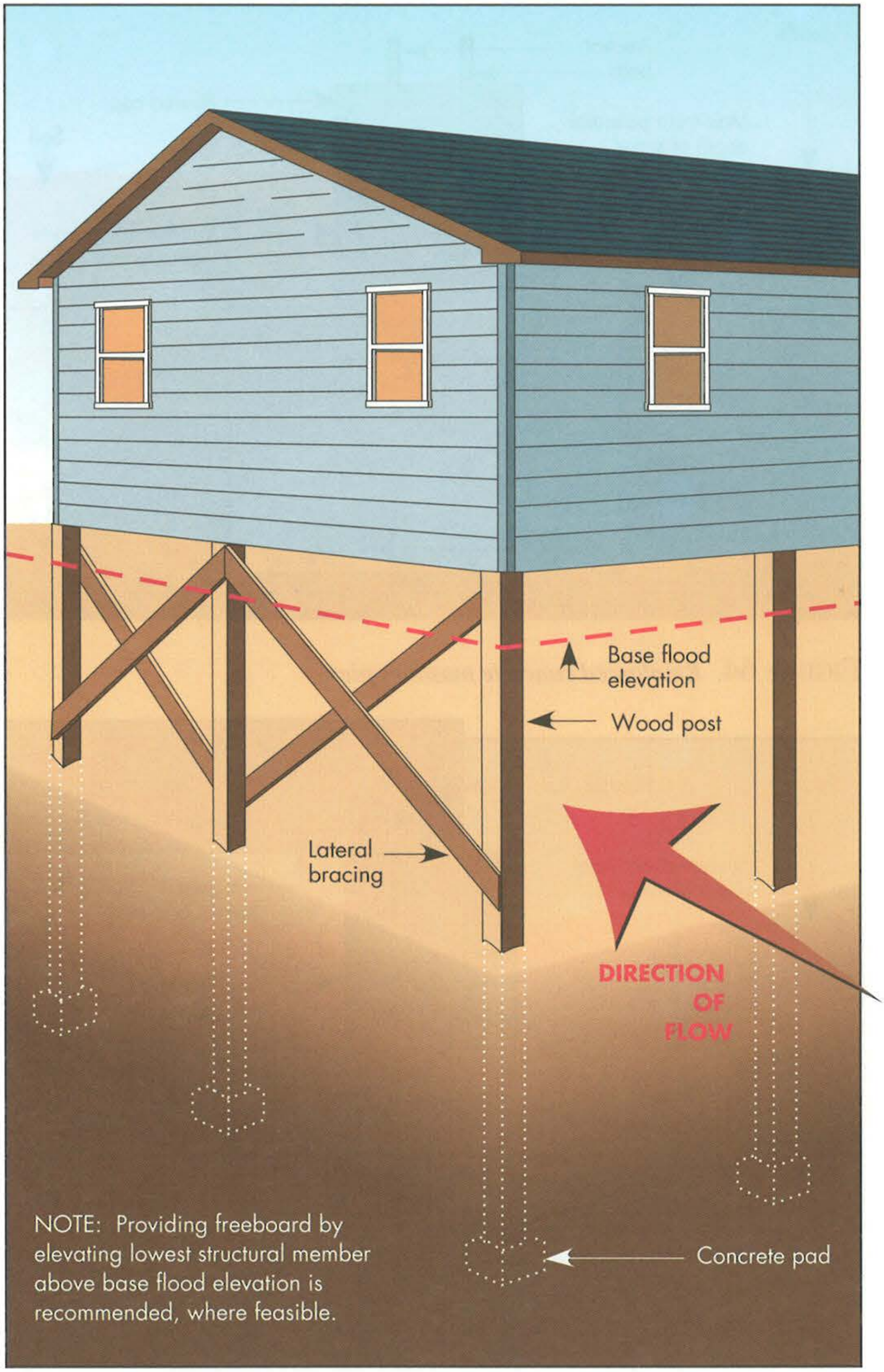


FIGURE 66. *Posts are placed into pre-dug holes and may be anchored in a concrete pad at the bottom of the hole. Lateral bracing should be oriented parallel to anticipated flow path.*

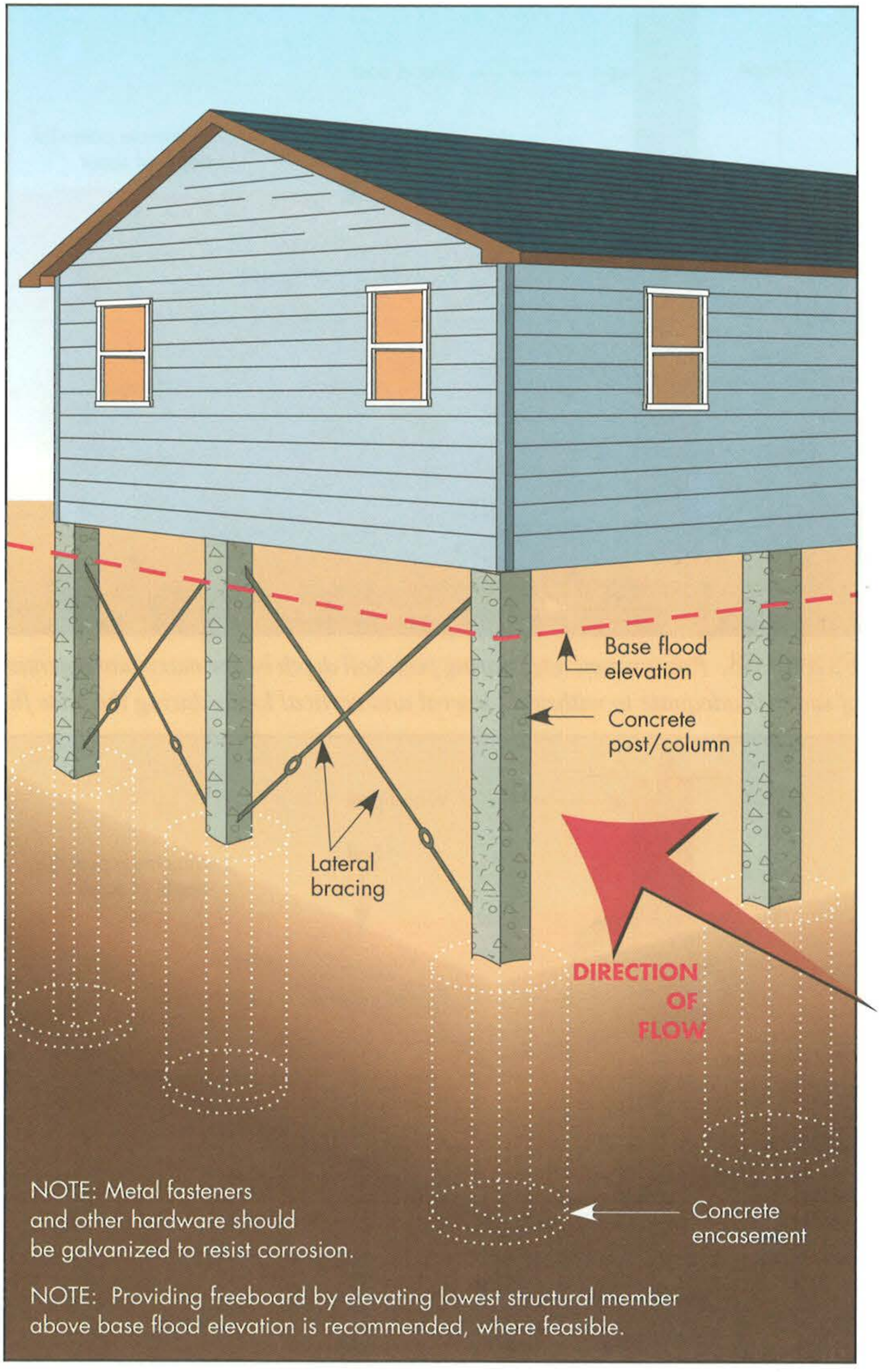


FIGURE 67. *Posts can also be anchored in concrete encasements.*

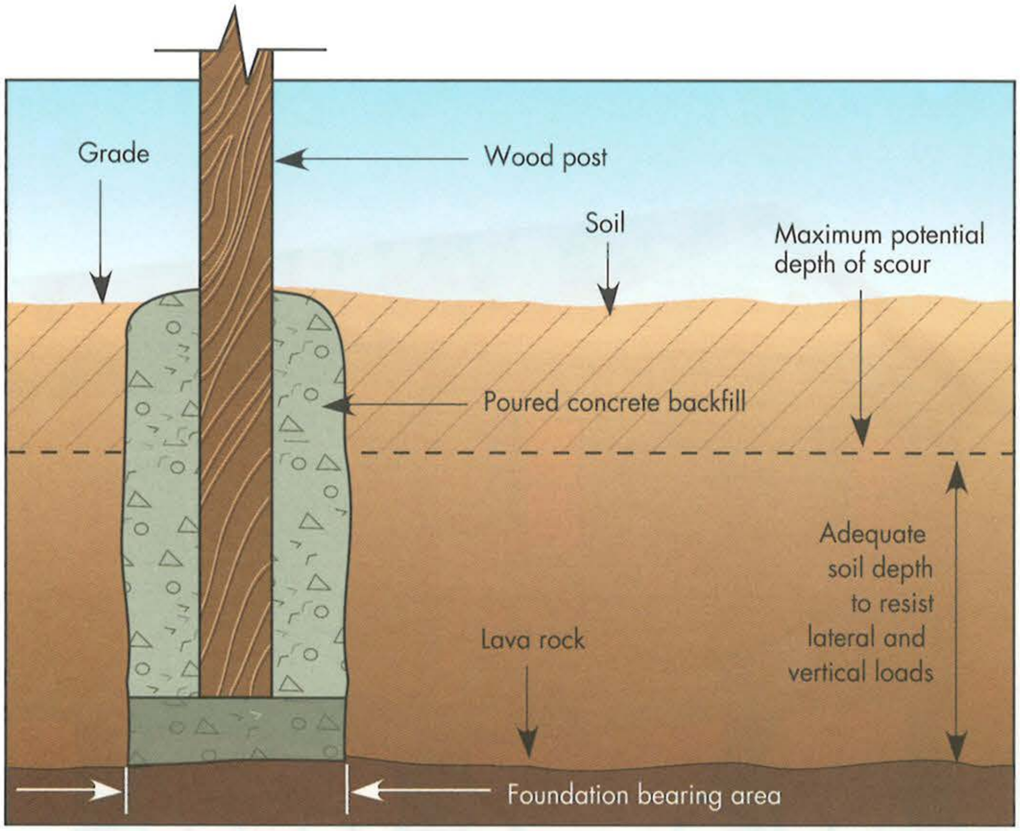


FIGURE 68. *Post on concrete bearing pad. Soil depth below maximum potential depth of scour is adequate to withstand lateral and vertical loads during the base flood.*

