RESIDENTIAL BUILDING DESIGN:
Comprehensive Comparative Guidelines for Building Single-Family Dwellings in Hawaii

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This work is dedicated to my parents and family for their constant encouragement and support.

RESIDENTIAL BUILDING DESIGN:

COMPREHENSIVE COMPARATIVE GUIDELINES FOR BUILDING SINGLE-FAMILY DWELLINGS IN HAWAII

by: Rochelle Morie Nagata
Submitted to the Department of Architecture on May 9, 1997 in partial fulfillment of the requirements for the Degree of
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ABSTRACT

Energy shortages, earthquakes, and hurricanes are environmental factors that challenge the home designers of Hawaii. The depletion of renewable natural resources and global warming trends foreshadow energy shortage and the increases of hurricane frequency. Thus, it is essential that future homes in Hawaii be energy efficient, earthquake resistant, and hurricane resistant.

Energy efficient and climate responsive designs are important for the economic and environmental future of Hawaii. Solar protection, daylighting, solar energy, and natural ventilation are design strategies that can promote energy efficient design. This thesis addresses energy efficient strategies that can be applied to site planning, building orientation, building form, roof design, wall design, and foundation design.

In addition to energy efficiency, homes in Hawaii must also provide protection from natural disasters. In the past, earthquakes and hurricanes have caused much destruction to Hawaii's homes, yet only within recent years have these damages been documented and analyzed. The building performance and structural assessment disasters has provided useful information on the survivability of certain structure types. This thesis identifies these structures and proposes suggestive strategies to increase the strength and integrity of homes. Hazard resistance strategies that can be applied to site planning, building orientation, building form, roof design, wall design, and foundation design are addressed. The Islands' climate and location also fosters termite infestation and salt corrosion. Design strategies to reduce damage from these problems are also presented.

This thesis investigates energy, earthquake, and hurricane design approaches and their application to residential buildings in Hawaii. It establishes the need for each approach through the identification of problems with existing homes. Design strategies and specific recommendations for building components are presented for each approach. This thesis combines these three essential design approaches and proposes an integrated design approach to designing single-family wood-framed dwellings appropriate for Hawaii's climate. It presents comprehensive comparative guidelines for Hawaii's homes.

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INTRODUCTION

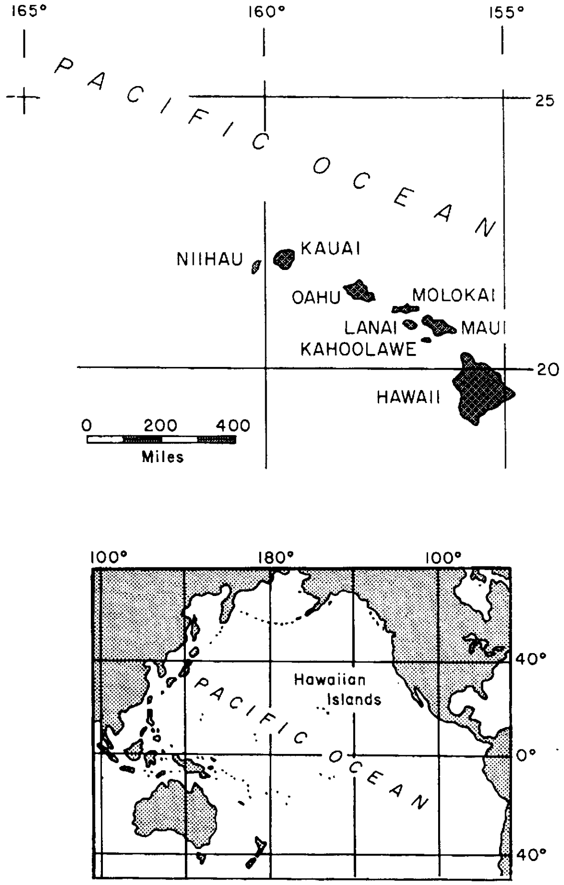
1.0 INTRODUCTION

The people of Hawaii rely on their homes to provide shelter, security and comfortable living condiitions. Homes must meet these occupant demands as well be sensitive to the surrounding environment. The climate, hazards, and history of each home's building site are factors that need to be considered in the development of an apropriate home design.

1.1 ENVIRONMENT OF HAWAII

Hawaii's location in the middle of the Pacific Ocean has a major influence upon its climate and its exposure to natural hazards. Due to its proximity to the equator, Hawaii has a mild tropical climate throughout the majority of the year. Its lattitude, the surrounding ocean, and trade winds combine to produce pleasant weather conditions with little seasonal variations and minimal temperature fluctuations throughout the day and year.

The islands' volcanic origins and its location in the warm waters of the Pacific Ocean also make Hawaii particularly susceptible to both earthquakes and hurricanes. Although these disasters are recognized threats to the people and buildings of Hawaii, only recently has the destruction caused by these natural disasters been documented and analyzed.



The Hawaiian Island chain lies isolated in the middle of the Pacific Ocean where it is vulnerable to earthquakes, tsunamis, and hurricanes (Gordon A. Macdonald & Agatin 4).

1.2 HISTORY OF THE HAWAIIAN HOME

The residential buildings in Hawaii have been designed with little consideration to the climate of Hawaii or the threat from natural disasters. Instead, the history of the islands has played a greater role in influencing residential design in Hawaii. The history of Hawaii accounts for the diversity of housing styles throughout the islands. People from all types of ethnic backgrounds immigrated to Hawaii and brought their own styles of building to the islands. House design and construction was based on each culture's aesthetic preferences and building experience. Over the years, house types of various forms and materials have been introduced to Hawaii. Hawaiian houses have been versions of architecture adopted from other regions and cultures of the world. Although these building types were aesthetically pleasing to their owners, they often resulted in building forms and details that were simply unsuitable for Hawaii.

When the ancient Hawaiians first settled on the Hawaiian Islands, they had to utilize indigenous materials and crude tools to construct shelters. They constructed grass huts, known as "hale," which were built by hand and used stones, branches, and grass. "Hale" were used for storage, security and shelter. Because of Hawaii's warm and mild climate, the need for buildings to provide climatic protection was minimal. The early Hawaiians spent most of their time living outdoors, only seeking shelter during bad weather. Grass thatched walls allowed ventilation, while providing protection from the rain.

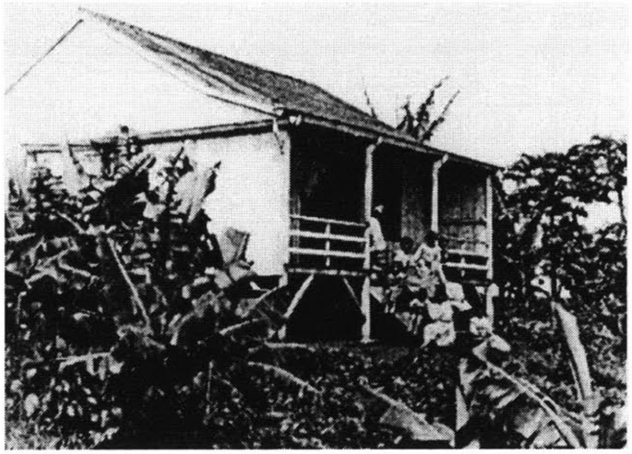
Top: Early Hawaiian grass huts were used for storage, security and shelter. Bottom: Misssionary "New England style" homes were unsuited for the Hawaiian climate (Jim Pearson 5).

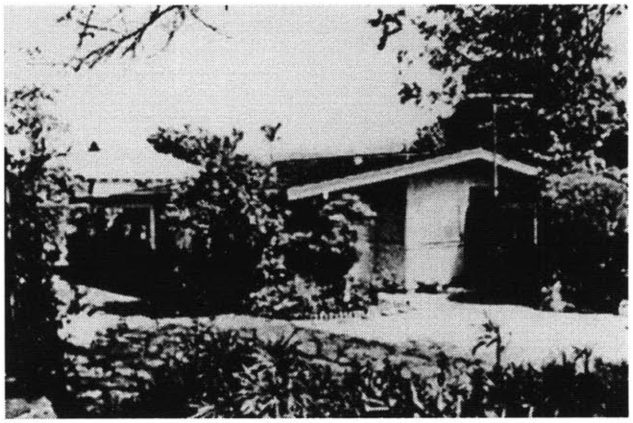
INTRODUCTION: HISTORY OF THE HAWAIIAN HOME

Shortly after the island's discovery by Captain James Cook in 1778, missionaries arrived, bringing "New England style" homes with them. New building types were imported to house the missionaries who regarded the "hale" as an inappropriate residence. These new homes had littleof the climatic or structural requirements of homes appropriate for Hawaii. They proved to be unsuited to the Hawaiian climate because of their poor ventilation and lack of solar control.