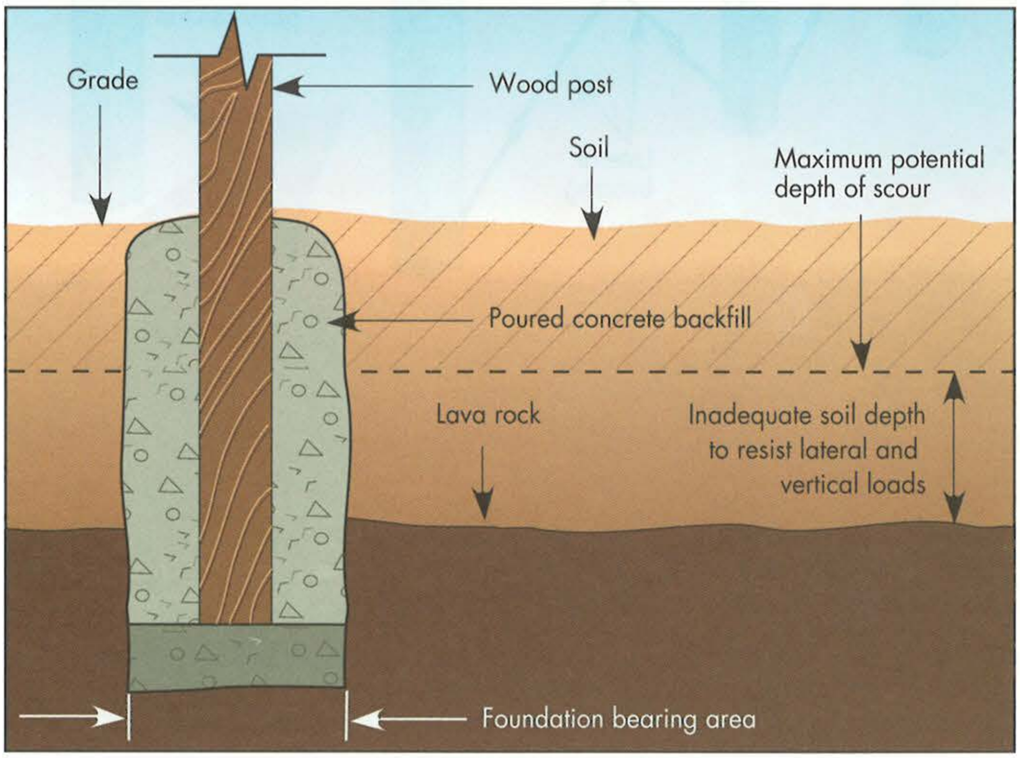


FIGURE 69. *Post on concrete bearing pad. Where soil depth below maximum potentail depth of scour is inadequate to withstand lateral and vertical loads during the base flood , bottom of concrete should be socketed into lava rock for increased load resistance.*

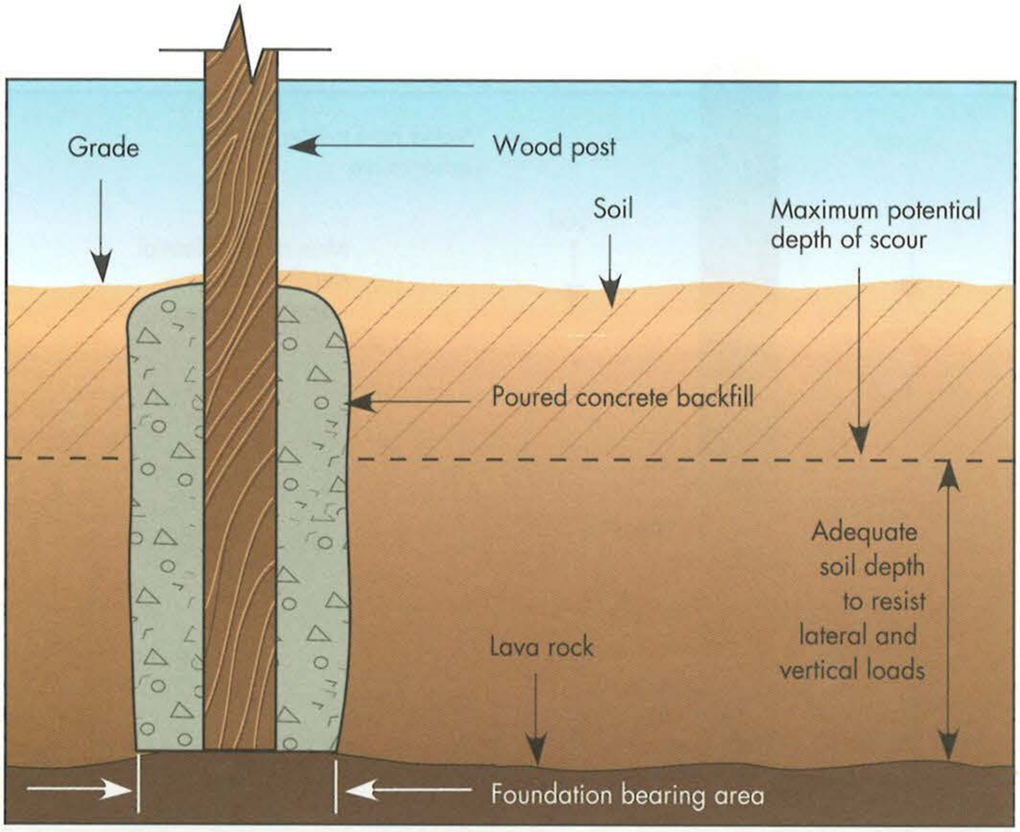


FIGURE 70. *Post in concrete backfill.*

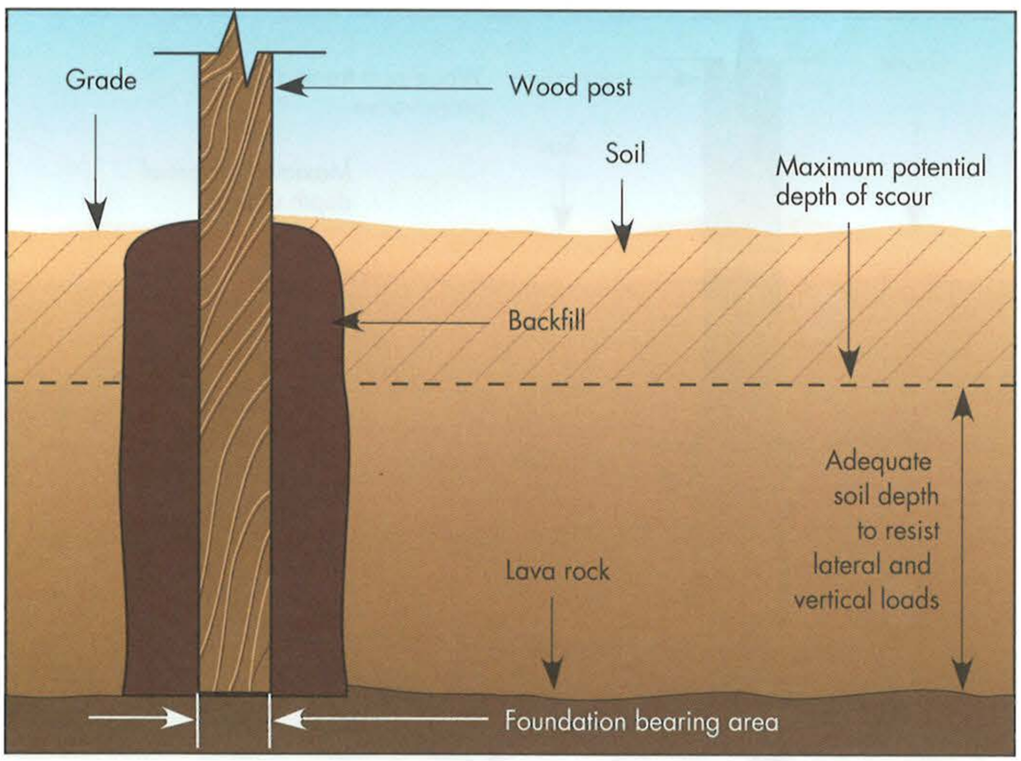


FIGURE 71. *Post on earth bearing.*

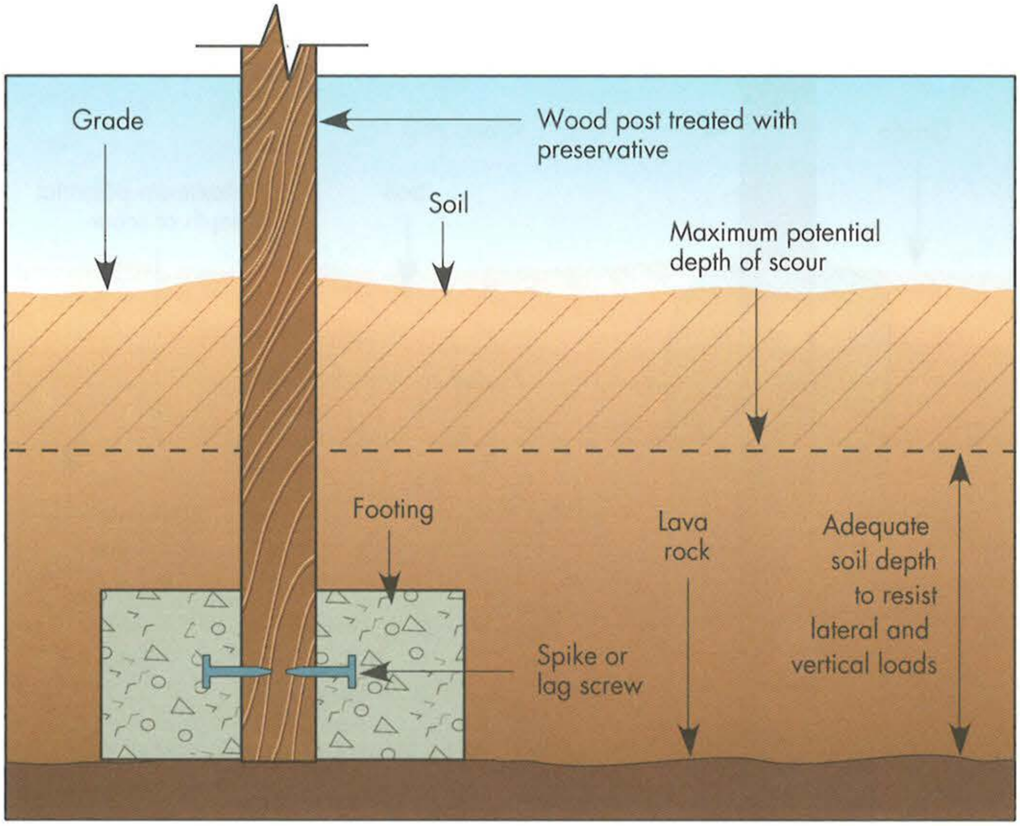


FIGURE 72. *Spike anchorage of post.*

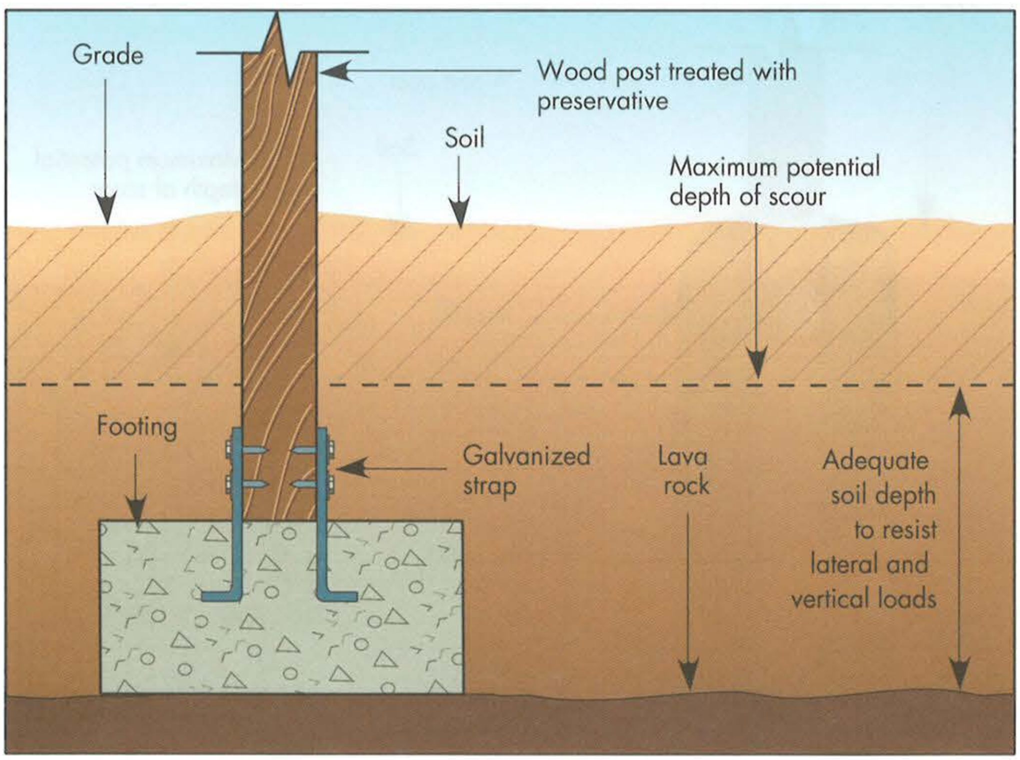


FIGURE 73. *Galvanized strap anchorage of post.*

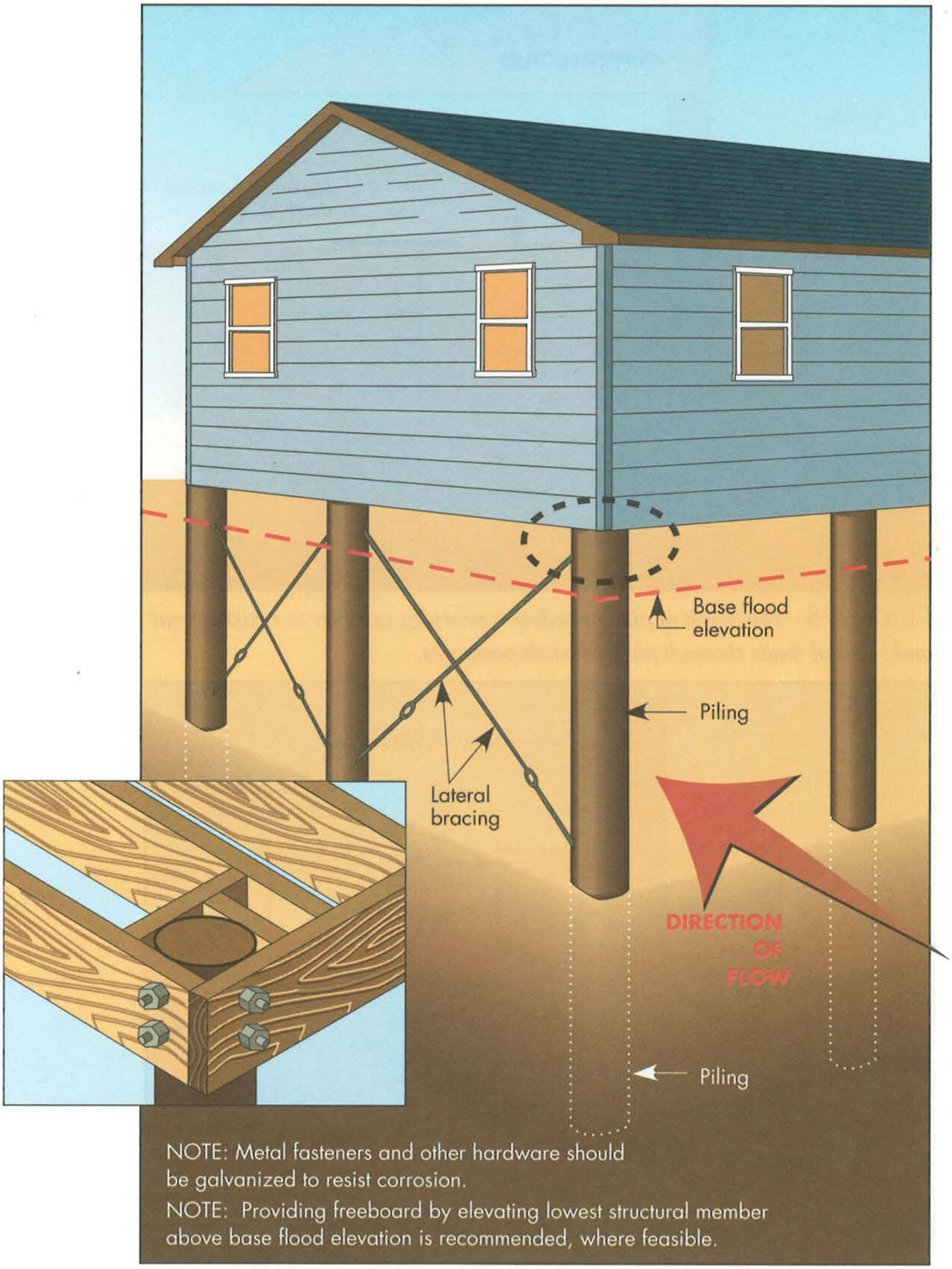


FIGURE 74. *Pilings are mechanically driven into the ground, making them less susceptible to velocity flooding, scour, and pullout.*

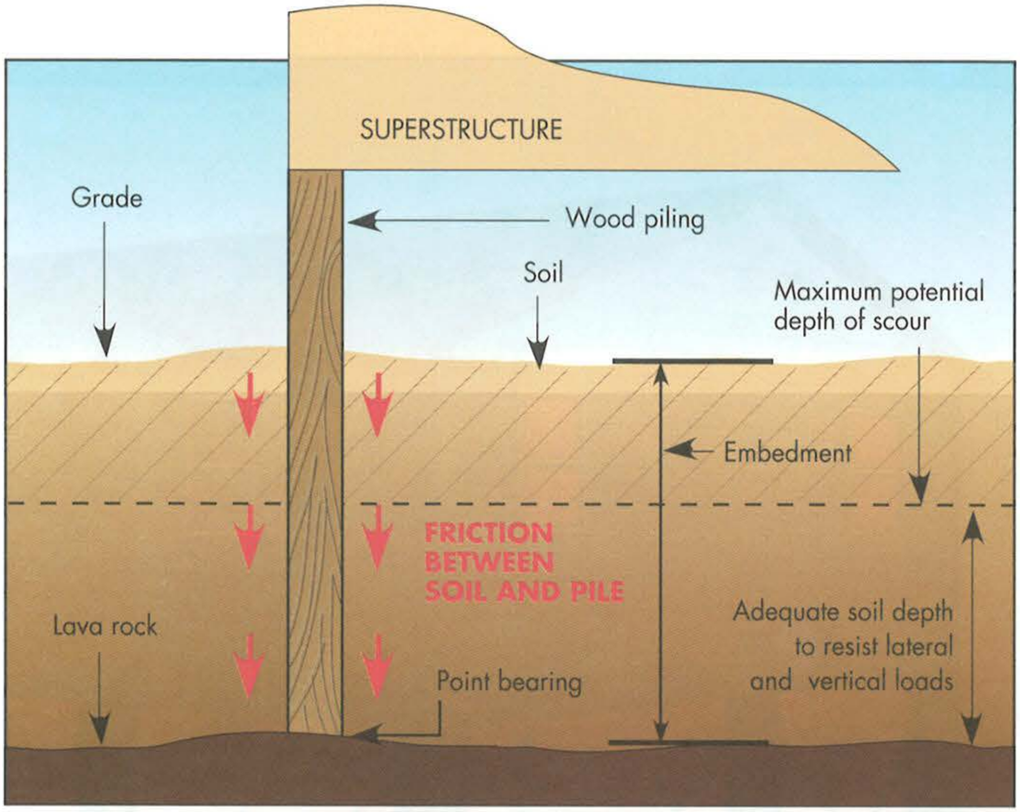


FIGURE 75. *The depth of pile embedment provides stability to resist lateral and vertical loads through passive earth pressures.*

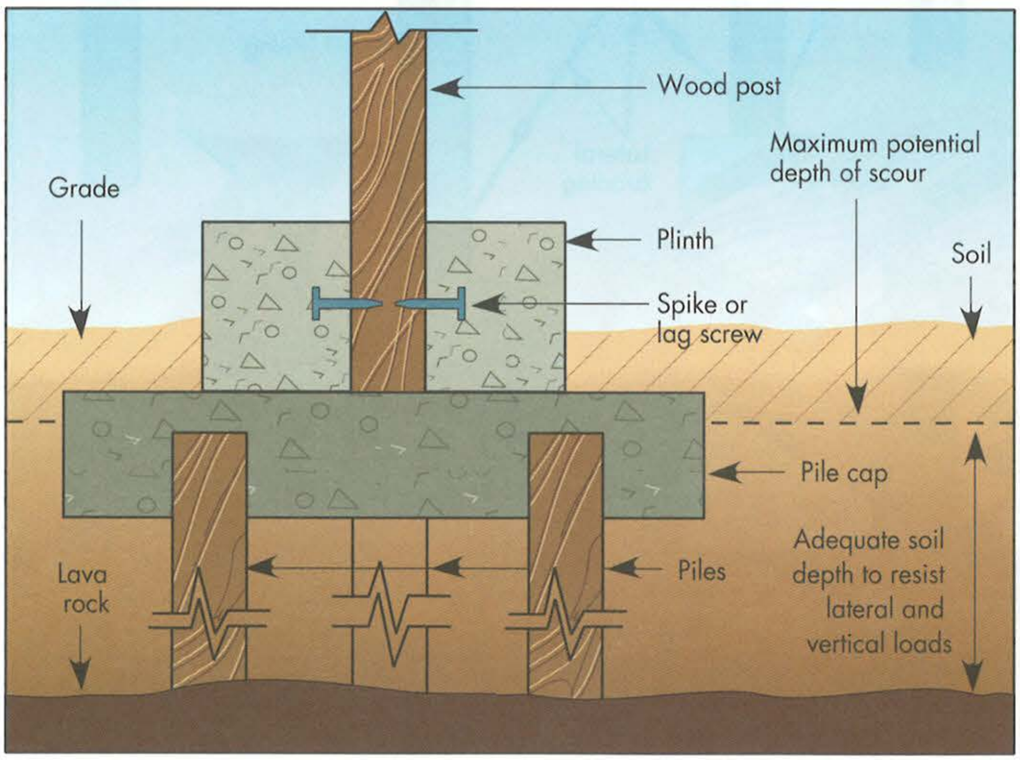


FIGURE 76. *Post/pile foundation.*

- In conjunction with NFIP requirements, future construction in areas subject to coastal flooding should be located as far back from the shoreline as is feasible or acceptable. This is based on the observed relationship between the distance a building was located from the shoreline and flood damage. The greater the distance, the less the damage due to dissipation of wave energy over the intervening area.

- FEMA and the State of Hawaii should provide technical assistance to Kauai County staff for administration of these NFIP requirements.

- FEMA, in cooperation with the State of Hawaii, Kauai County, and the local building industry, should sponsor a series of workshops in Kauai on floodplain requirements and prudent construction techniques in these hazardous areas. Such training and education will increase the knowledge base and awareness of business and homeowners, construction tradespeople, Engineers/Architects, supervisors, plan reviewers, and inspectors.