The warm climate and rich soil in Hawaii favored a variety of marketable crops and resulted in the establishment of large corporations and trading companies during the 1800's. Pineapples, coffee, and sugar plantations were developed throughout the islands. As the sugar plantation industry in Hawaii thrived, people from China, Portugal, Japan, Puerto Rico, Korea, and the Philippines immigrated to Hawaii in hope of better lives. Plantation workers brought with them their own building designs. The Japanese built thatched roof houses with gabled roofs and porches with large overhangs. These homes were better suited for the climate of Hawaii than the "New England style" homes, as they allowed for natural ventilation while providing protection from the rain and sun.

The "Plantation style"home evolved over the years and became more appropriate for the Hawaiian climate. Single-wall construction, raised floors, gabled roofs, and porches were typical of features of "plantation style" homes. Plantation homes were raised





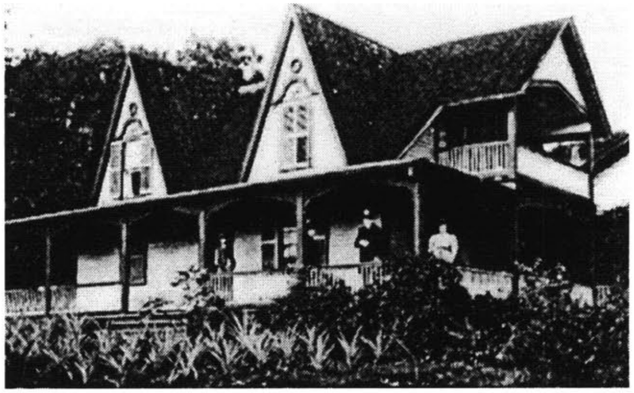
Top: Early single-wall "plantation style" home. Bottom: Modern day lower cost single-wall home (Jim Pearson 7).

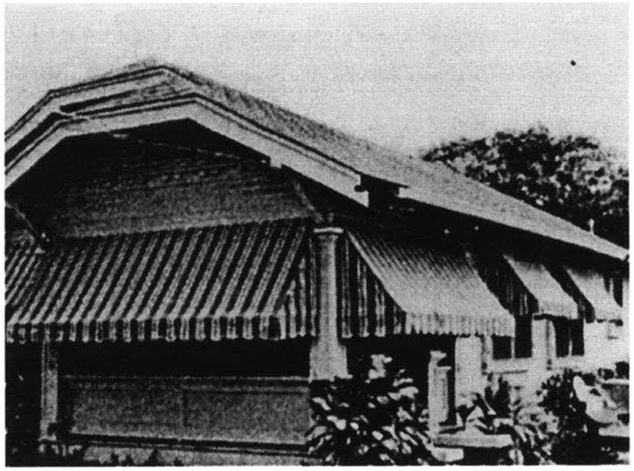
above the ground level for ventilation and termite control. Porches with large overhangs provided a shaded outdoor living area in front of the home. Inside the home, ventilation was generally poor. The use of corrugated metal roofing and the lack of roof vents made the interior uncomfortably warm.

The foundation of plantation homes consisted of wood posts upon concrete footings or masonry piers. The posts supported a raised wooden floor. Building materials were minimized due the demand for low-cost structures and the mild climate conditions. Single-wall construction walls consisted of widely spaced timber members and a single exterior layer of wood planks or tongue-and-groove board. Corrugated metal roofs were commonly supported by trusses constructed on the site.

Single-wall construction has been commonly used throughout the islands, popularized by the need to reduce costs. It was quick and easy to construct. These homes were raised off the ground for ventilation and termite control. They had low hipped roofs to provide rain and sun protection. Polished corrugated metal roofing and roof vents controlled heat gain through the roof. The surrounding landscape also aided in cooling and providing protection from the sun. Variations with gabled roofs were also common, but these generally provided less sun control for windows.

As more people immigrated to Hawaii, other building forms were introduced. During the early twentieth century "Western style"





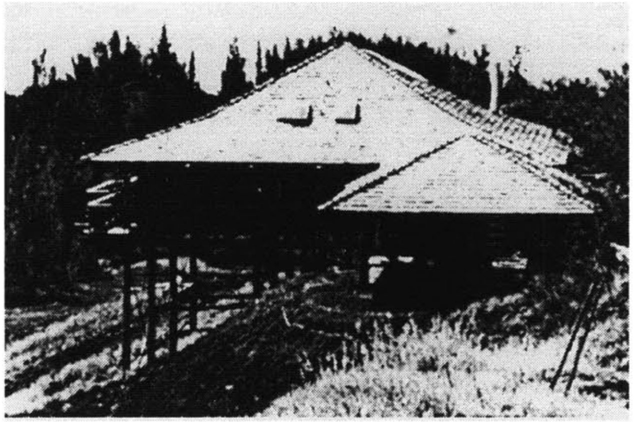
Top: "Western style" homes that were later adapted to fit the climate Botttom: "California bungalow style" home (Jim Pearson 7).

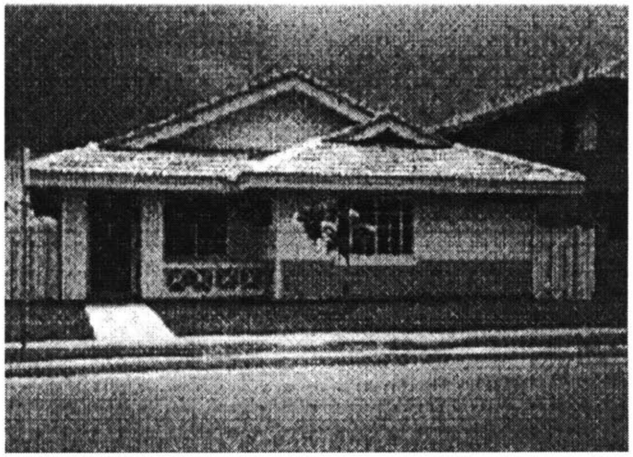
homes with double hung windows and no roof overhangs were brought to Hawaii. These were later adapted to fit the tropical environments with the addition of sleeping porches and lanais. The "California bungalow style" home of the 1920's and 1930's was also unsuited for Hawaii. Awnings and other types of shading devices were added to provide needed protection from the sun and rain.

The Hawaiian "pole house" was developed within the islands and therefore was well-suited to Hawaii's climate. It utilized the double pitched "Hawaiian style" roofs which allowed low sloping roof over wide lanais (porches)[1]. The high roofs and raised floors encourage natural ventilation of the home.

Today's homes are found in a variety of forms and materials. Semi-gabled roofs combine the ventilation opportunities of the gable roof while providing the solar and rain protection of the hipped roof. Large lanais have often been eliminated to minimize the cost of homes.

The majority of the homes commonly employ double-wall timber-framed construction. Typically these homes are constructed with pressure treated plywood and dimensioned lumber. Homes use conventional "mainland" framing methods (a single row of timber





Top: Hawaiian "pole house" was well suited to the Hawaiian climate (Jim Pearson 8) Botttom: Typical modern home in Hawaii (Del Osman Realty).

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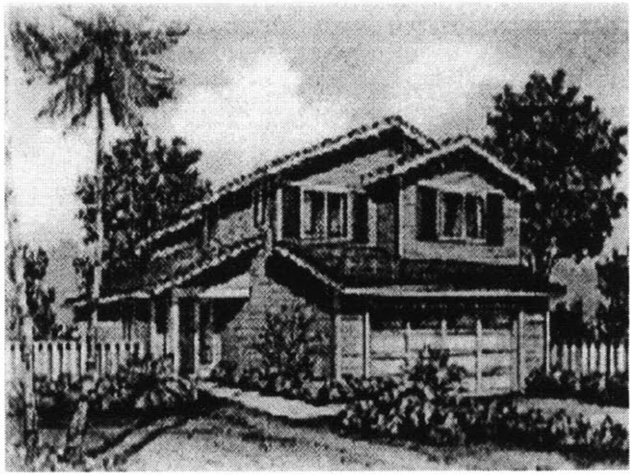
[1] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 13.

studs with exterior and interior sheathing). Other types of construction (concrete, concrete masonry, stucco, light-gauge metal) are also used. Concrete slab-on-grade foundations are common to both building types.



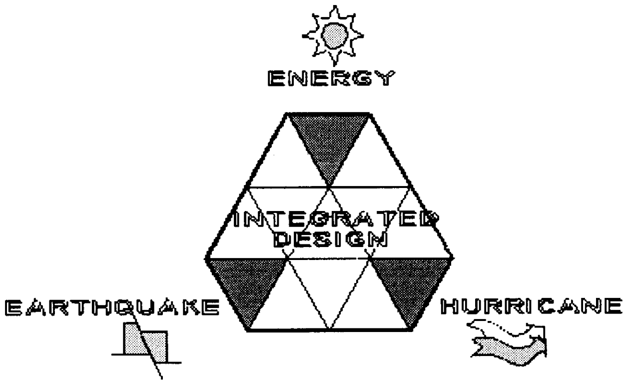
Typical two story modern home in Hawaii (Del Osman Realty)

1.3 NEED FOR AND INTEGRATED DESIGN APPROACH

Although some homes do incorporate energy-efficient and climate responsive design, many fail to address hazard-resistance issues. Structural weaknesses, for example, often result from poor construction practices, caused by rapid development and/or unfamiliarity with new building materials.