- The FIRM for Kauai County predicts flooding in coastal areas based on the threat of tsunamis. Along the south shore of Kauai, a hybrid system which also considers wave runup recorded from Hurricane Iwa (1982) is used to predict flood levels on the FIRM. However, in many areas along Poipu Beach, the flood elevations and penetration produced by Hurricane Iniki surpassed those designated on the FIRM. Therefore, in the short-term (1-3 years), Kauai County should consider adoption of a dual management approach for the design of floodplain construction in the Poipu Beach area. This pertains to new construction and the repair of substantially damaged buildings. The lowest floors of such buildings should be elevated to or above the flood elevations shown on the FIRM or those experienced during Hurricane Iniki, whichever are greater.

4.2 Wind Damage and Wood-Frame Construction

- The design and construction of properly engineered buildings, in compliance with the most current Code, which consider the continuous load transfer path from roof to foundation should be integrated at all levels and into all stages of the building process in Kauai County (Figures 77-80).

- Hurricane clips and straps, as key elements, must be used to help ensure the integrity of a structure's load path. Emphasis should be placed on the proper sizing, design, installation, and protective coating of these and other metal fasteners (Figures 74 and 81). (As noted previously, use of hurricane clips does not, in and of itself, ensure successful building performance).

- Emphasis should be placed on adhering to Code for nailing requirements in general, with special attention to roof and wall sheathing, top and bottom wall plates, and hurricane clips and metal fasteners.

- Additional structural ties at the ceiling line should be provided between large exterior walls and interior walls for large residential units to maintain integrity in the event of the loss of roofing.