In recent years, the rising price of energy costs and the occurrence of Hurricane Iwa and Iniki have made the people of Hawaii aware of the inadequacies of their homes, but have had a minor impact on the home-building industry. Energy-efficient and hurricane design strategies have been haphazardly implemented as owners, designers, and builders often try to get away with the minimum code compliance and cost.

Many people are typically more concerned with aesthetic or energy related issues rather than hurricane or earthquake safety issues. The lifetime of a home, however, extends for many years in which a natural disaster is likely to occur. When natural disasters occur, the buildings are likely to be subjected to tremendous forces. As the extensive damage from past natural disasters has demonstrated, the safety and the structural integrity of homes should be primary design concerns.



Separate design approaches that currently exist and need to be integrated to produce a single comprehensive design approach for Hawaii's homes

Because the housing sector constitutes a major portion of the buildings in Hawaii, residents, designers, and builders need to focus more attention on the design of these structures. In order to build buildings appropriate to the Hawaiian climate, energy-conservation and hazard-reduction measures need to be incorporated into the design and building practices of residential construction. In summary, buildings in Hawaii must be designed with consideration of energy, earthquake and hurricanes.

1.4 SCOPE OF WORK

This thesis describes a comprehensive approach to the architectural design of housing appropriate for Hawaii. It explores essential, economical strategies for energy-efficiency and hazard reduction that should be an integral part of building in Hawaii's unique environment. Three different design approaches are presented: energy efficient and climate responsive design (Section 2), earthquake resistant design (Section 3), and hurricane resistant design (Section 4). Each section establishes the importance of the particular design approach and presents overall and specific building design strategies.

The final section (Section 5) presents additional design considerations for homes in Hawaii. It proceeds to describe an integrated approach that combines the strategies of the three design approaches and suggests a comprehensive approach to designing residential architecture appropriate for Hawaii. Lastly, several existing building designs are analyzed with respect to their compatibility with this integrated design approach.

The focus of this thesis is on architectural decisions made during the schematic design and design development stages of a project that can greatly improve the energy efficiency and structural stability of a home. Deficiencies in existing homes and suggestive design strategies to improve building performance are discussed. Construction methods, material selection and details are recommended.

INTRODUCTION: SCOPE OF WORK

The responsibility of understanding design and construction strategies for an energy and structurally efficient home lies in the hands of the owner, designer, and builder. The guidelines presented in this thesis are for owners who want to improve and strengthen a new or existing dwelling by increasing its energy efficiency and its resistance to earthquake and hurricane damage. The guidelines have also been developed to educate architects and designers by heightening their awareness of the multitude of concerns involved in the design of Hawaii's residential architecture.

ENERGY EFFICIENT DESIGN

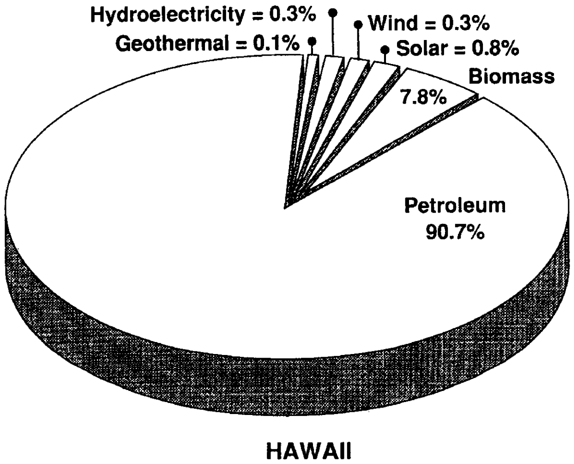
2.0 ENERGY EFFICIENT & CLIMATE RESPONSIVE DESIGN

The world has once again become aware of its precarious dependence upon the rapidly depleting supply of fossil fuels. It has begun to take energy conservation measures and inexhaustible, nonpolluting energy sources such as solar energy have been promoted as alternatives. Building designs that are more responsive to their climate and energy efficient buildings have also been promoted in order to reduce energy consumption.

2.1 ENERGY IN HAWAII

Energy efficiency is a particular concern in Hawaii. Because of the volcanic origin of the islands, there are no fossil fuel deposits such as natural gas, oil, or petroleum. Hawaii is heavily dependent on external, non-renewable resources, with petroleum accounting for approximately 90% of its total energy supply[1].

More than one quarter of the state's oil is used to produce electricity, of which the majority is consumed in buildings[2]. With its high dependence on outside sources, it is no wonder that the price of electricity in Hawaii is high compared to other mainland states.



Hawaii Energy Sources (State of Hawaii, Department of Business, Economic Development, and Tourism 8)

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[1] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 8.

[2] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 8.

ENERGY EFFICIENT & CLIMATE RESPONSIVE DESIGN: ENERGY IN HAWAII

Hawaii's climate offers many opportunities for energy conservation, whether designing a new home or retrofitting an existing one. Solar energy, daylighting, and natural ventilation are effective energy-reducing strategies that can be readily implemented in Hawaii. Solar energy offers a renewable alternative energy source, while natural ventilation and daylighting present opportunities in the Hawaiian home to provide human comfort and natural light without the consumption of electrical energy.

Although only limited measures can be applied to retrofitting an existing home, small changes can be made to improve a home's energy efficiency. Still, the potential for cost effective architectural measures is much greater in new construction than in retrofitting since a new home offers the opportunity to integrate energy-saving strategies into the early phases of design.[3].

The design of a home determines its energy efficiency. It can enhance a building's ability to collect solar energy on the exterior while providing daylighting and human comfort within the interior. In most cases, houses in Hawaii can be designed to maintain a naturally comfortable interior climate throughout the year. By designing homes with consideration to Hawaii's climate, the demand for energy will be reduced.

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3. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 9.

2.2 CLIMATE OF HAWAII

Hawaii's unique climate results from the interaction of its latitude, the surrounding ocean, the tradewinds, and the topography of the land. The Hawaiian Island chain stretches from 19 to 22 degrees North latitude and experiences little variation in daylight hours. Due to its proximity to the equator, Hawaii is exposed to high sun angles and experiences minimal seasonal changes throughout the year. These factors result in a relatively consistent amount of solar energy year round.

Seasons

Although seasons in Hawaii are not distinct, two different seasons are recognized. A five month dry season extends from May through September and is characterized by high-sun positions, warm temperatures, and steady trade winds. The wet season occurs during the remaining seven months of the year and is characterized by cooler temperatures, less frequent tradewinds, and widespread rainfall[4].

Temperature

Hawaii's climate has very small temperature fluctuations throughout the day, as well as the entire year. This is due to Hawaii's proximity to the equator and the surrounding ocean. Throughout the islands, August and September are the warmest months with tem-

HILO. HAWAII NORMALS. MEANS AND EXTREMES

LATITUDE: 19° 43'N LONGITUDE: 155° 04'W	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F:													
NORMALS													
-DAILY MAXIMUM	79.5	79.0	79.0	79.7	81.0	82.5	82.8	83.3	83.6	83.0	80.9	79.5	81.2
-DAILY MINIMUM	63.2	63.2	63.9	64.9	66.1	67.1	68.0	68.4	68.0	67.5	66.3	64.3	65.9
EXTREMES													
-RECORD HIGHEST	91	92	93	89	94	90	89	93	92	91	90	93	94
-RECORD LOWEST	54	53	54	56	58	60	62	63	61	62	58	55	53
NORMAL DEGREE DAYS													
-COOLING (base 65°F)	198	176	202	222	267	294	322	338	324	319	258	214	3134
% OF POSSIBLE SUNSHINE	47	46	41	35	37	43	42	42	44	39	34	37	41
PRECIPITATION (INCHES)													
WATER EQUIVALENT													
-NORMAL	9.42	13.47	13.55	13.10	9.40	6.13	8.68	10.02	6.63	10.01	14.88	12.86	128.15
WIND													
MEAN SPEED (MPH)	7.5	7.7	7.6	7.4	7.3	7.1	6.9	6.8	6.7	6.7	6.7	7.2	7.1
PREVAILING DIRECTION THROUGH 1963	SW	SW	SW	WSW	WSW	WSW	WSW	WSW	WSW	SW	WSW	SW	WSW