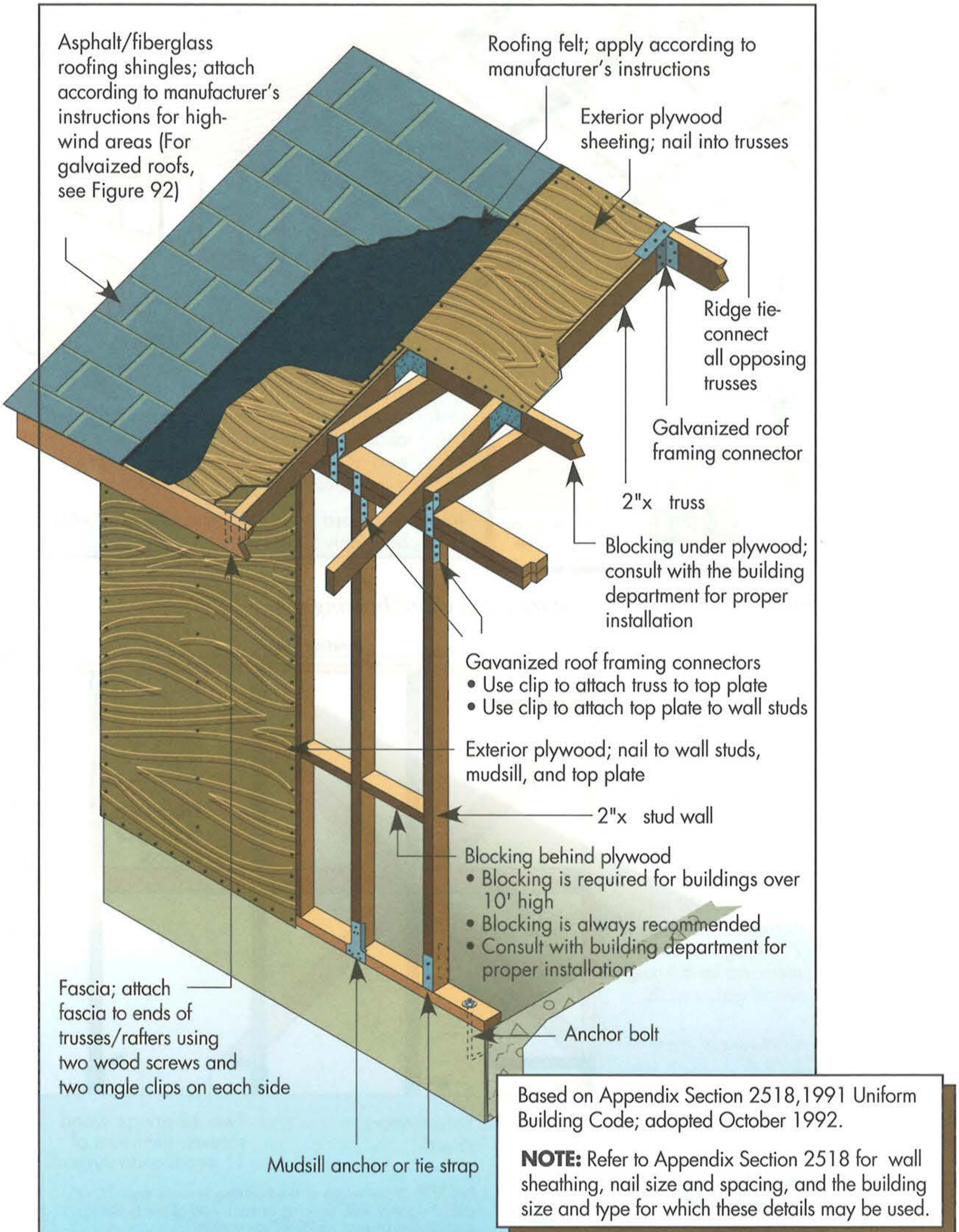


FIGURE 77. *Recommended wood-frame construction.*

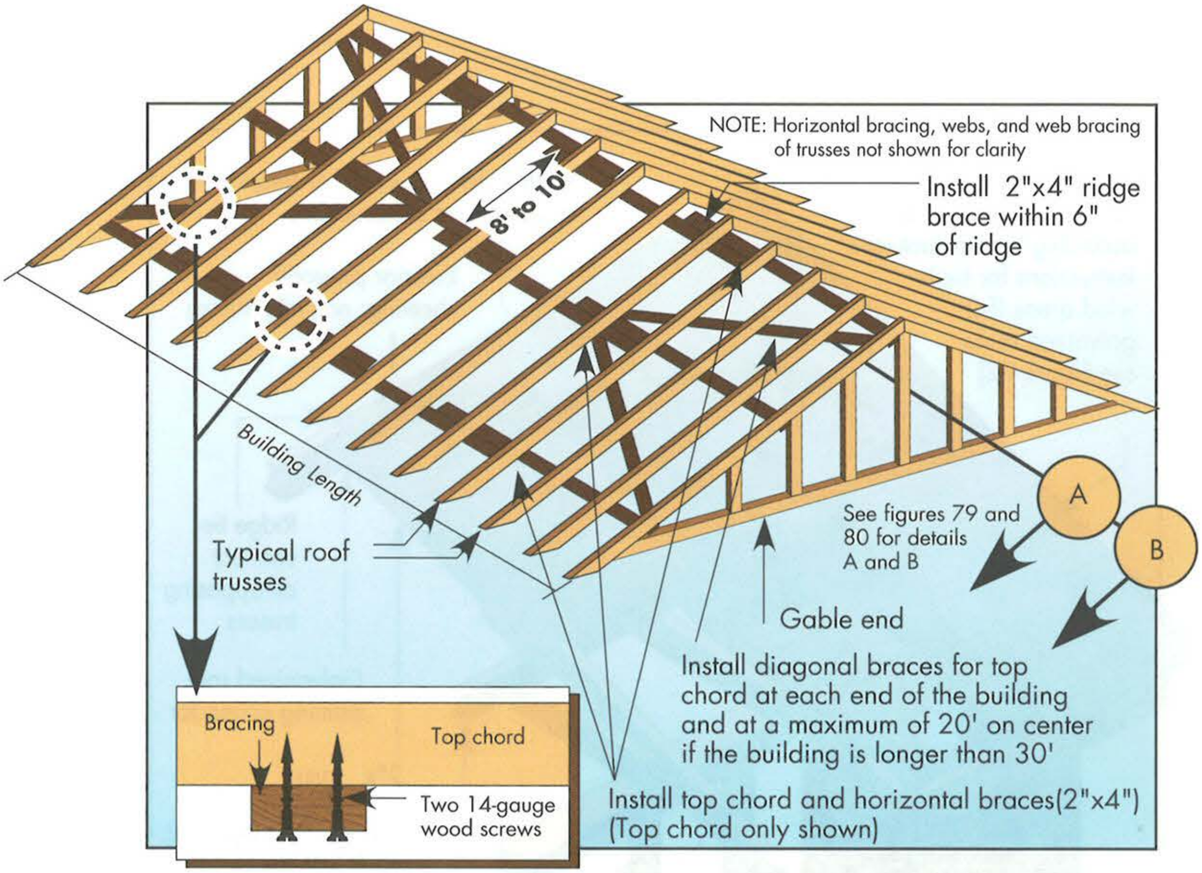


FIGURE 78. *Typical roof truss top chord bracing.*

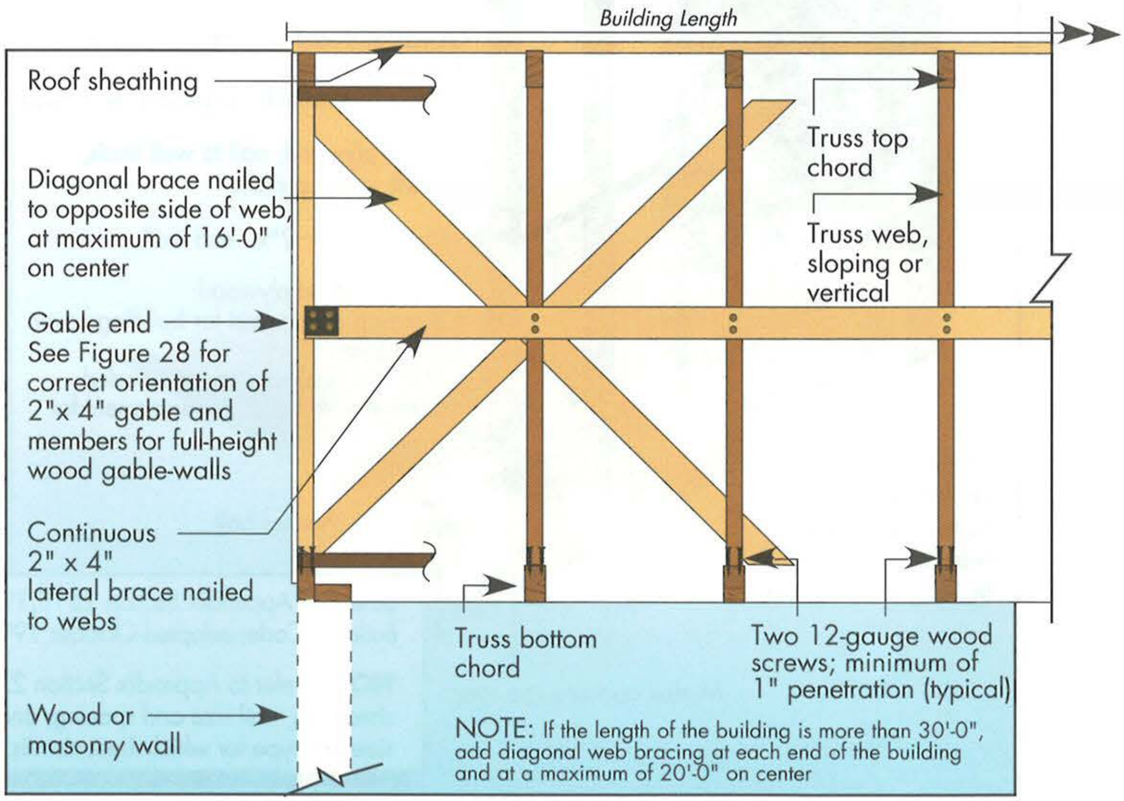
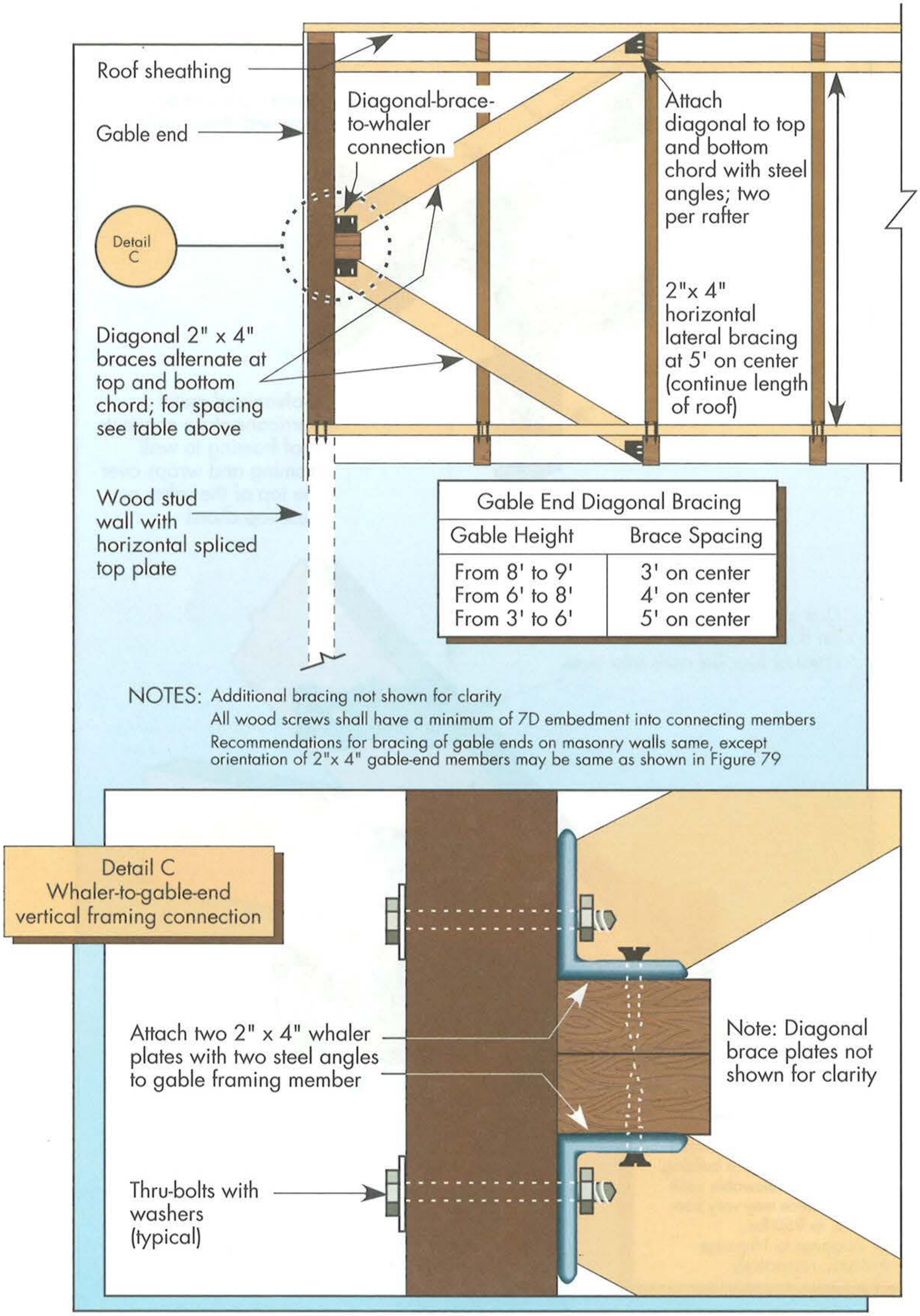


FIGURE 79. *Detail A– Typical web bracing.*



Gable End Diagonal Bracing	
Gable Height	Brace Spacing
From 8' to 9'	3' on center
From 6' to 8'	4' on center
From 3' to 6'	5' on center

NOTES: Additional bracing not shown for clarity
All wood screws shall have a minimum of 7D embedment into connecting members
Recommendations for bracing of gable ends on masonry walls same, except orientation of 2"x 4" gable-end members may be same as shown in Figure 79

FIGURE 80. *Detail B– Typical wood gable-wall bracing with nailed connections.*

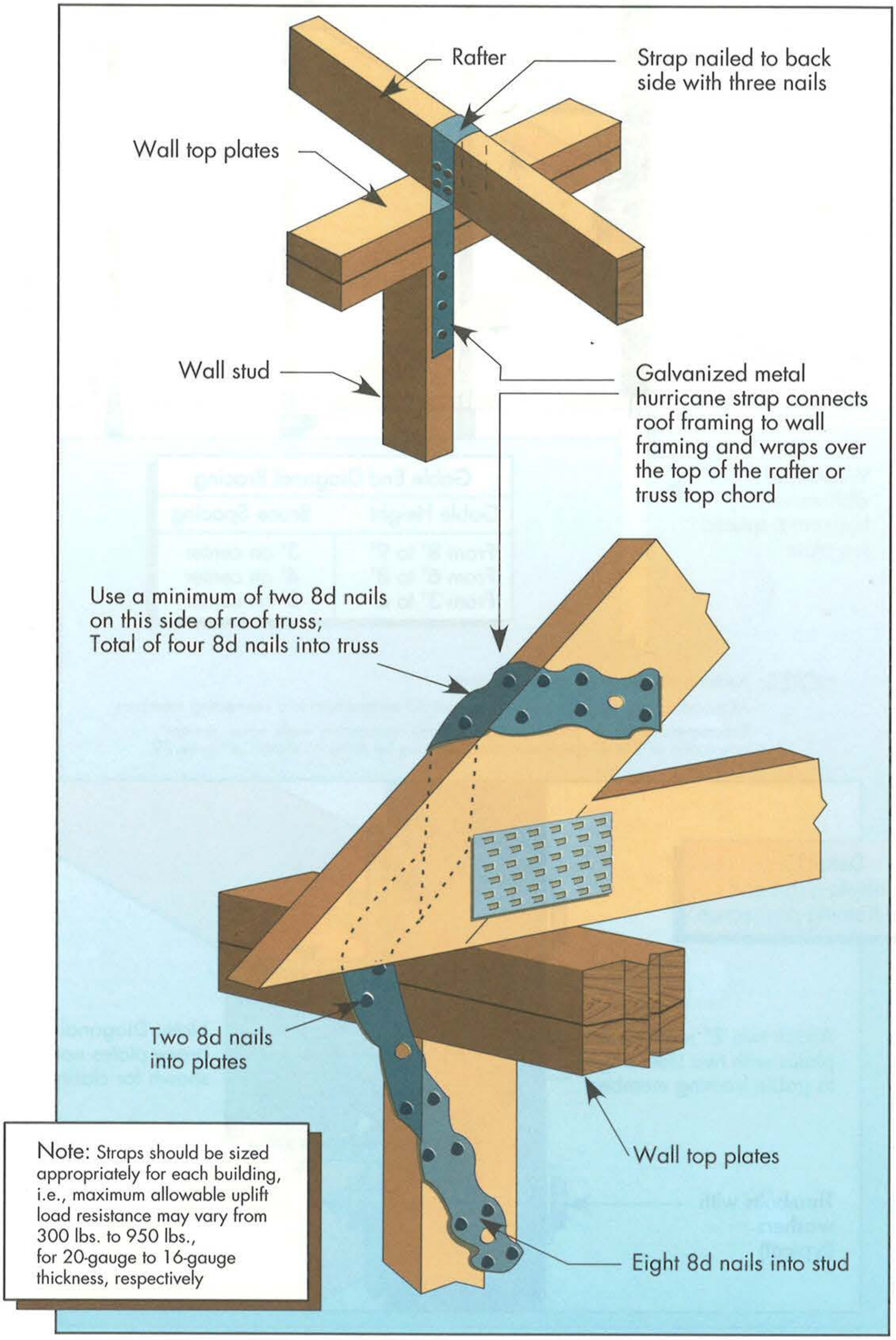


FIGURE 81. *Typical hurricane strap to roof framing detail. Rafter or prefabricated roof truss.*

- The design of more aerodynamic building shapes should be encouraged, where feasible. Substituting low-angled hip roofs for steep angled, gabled-end, and clearstory roofs, and other such designs would be particularly advantageous (FIGURES 82 and 83).