HONOLULU. OAHU NORMALS, MEANS AND EXTREMES

LATITUDE: 21° 20'N LONGITUDE: 157° 56'W	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F:													
NORMALS													
-DAILY MAXIMUM	79.9	80.4	81.4	82.7	84.8	86.2	87.1	88.3	88.2	86.7	83.9	81.4	84.2
-DAILY MINIMUM	65.3	65.3	67.3	68.7	70.2	71.9	73.1	73.6	72.9	72.2	69.2	66.5	69.7
EXTREMES													
-RECORD HIGHEST	87	88	88	89	93	92	92	93	94	94	93	89	94
-RECORD LOWEST	53	53	55	57	60	65	67	67	66	64	58	54	53
NORMAL DEGREE DAYS													
-COOLING (base 65°F)	236	221	291	321	388	423	468	496	468	450	348	279	4389
% OF POSSIBLE SUNSHINE	63	65	69	67	69	71	74	75	75	68	61	59	68
PRECIPITATION (INCHES)													
WATER EQUIVALENT													
-NORMAL	3.79	2.72	3.48	1.49	1.21	0.49	0.54	0.60	0.62	1.88	3.22	3.43	23.47
WIND													
MEAN SPEED (MPH)	9.6	10.3	11.4	12.0	11.9	12.7	13.3	13.0	11.4	10.6	10.8	10.5	11.5
PREVAILING DIRECTION THROUGH 1963	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE	ENE

Weather Data for Hilo and Honolulu (State of Hawaii, Department of Business, Economic Development, and Tourism 10)

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4. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 10.

peratures in the mid-eighties. January and February are the coldest months with temperatures in the high-seventies. Annual mean temperatures throughout the island chain remain in the seventies (degrees F).

Microclimates

Although temperatures along the coastline remain virtually constant, the topography of the land produces marked variations in wind speed, cloud cover, and rainfall from one locality to another. The windward sides of the islands tend to be rainy, while the leeward areas tend to be drier and hotter. These conditions produce a multitude of microclimates ranging from excessively rainy and windy valleys to dry scorching deserts. Various microclimates foster different living patterns and building types and thus each building design must consider the unique microclimate of its site.

Winds

Hawaii experiences a variety of wind directions and speeds throughout the year. Winds velocities range from gentle blowing tradewinds to high speed violent gusts. Prevailing winds in Hawaii are generally from the northeast. Gentle, ocean-cooled tradewinds blow across the island chain and aid in providing a comfortable natural environment. Although the weather conditions are pleasant throughout most of the year, violent and sudden changes in the form of storms or hurricanes can also occur.

2.3 DESIGNING WITH CLIMATE

Hawaii has one of the most ideal climates in the world. During most of the year, human comfort can be easily attained naturally without the aid of energy-consuming systems such as air conditioners. Well-designed homes can take advantage of Hawaii's mild climate by mitigating the effects of the surrounding environment, naturally maintaining a comfortable interior climate, and minimizing energy use. In Hawaii the weather is predominately warm and humid, thus cooling is mainly required throughout the year.

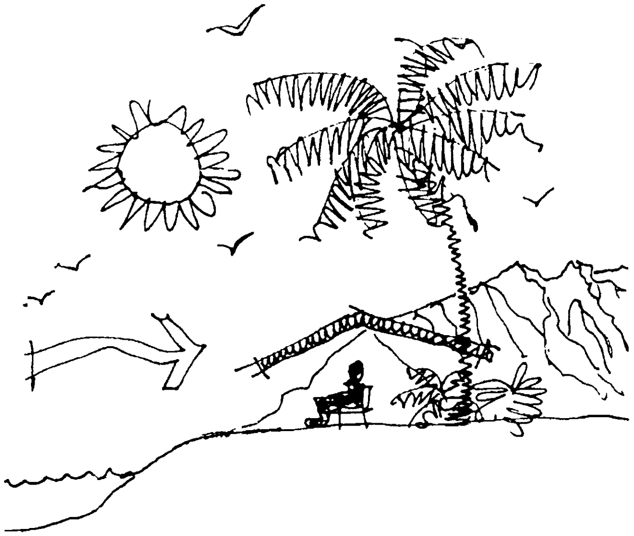
Active vs. Passive Design

The function of a home is to filter, absorb, or repel the elements of the natural environment and maintain a comfortable interior climate. The interior climate of a home can be regulated and maintained by heaters, air conditioners, or room fans. These mechanical systems are called "active" systems.

Passive designs regulate a home's interior climate with the very design of the structure itself. A passively designed home is physically responsive to its surrounding environment. A climate-responsive house is, in itself, an effective barrier to the sun's heat that remains open to and even enhances natural wind ventilation.

Human Comfort

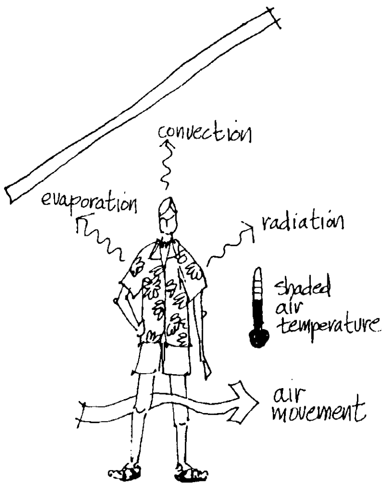
Climatic factors that affect human physical comfort are: temperature, relative humidity and air movement (ventilation), and radiation. The human body remains comfortable when all three of these bioclimatic factors are in balance.

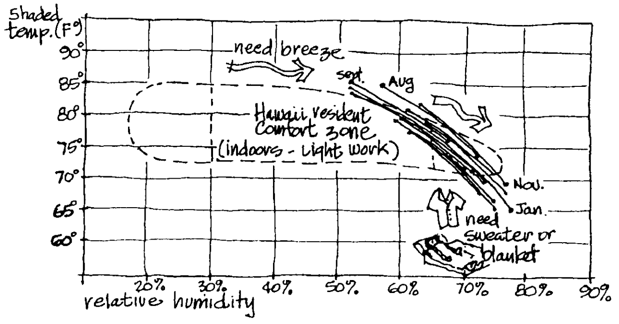


Designing with climate (Jim Pearson 9)

The bioclimatic chart is a schematic graph of relative humidity and outdoor shaded temperature plotted throughout the year. The comfort zone is a function of various climatic factors and indicates the climate conditions needed to produce an environment comfortable for the human body. The natural climate conditions in Hawaii mainly lie within this zone of comfort. During times when conditions are too warm, comfort can be achieved with an increase in air movement. During the times when conditions are too cool comfort can be attained with the addition of clothes.

Hawaii's weather is predominately warm and humid, thus cooling is the main objective for achieving adequate levels of human comfort. Comfortable conditions can be maintained by merely providing adequate solar protection and ample natural ventilation.

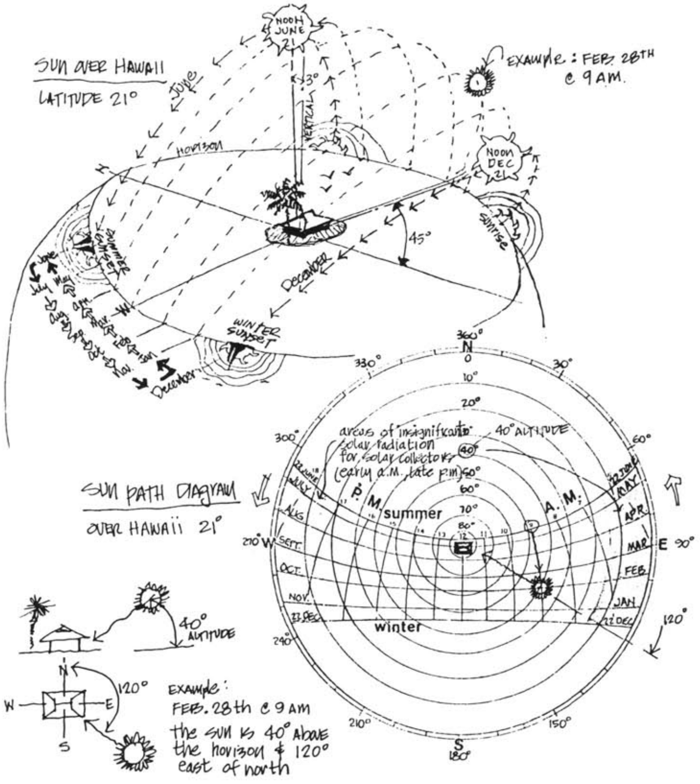




Top: Factors influences human comfort (Jim Pearson 9)
Bottom: Bioclimatic chart for Hawaii (Jim Pearson 10)

2.4 SOLAR CONTROL

In Hawaii and other warm climates, the primary design objective is to prevent solar gain. Heat from the sun out of the house should be minimized, while removal of interior heat is maximized. As indicated by the bioclimatic chart and comfort zone, the two necessary ingredients for natural comfort in Hawaii are temperature control and ventilation. Temperature can be controlled with adequate solar protection. It is human nature to get out of the sun and seek shade when conditions are too hot. Thus, the first step in regulating interior temperatures is solar control.