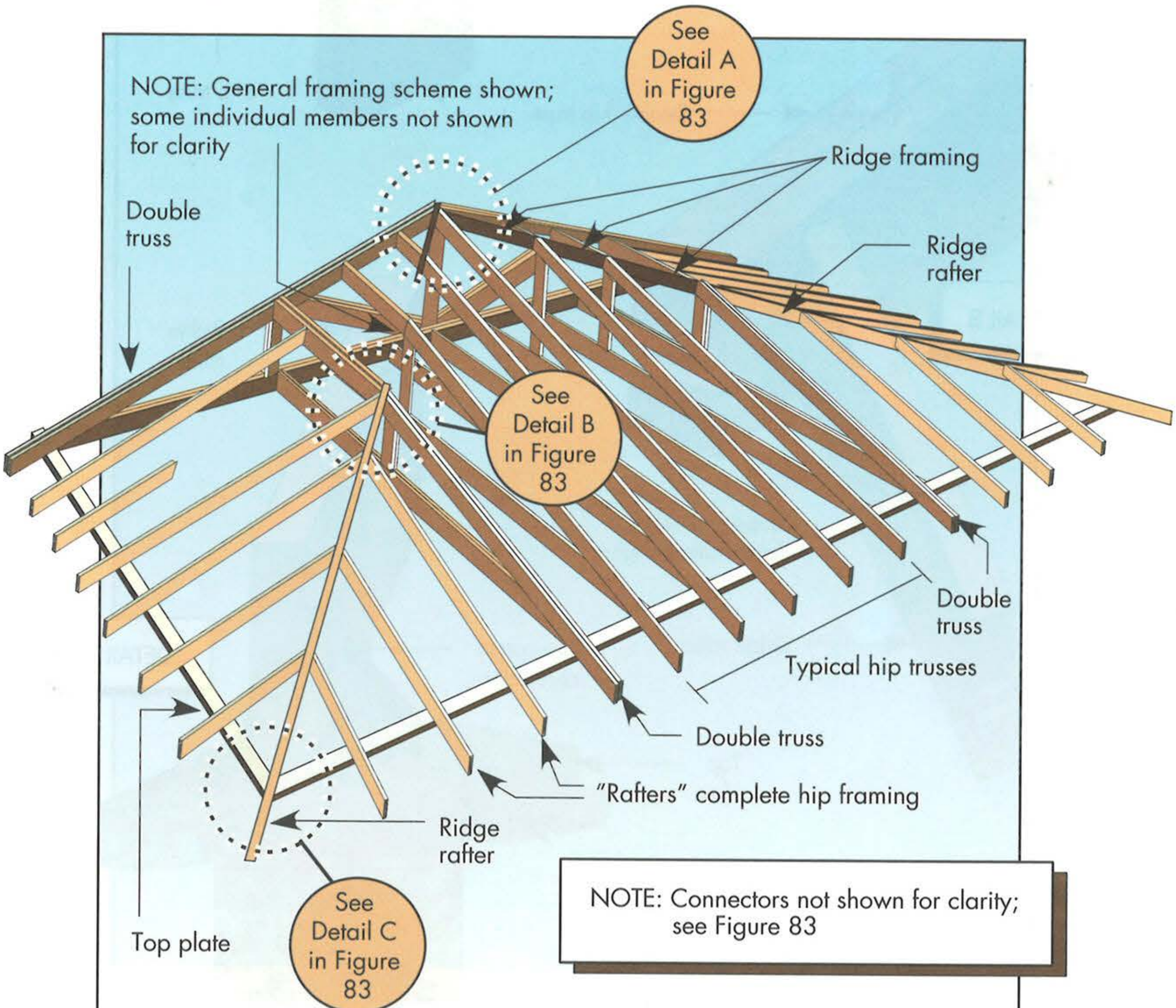


FIGURE 82. *Recommended hip roof framing.*

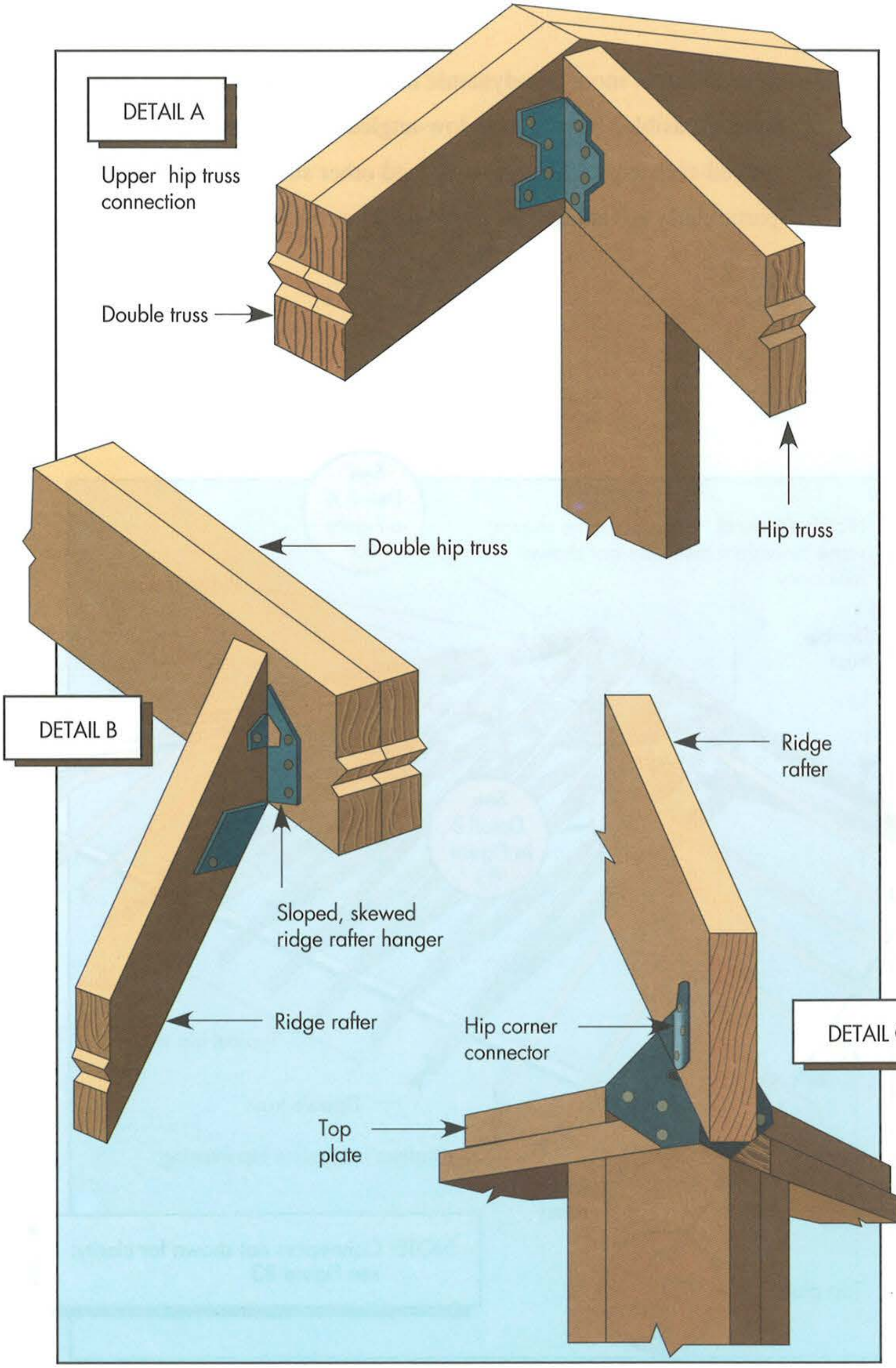


FIGURE 83. *Hip roof framing connectors.*

- Large roof overhangs should be reviewed closely. Uplift-resistant connections for large overhangs should be engineered.

- Requirements for tiedown straps for widely spaced roof framing members and corresponding wall-to-foundation connections should be defined.

- Conventional construction Code requirements appear to take into consideration lateral forces such as wind and seismic loading; however, special consideration must be given to construction in areas where wind speed is amplified or areas of great exposure due to extreme topography (FIGURES 84-87).

- Adoption of the 1991 UBC Appendix Section 2518 should be permanent. Appendix Section 2518 addresses previous Code deficiencies which relied on implicit provisions in the 1985 UBC. Appendix Section 2518 is very explicit in its requirements and contains graphical representations not previously contained in older versions of the Code.

SOURCE: Structural Engineers Association of Hawaii, *Tips on Improving Wind Resistance for One Story Single Family Dwelling Repairs on Kauai*, October, 1992.

GENERAL:

1. All work shall conform to the building code of the County of Kauai.
2. There are many different types of construction and details for existing single-family dwellings. The information and drawings presented are for general informational purposes only to illustrate the concept of the complete load path to resist high winds. The drawings are not complete design details or drawings and shall not be used as such. The information and details provided shall not be used or relied upon for any specific application without independent professional examination and verification of their accuracy, suitability, and applicability.
3. The details are based on the following types of construction:
   A. Repair work only (not new construction)

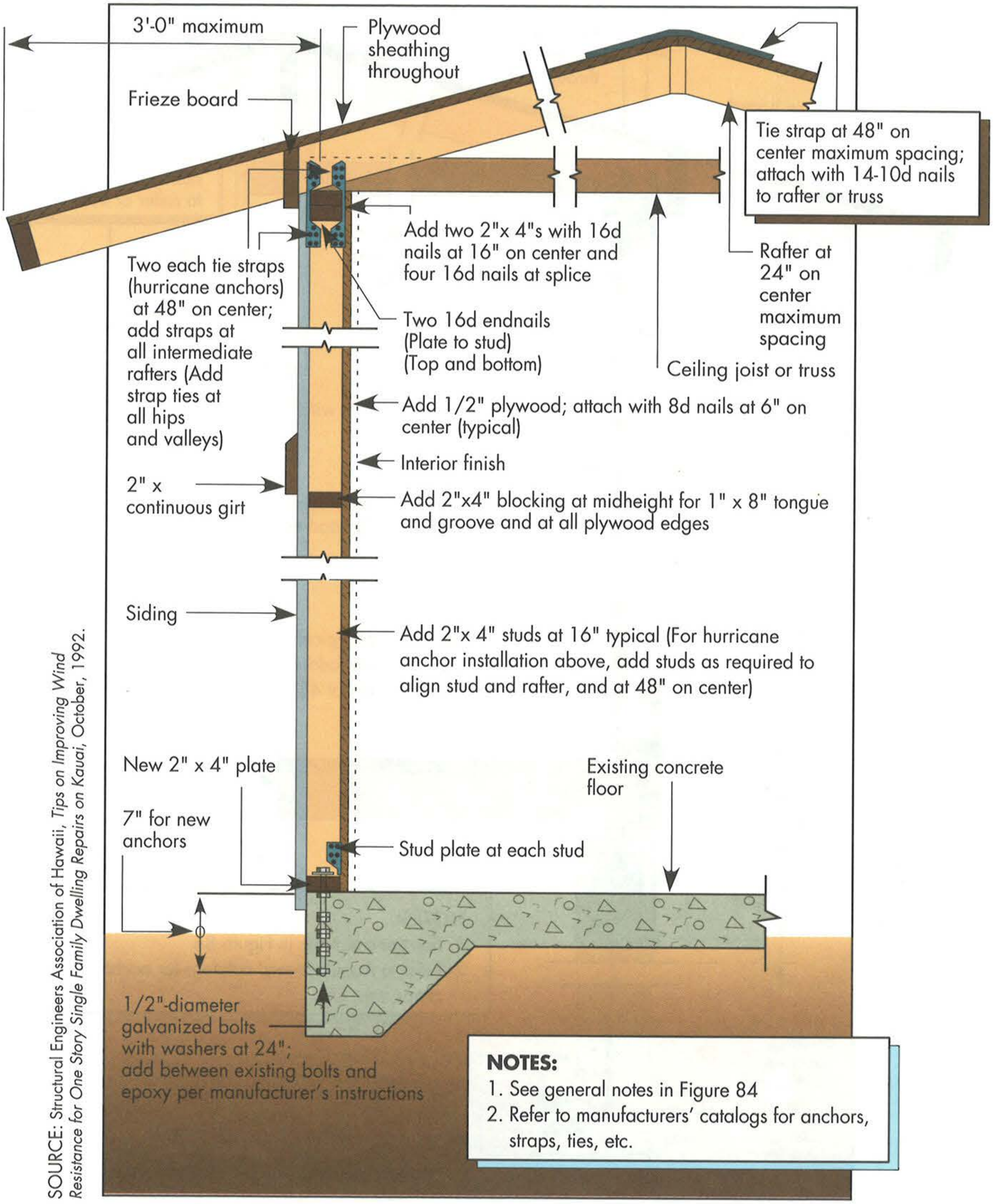
   B. Single-story, single-family dwelling, with floor-to-ceiling height of approximately 8 feet

   C. Regular-shaped buildings with floor area of approximately 1,200 square feet, constructed on stable ground

MATERIALS:

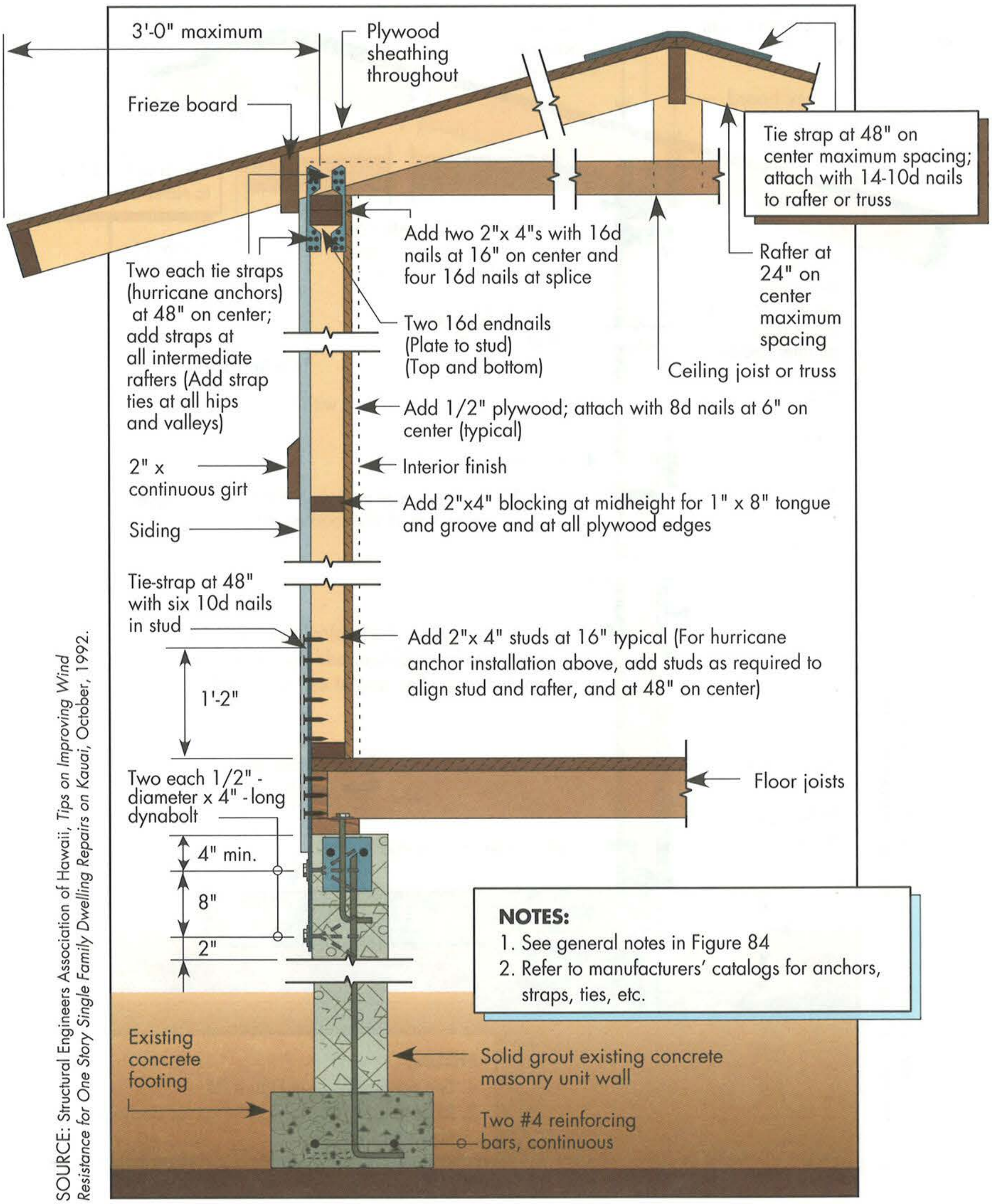
1. Lumber: Douglas Fir/Larch, preservative treated, S4S, No. 2 Grade or better.
2. Unless noted otherwise, all nailing shall be galvanized common nails and shall conform to Table 25-Q of the 1985 Uniform Building Code.
3. Framing hardware: Galvanized and of adequate strength.
4. Framing, finish, and trim shall be notched for hardware as required to provide snug fit at all joints.
5. Trim and finish details are not shown on framing details and sections.

FIGURE 84. *General notes for Figures 85-87.*



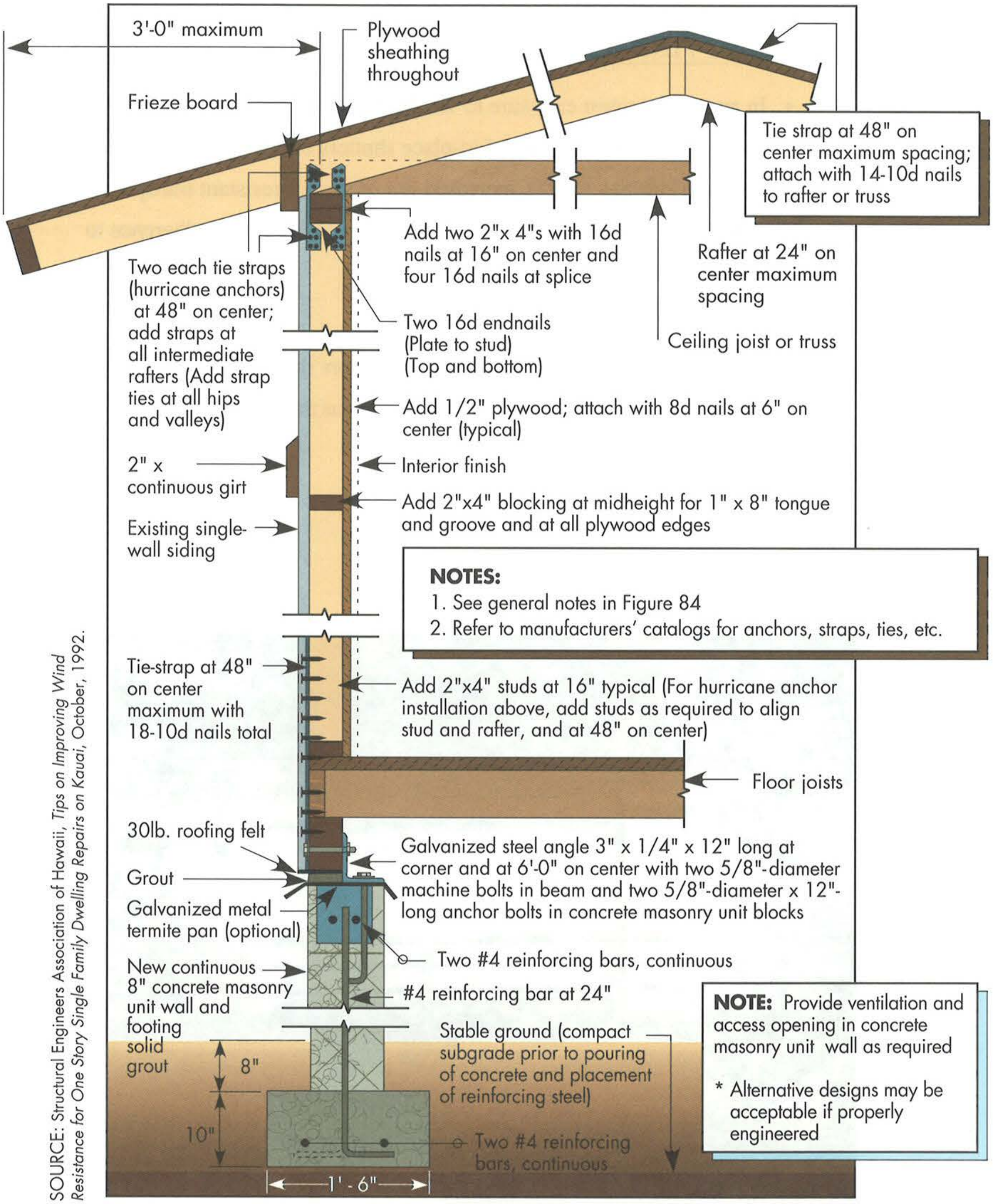
SOURCE: Structural Engineers Association of Hawaii, *Tips on Improving Wind Resistance for One Story Single Family Dwelling Repairs on Kauai*, October, 1992.

FIGURE 85. *Existing "single wall" on slab-on-grade.*



SOURCE: Structural Engineers Association of Hawaii, *Tips on Improving Wind Resistance for One Story Single Family Dwelling Repairs on Kauai*, October, 1992.

FIGURE 86. *Existing "single wall" on existing concrete masonry unit wall.*



SOURCE: Structural Engineers Association of Hawaii, *Tips on Improving Wind Resistance for One Story Single Family Dwelling Repairs on Kauai*, October, 1992.

FIGURE 87. *Existing "single wall" on new concrete masonry unit wall and footing.*

4.3 Glazing And Transparent Structural Openings

- In areas of greatest exposure to windborne projectiles, consideration should be given to the use of in-place shutters or emergency protection devices (FIGURES 88-91), increased use of shatter-resistant transparent material, a reduction in the use of glazing, and improved adherence to adequate attachment procedures.

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

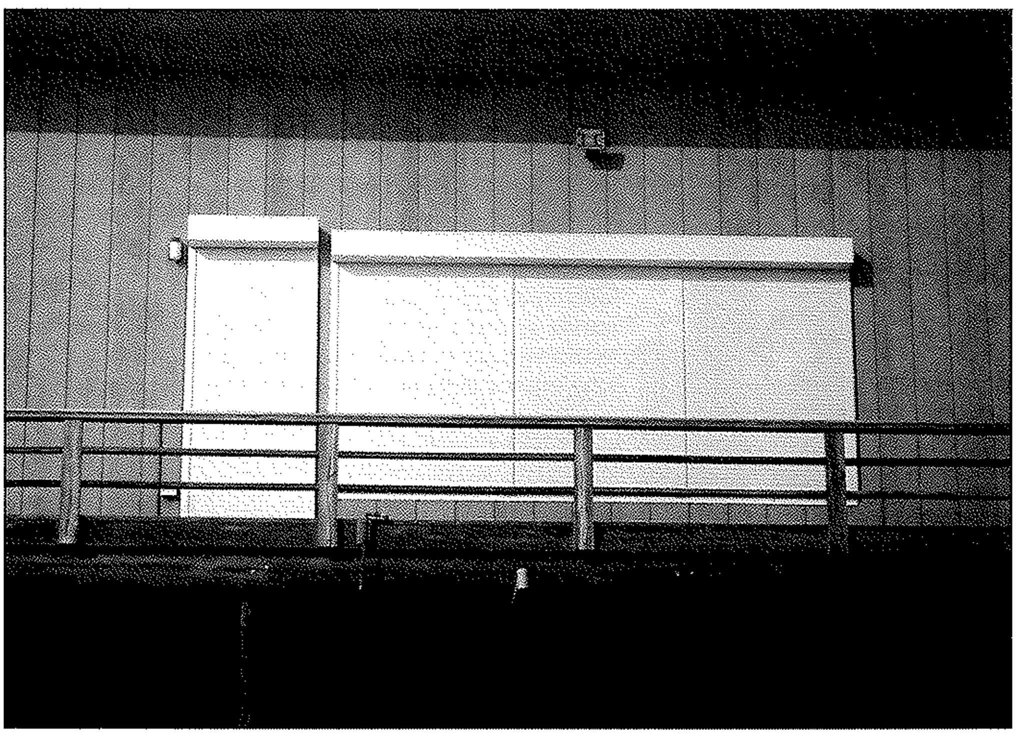


FIGURE 88. *Prefabricated storm shutters.*

FIGURE 89. *Previously purchased plywood stored for use as openings protection during storm conditions.*