Sun path diagrams for Hawaii (Jim Pearson 14)

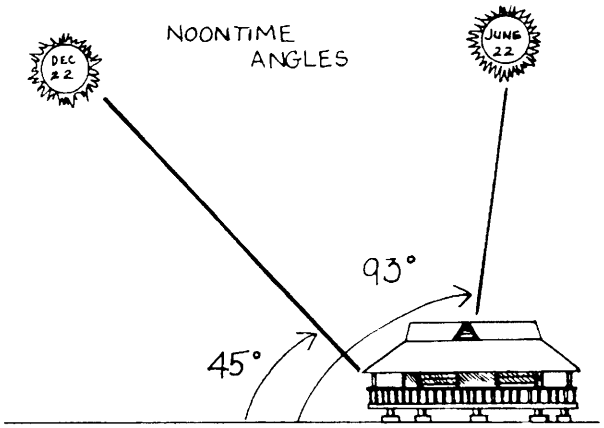
Sun Path

In order to provide adequate solar protection in the design of a building, there must first be an understanding of the sun's path across the sky, and how it varies throughout the year. A sun path diagram shows the location of the sun at any time or date in Hawaii. Only seven monthly paths are shown due to the retracing of the paths during the remaining five months. The sun retraces its path from the low point (December) to its high point (June). Concentric circles indicate the angle of sun's altitude above the horizon. The position of the sun in the sky is described by the sun azimuth (angle from due South) and the sun altitude (angle above the horizontal ground plane).

Summer and Winter Solstice

Home designers only need be concerned with the extreme positions of the sun's path in order to provide protection throughout the entire year. The winter solstice occurs on December 22nd and is when the most extreme winter position and the shortest day of the year occur. On this day the sun in Hawaii rises at the extreme south-east position with an azimuth angle of 65 degrees. On the same day the sun's noon time altitude is 45 degrees from the southern horizon. This low sun angle causes intense solar exposure on the south side of buildings.

June 22nd is the summer solstice. It is the longest day of the year and when the sun rises further north on the eastern horizon and sets further north on the western horizon than any other day of the year. The azimuth angle at sunrise and sunset on this day is 115 degrees. On the same day at noon, the sun reaches its greatest angle from the southern horizon with an altitude of 93 degrees. Hawaii is the only state where the summer sun at noon shines from the north. This indicates that houses in Hawaii, in contrast to "mainland" homes, have to be designed to provide shading on the north as well as south sides.



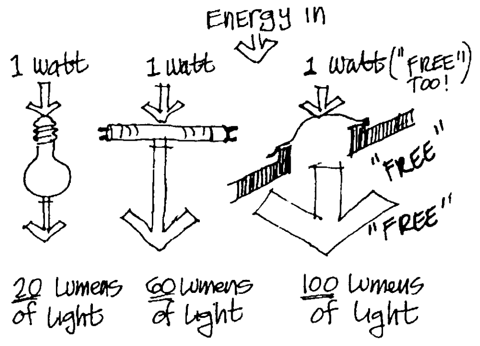
Extreme sun angles in Hawaii (State of Hawaii, Department of Education 12)

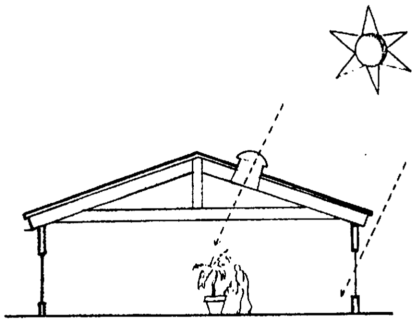
2.5 DAYLIGHTING

The abundance of sunlight throughout the year provides Hawaii with another excellent opportunity to reduce energy costs through daylighting. Daylighting refers to the controlled use of daylight to reduce the demand for electric lighting. Although direct solar radiation should be blocked from entering the building interior (see Solar Control, Section 2.4), daylight can and should be utilized in order to reduce the amount of energy consumed by electric lights during the daytime. Sunlight, often called "free light", also has the benefit of reducing the amount of cooling required by eliminating heat gain from electrical lights.

Direct vs. Indirect Daylighting

Designers must be careful to avoid direct sunlight and skylight when providing daylight to a space. Direct light causes excessive glare and unwanted heat gain, thereby causing human discomfort and the need for more cooling. Direct sunlight that is too intense to be used as a light source,. It should be reflected off of several surfaces before lighting interior spaces. Re-directed, bounced light results in an indirect light that provides comfortable ambient light to a space, reduces glare, and evens brightness patterns. Direct view to the sky should be avoided as uneven and variable brightness in the sky can produce visual discomfort[5].





Top: Daylighting in Hawaii can save energy (Jim Pearson 34) Bottom: Direct sunlight is too intense and causes glare (State of Hawaii, Department of Business, Economic Development, and Tourism 24)

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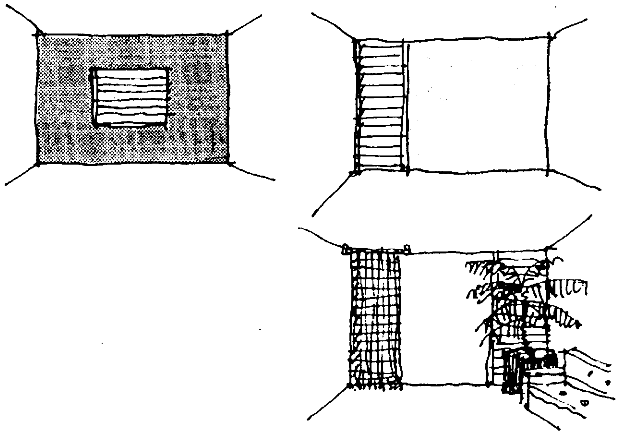
[5] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 24.

Since the amount of light bouncing off a surface is proportional to the surface's reflectance, lighter-colored surfaces are more optimal for aiding daylighting. When using windows for natural lighting, it is important to avoid excessive glare and contrast between bright openings and the wall surface. Shading devices such as blinds or drapes can help diffuse and block light to reduce this contrast. Light colored interior surfaces of exterior window walls can also help diminish contrast and glare.



Avoid excessive glare between bright windows and walls (Jim Pearson 34)

2.6 SOLAR ENERGY

Solar energy is an inexhaustible, non-polluting energy source that is readily available in the islands. Hawaii, with its relatively consistent supply of sunshine and clear skies, provides an excellent opportunity to exploit the sun's energy. In recent years the use of solar energy in the Hawaiian household environment has become widespread. Solar water heating systems have been incorporated into new homes and added to existing homes, reducing the amount of non-renewable energy consumption. Tax incentives and rising energy costs in Hawaii, along with environmental concerns, encourage the use of solar systems.

2.7 NATURAL VENTILATION

A properly designed building that is naturally ventilated can provide comfortable interior conditions throughout most of the year. Naturally ventilated buildings provide significant energy savings by reducing the demand for air-conditioning. The successful use of natural ventilation strategies requires detailed site and wind analyses during the early planning phases of design. Buildings should be designed to take advantage of the favorable wind conditions of the site.

Wind Patterns

An awareness of local wind patterns is important in order to take advantage of local tradewinds as a means of cooling and ventilating a building. As each site is different and microclimates vary widely, a careful study of wind patterns on each individual site should be conducted.

Tradewinds

Tradewinds in Hawaii generally approach from the north-east direction and occur 90% of the time during the summer. During the winter, tradewinds associated with Kona storms approach from the south-west and occur 50% of the time[6]. Wind directions and intensities vary significantly from each location because of the land topography (see Surface wind diagrams on page 31).

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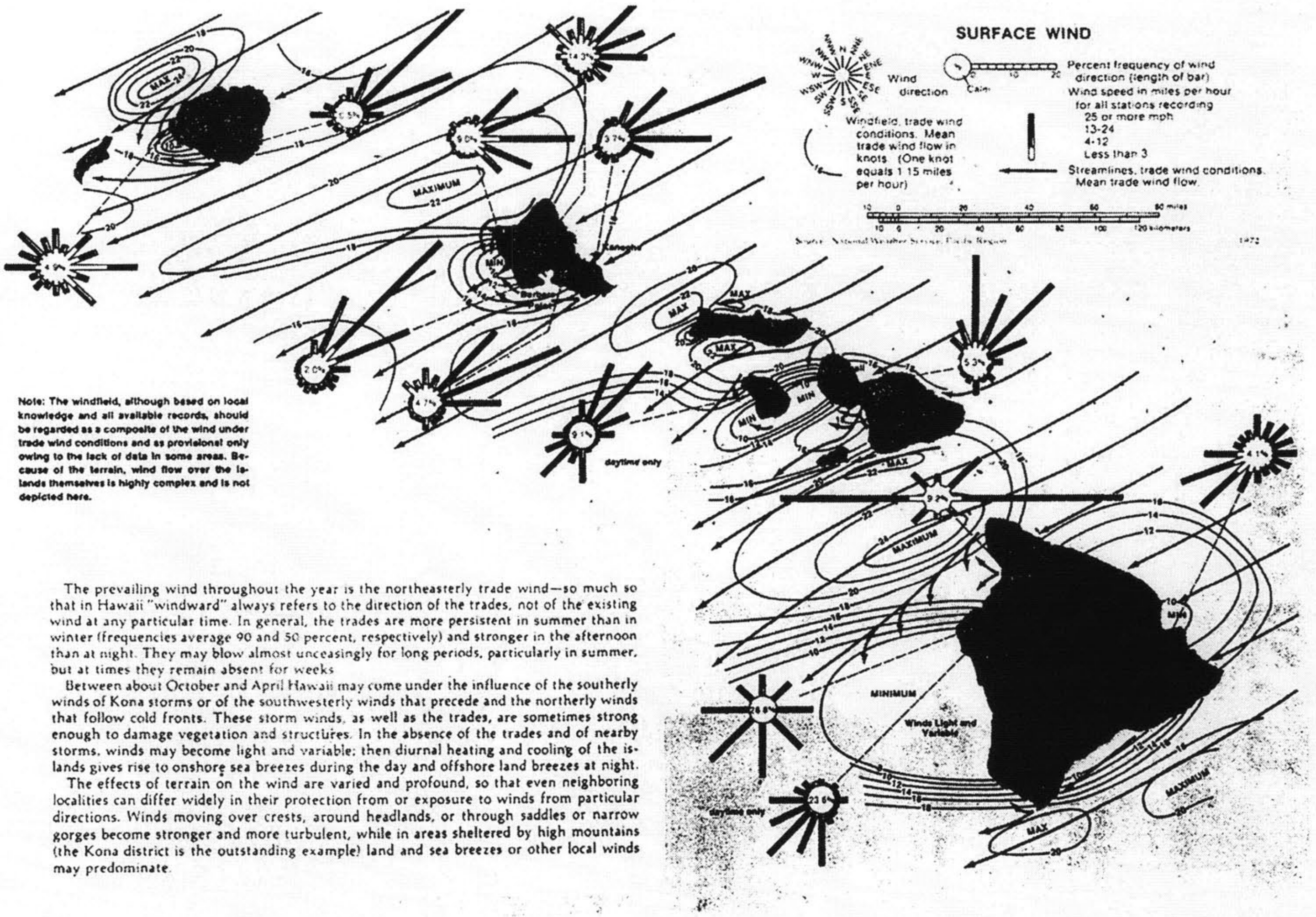
[6] James Leonard, Houses in the Sun, Solar Conscious Architecture for Hawaii and the Tropics, pamphlet (Hawaii: Department of Education, 1979) 13.



Note: The windfield, although based on local knowledge and all available records, should be regarded as a composite of the wind under trade wind conditions and as provisional only owing to the lack of data in some areas. Because of the terrain, wind flow over the islands themselves is highly complex and is not depicted here.

The prevailing wind throughout the year is the northeasterly trade wind—so much so that in Hawaii "windward" always refers to the direction of the trades, not of the existing wind at any particular time. In general, the trades are more persistent in summer than in winter (frequencies average 90 and 50 percent, respectively) and stronger in the afternoon than at night. They may blow almost unceasingly for long periods, particularly in summer, but at times they remain absent for weeks.

Between about October and April Hawaii may come under the influence of the southerly winds of Kona storms or of the southwesterly winds that precede and the northerly winds that follow cold fronts. These storm winds, as well as the trades, are sometimes strong enough to damage vegetation and structures. In the absence of the trades and of nearby storms, winds may become light and variable; then diurnal heating and cooling of the islands gives rise to onshore sea breezes during the day and offshore land breezes at night.

The effects of terrain on the wind are varied and profound, so that even neighboring localities can differ widely in their protection from or exposure to winds from particular directions. Winds moving over crests, around headlands, or through saddles or narrow gorges become stronger and more turbulent, while in areas sheltered by high mountains (the Kona district is the outstanding example) land and sea breezes or other local winds may predominate.

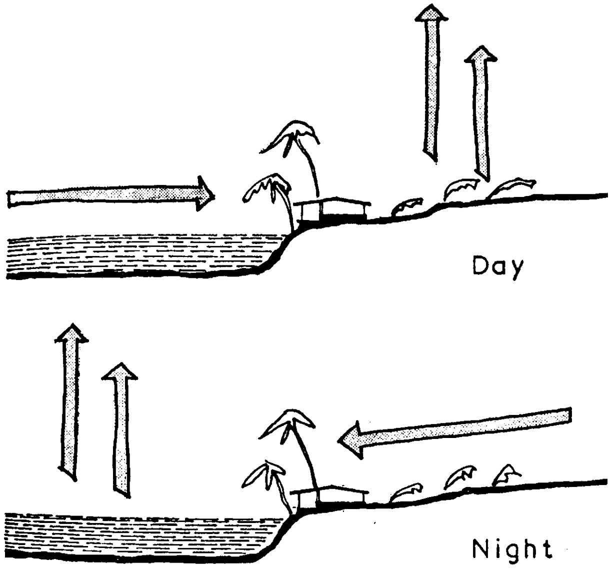
Surface wind diagrams (Jim Pearson 105, reprinted from Atlas of Hawaii, copyright 1973 by the University Press of Hawaii)

Land and Sea breezes

On leeward coasts, mountains block tradewinds and land-and-sea breezes produce another type of wind pattern. Land-and-sea breezes are a result of convective currents induced by the differences in diurnal temperatures between the land and ocean. Because water has a higher thermal storage capacity than the land, it slowly heats during the day and remains warm during the night. Differences in the temperature between the land and water cause the the wind to blow toward the land during the day and toward the ocean at night. This creates an onshore sea breeze during the day and an offshore land breeze at night.

Topographical Effects on Wind

Both the island's topography and a specific building site's topography greatly affect local wind patterns. Sites near the crest of hills or ridges may provide increased exposure to winds while valleys and sheltered locations may have little air movement. Ridge crests can receive wind speeds which are often 20% to 80% higher than the surrounding flat ground[7]. Tradewinds moving through narrow gorges may also be intensified and more turbulent.



Land and sea breezes during the day and night (David Oakley 185)

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[7] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 30.

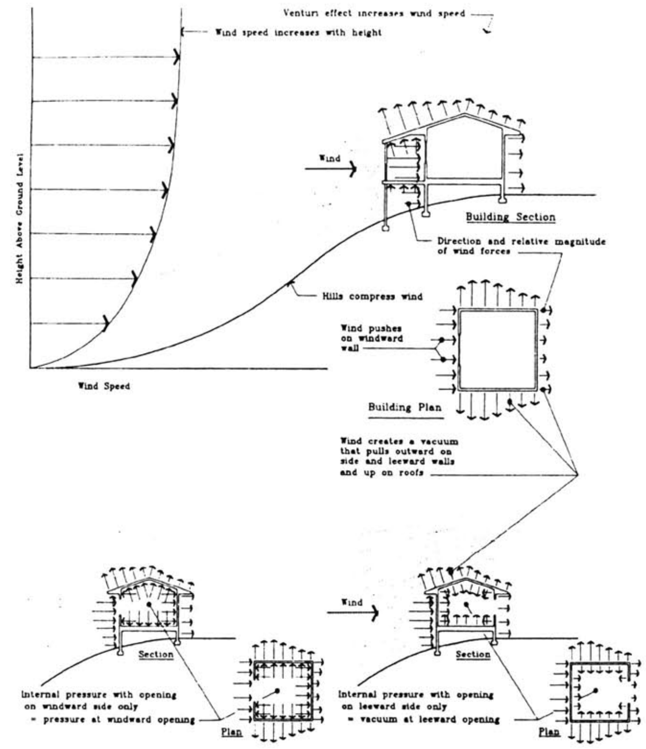
Wind Pressures and Flow Around a Building

Wind pressures occur on all surfaces of a building in the air flow path. Pressure results on both external and internal surfaces and varies in magnitude depending on several factors. These factors include:

a) velocity of wind
b) height of the surface above the ground
c) shape of the surface
d) surface orientations with respect to the air flow path

Wind pressure is proportional to the square of wind velocity. The faster the wind, the stronger the pressure upon a building. Thus, hurricane winds of a create immense pressure upon building components. Wind pressure increases with the height above the surface of the ground. This is because ground friction (due to the ground surface, vegetation and trees) occurs near the surface which slows the velocity of the wind.