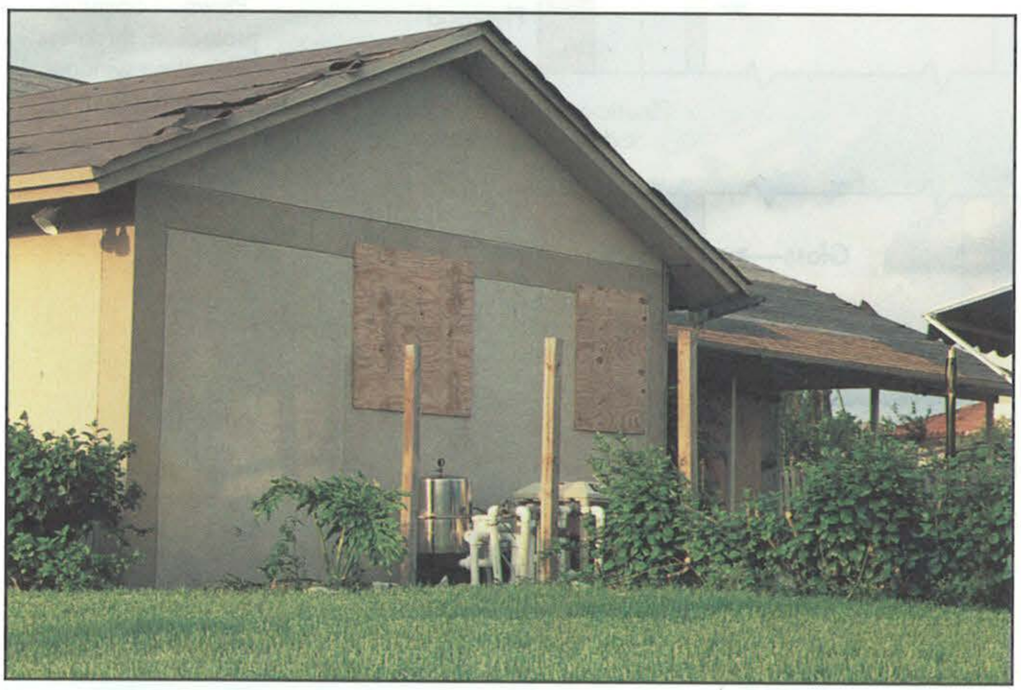


FIGURE 90. *Plywood used as openings protection installed. See Figure 91 for details.*

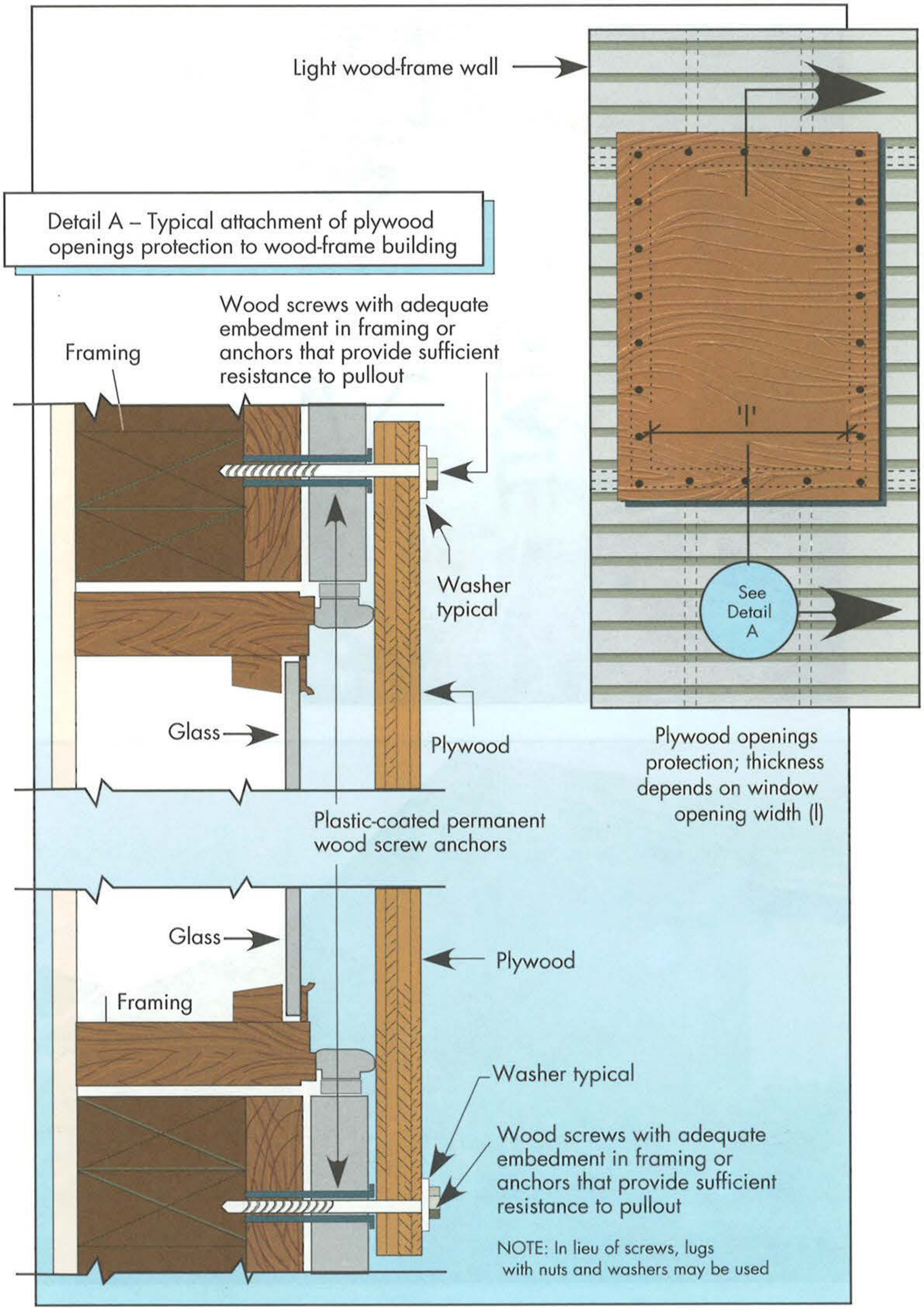


FIGURE 91. *Typical installation of plywood openings protection for wood-frame building.*

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

4.4 Roofing

- Recognized procedures for testing roofing for resistance to wind (across the surface of the roofing) need to be developed.

- Roofing materials should be installed according to the latest manufacturer's recommendations (Figure 92).

- Roofing suppliers, manufacturers and associations should educate specifiers and installers concerning the proper installation requirements and techniques.

- A program of periodic roof cladding inspection during installation should be adopted where such a program would not be cost-prohibitive.

4.5 Building Permitting, Plan Review And Inspection

- Consistency of quality construction workmanship should be encouraged. Properly engineered construction drawings that are more prescriptive and detailed should be provided, and the depth of construction inspection should be increased, especially for tracts of homes of repetitive design.

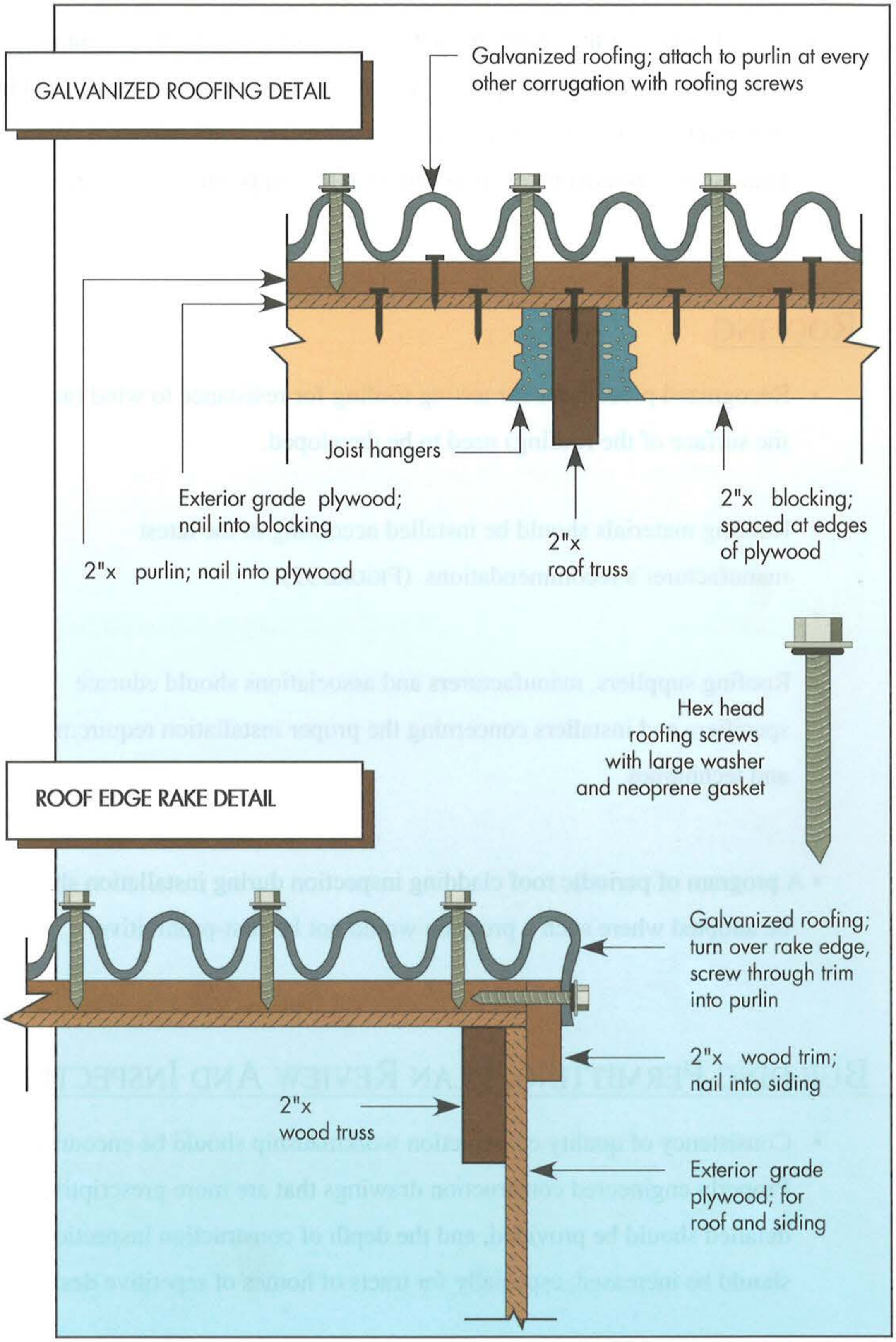


FIGURE 92. *Tips for galvanized roofing.*

- Kauai County should retain a person qualified in structures on staff to assist in examining the adequacy of construction plans. This in-house expertise will allow for greater indepth County review of design and construction inspection. Responsibilities should include a program of systematic wall and roof framing and roof sheathing inspections.

- Permit drawings for construction should include details and a narrative statement that explains the building system's transfer of forces, especially between the roof and wall systems, and the wall system and foundation. These permit drawings should include a checklist which verifies that the necessary continuous load transfer path has been provided.

- Implementation of UBC Section 306, Special Inspection, requirements for large multi-family, commercial, and resort projects should be considered.

4.6 Training And Education

- The State and Kauai County governments and the local building industry, in cooperation with FEMA, should sponsor a program of training and continuous education in Kauai on Code requirements and construction techniques. In addition to structural design, these programs should cover roof sheathing, proper attachment of roof cladding, prevention of wood and metal deterioration, and the design and prudent use of glazing and transparent structural openings. Such training and education will increase the knowledge and awareness of business and homeowners, construction tradespeople, Architects/Engineers, supervisors, plan reviewers, and inspectors.

- Considerable effort should be given to teaching building contractors, and especially home owners, the proper attachment of corrugated metal roofs to the underlying rafters and purlins.

- A program should be established to gain the fullest participation of the citizens of Kauai County in the building development process and to ensure their awareness of the need to maintain critical building components.

- A program should be established to educate sub-professionals who prepare plans to comply with current Code provisions. Review of these plans by qualified professionals should be encouraged.

4.7 Repair/Retrofit Of Partially Damaged And Undamaged Buildings

- During the Hurricane Iniki rebuilding period, Kauai County should explore all available resources for expanding the pool of qualified building inspectors.

- Although some buildings suffered irreparable damage, most buildings are repairable, and repairs should be carried out with attention to the recommendations made in this report.

- Retrofitting of undamaged buildings should be strongly encouraged so that wind damages to buildings constructed under the previous Code are minimized.

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Appendix A

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