The building form also affects the wind pressure on its surfaces. Whenever an obstruction is in the path of the wind, air must flow around it. This creates localized increases in velocity and turbulence as air flow is channeled or disrupted. The forces are often concentrated at angular corners and edges of objects and can cause an increase in pressure that can significantly affect a building. Pressure can be positive (inward) or negative (outward) and is dependent upon the orientation of the surface to the wind direction.



Wind flow and pressure around a building (Nick Huddleston 19)

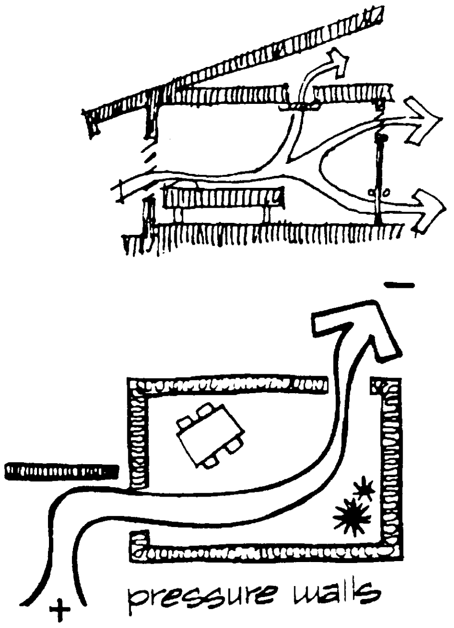
The form of a building can be shaped to capture breezes (increases pressure) or to be aerodynamic (reduces pressure). Passively cooled building can be designed to capture breezes, but may have wind load problems during high wind conditions.

For a rectangular-shaped building, positive pressure typically occur on surfaces oriented to the windward side; negative pressure occurs on the leeward surfaces and surfaces parallel with the wind path. The roof can experience positive or negative depending on the angle of slope of the roof planes. Some surfaces inclined toward the flow of the wind may experience both positive and negative pressures over different areas of the same surface.

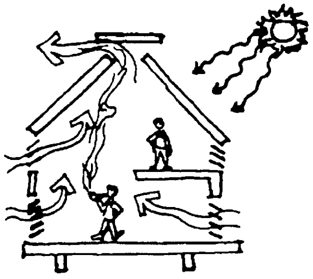
Internal pressures can also occur within a building. This is especially so when building openings exist. The orientation of the openings with respect to the wind path determines the nature of the internal pressure. Pressure differences around building openings can encourage natural ventilation or exert forces on building components.

Types of Ventilation

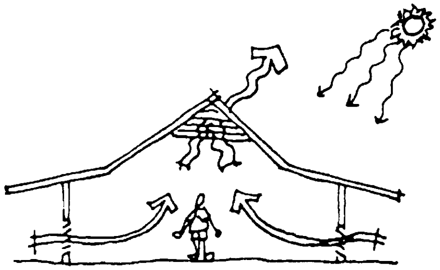
There are two methods of naturally cooling a home, cross ventilation and stack ventilation. Cross ventilation is the lateral movement of air through a building. This type of ventilation provides the greatest interior velocities and best overall air distribution pattern when optimized[8]. The placement of windows and the orientation of



Wind flows from possitve pressure to negative pressure. Placement of pressure walls can help circulate air in a room (State of Hawaii, Department of Education 41) a building to prevailing winds greatly affect cross ventilation. In order for cross ventilation to occur, openings with both positive and negative pressure are required. This establishes a pressure gradient which forces air to move across a space from the high to lower pressure areas. Placement of openings for effective cross ventilation also depends on the room shape and wind directions.



In addition to the patterns of wind that flow horizontally through a building, a building can also be cooled by the buoyancy effects and the vertical displacement of air. This is known as stack ventilation. As air gets warmer it expands, becomes lighter, and rises to the highest point in the space. If the roof allows warm air to exit through openings at the high point, the internal air will be kept moving through this buoyant effect . As warm air is released from the top, cooler air is drawn into the space at the living level. Stack ventilation can be enhanced by placing the outlets on the leeward side of a roof. Wind flow over roof ridges results in suction pressures that “pull” air out through the ridge vent.



Buoyancy effect causes stack ventilation (State of Hawaii, Department of Education 41)

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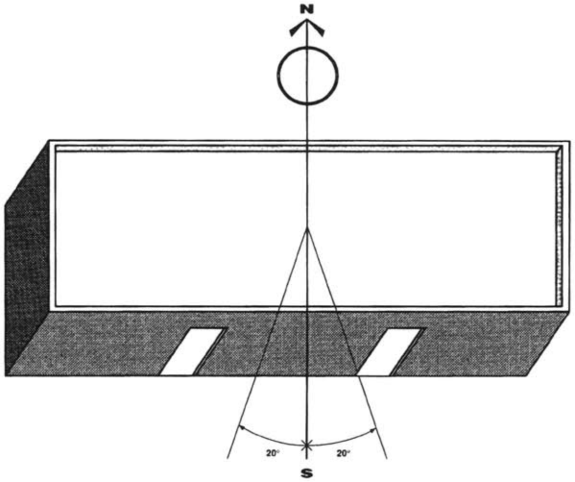
8. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 32.

2.8 BUILDING ORIENTATION

The orientation and configuration of a building is very important in determining its solar control, daylighting, and natural ventilation capabilities. Building orientation determines the amount of solar radiation incident upon the walls and roof and the ventilative effectiveness of a building's openings.

Orientation for Solar Control

In Hawaii it is desirable to minimize solar heat gain. Thus, the wall area and the amount of glazing on the east and west side should be minimized. The east and west sides receive extended periods of exposure to the hot summer sun and are difficult to shade effectively. The optimal shape for thermal considerations is a rectangular building with its longitudinal axis running east to west. Variations of 15 to 20 degrees from this axis has a minimal effect on the thermal performance of a small building[9].



Variations from due north and south up to 20 degrees has a minimal effect upon solar control and thermal performance (State of Hawaii, Department of Business, Economic Development, and Tourism 8)

Orientation for Daylighting

Solar control is needed to prevent unwanted heat gains, yet sunlight is desirable for natural lighting. Because daylighting is provided through openings in the building enclosure, the orientation of the openings is more critical than the overall orientation of the home.

Large north facing windows and skylights provide even light and

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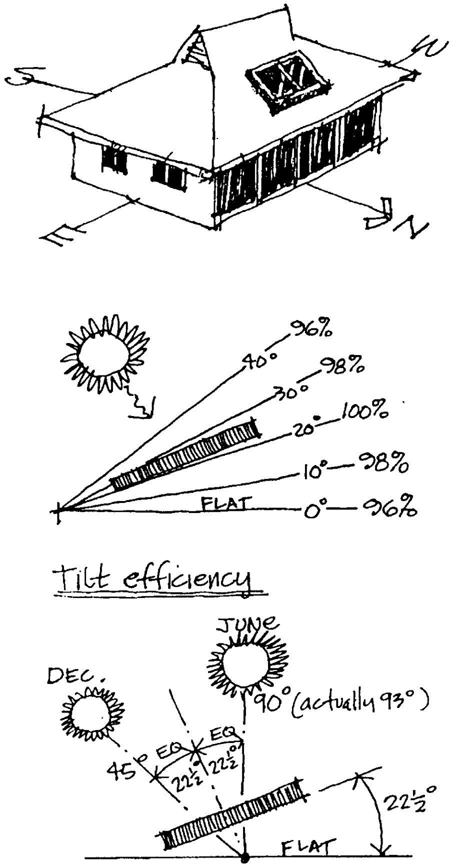
[9] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 14.

are protected from the direct rays of the sun throughout most of the year. Lighting from openings on other sides can also be used if direct sun and sky exposure are avoided. Lighting from several directions also aids in reducing glare.

Historically, many believed that the daylight from the north sky was ideal for its uniformity and color. Aside from very slight differences in the color spectrum, the light from the north is no different from the east, west or south. The only difference lies in that the other sides receive more direct sun than the north side, making the light seem more intense and variable. If adequate shading from direct sun is provided, all orientations can be used to provide successful daylighting[10]. Thus, the orientation of the building for the purpose of daylighting is not critical as long as openings are shaded to eliminate exposure to direct sunlight.

Orientation for Solar Energy

Solar energy systems need to be responsive to the sun and its location as it moves across the sky. The placement of solar collectors will affect the efficiency of the solar energy system. In Hawaii the collector should face due south at an approximate angle of 22 degrees from the horizontal for the greatest and most consistent energy output[11]. However, variations in the horizontal angle of the



Top: Lighting from the north sky experiences the least brightness and intensity fluctuations (Jim Pearson 34) MIddle & Bottom: Tilt efficiency for solar collector panels can vary up to 30 degrees with minimal effects (Jim Pearson 75)

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[10] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 14.

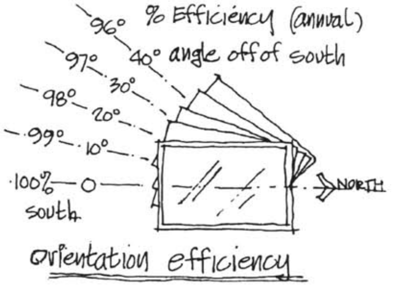
[11] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 75.

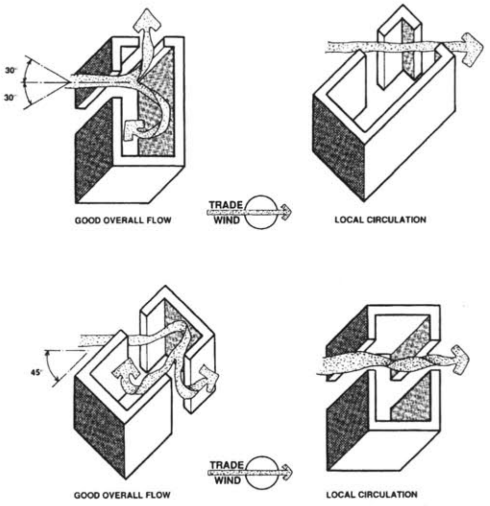
collector up to 30 degrees have little effect on the yearly efficiency of the system. It has also been discovered that deviation from facing due south by angles not exceeding 25 degrees has a negligible effect [12].

Orientation for Natural Ventilation

The orientation and configuration of a building also strongly impact the natural ventilation capabilities of a building. A building's orientation with respect to prevailing winds will determine the ventilative effectiveness of the its openings. The building shape will also determine the effectiveness of the cross ventilation.

Good ventilation occurs when there is a high average air velocity with air flow distributed throughout all occupied parts of a space. Optimal orientation for ventilation depends on window location as well as the direction of the prevailing winds. When openings are located on adjacent walls, the optimal ventilation occurs when the long facade is perpendicular to prevailing winds. Shifting the orientation 20 to 30 degrees degrees from perpendicular will not seriously affect the ventilation effectiveness. Wind approaching at 45 degrees results in average interior velocities that are 15%-20% lower than those which occur when the wind approaches normal to the building face [13].





Top: Solar collection panel orientation efficiency for various angles (Jim Pearson 76) Bottom: Optimum orientation of ventilation for rooms with openings on opposite sides (State of Hawaii, Department of Business, Economic Development, and Tourism 15)

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[12] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 76.

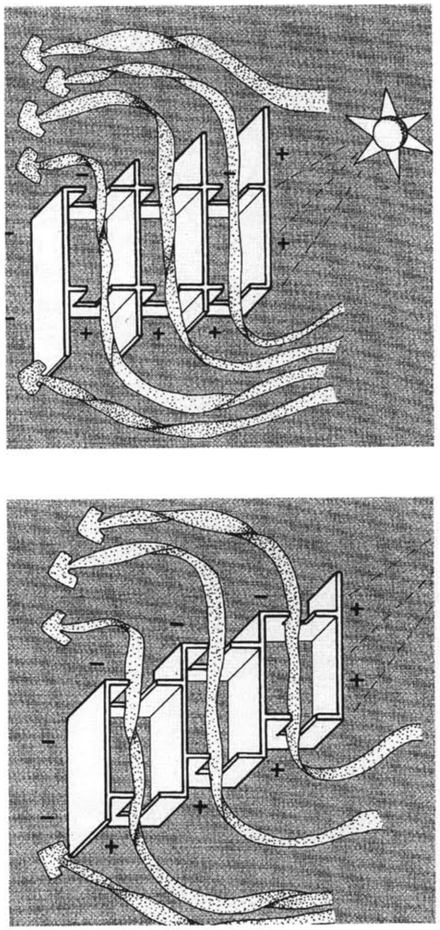
[13] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 15.

When windows are located on opposite walls, rotating the building 45 degrees with respect to prevailing wind direction provides the highest average and best overall distribution of air movement within the space. Wind approaching at 90 degrees is 15%-20% less effective; air basically flows straight into and out of the building[14]. Wind parallel to the opening produces ventilation that depending entirely on fluctuation in the wind and is therefore inconsistent.

Overall Orientation

The overall building orientation is most critical to solar control and natural ventilation, as these will have the greatest effect upon reducing heat gain and providing a comfortable thermal environment. The orientation of a building to optimize ventilation often does not coincide with the orientation for solar control or daylighting. When a conflict exists between the two, the building form determines which strategies take precedence.

In taller, larger buildings, solar considerations usually take precedence. This is because wind can be manipulated more than sunlight. Inlets for natural ventilation can be designed for less than optimal wind orientation more easily than solar control devices can be designed for extreme sun conditions. Carefully placed wing walls and staggered rooms can satisfy requirements for solar con-



Top: Wingwalls can increase ventilation through rooms Bottom: Staggering rooms can increase ventilation through rooms (State of Hawaii, Department of Business, Economic Development, and Tourism 16 & 17)

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14. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 15.

trol while catching winds for natural ventilation.

In carefully designed low rise buildings ventilation has the greater effect on internal conditions and thermal comfort. Therefore, orientation with respect to the prevailing winds should take precedence over solar considerations.

When the orientation with respect to solar control is compromised, there are several strategies that can improve the effectiveness of the design. Using light colored wall surfaces, exterior shading systems for windows, and extra insulation can reduce the heat gain of a building.

Building orientation for daylighting and solar energy are not as critical. Daylighting is more dependent upon the placement of openings as solar energy is upon the placement of the solar collectors. The placement of these components is more flexible in comparison to solar control and natural ventilation and should have less impact upon the building orientation.

2.9 BUILDING DESIGN

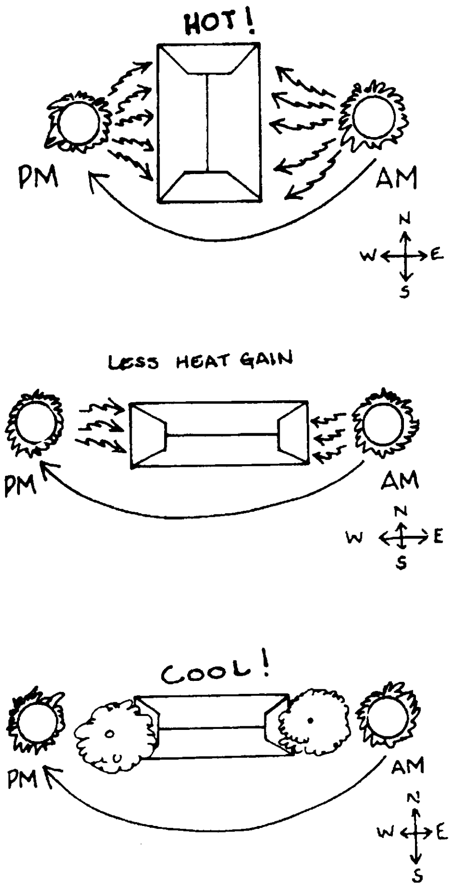
Along with the overall orientation of a building on a site, the building itself can contribute to the promotion of solar control, daylighting, solar energy collection, and natural ventilation. The design of the form, details and materials of the overall building and its components have a significant impact upon the energy efficiency of a building. The proper design of roofs, walls, and foundations is essential to minimize energy use in a home.

Building Form

Building Form for Solar Control

In order to minimize solar heat gain, the exposed exterior surface area of a building should be minimized. Simple forms should be used instead of complex forms. Complex forms increase the perimeter surface areas and allow for more heat gain to occur. The building form is also influenced by the amount of solar exposure to the various sides. East and west sides experience extreme morning and afternoon sun conditions so it is especially critical to minimize surface area exposed to these sides.

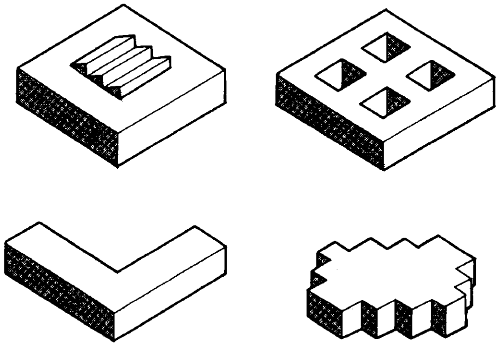
Zoning of spaces within a building can also reduce thermal heat gain. Rooms which require little cooling or light (closets, storage, garage, laundry rooms or stairways) can be placed on the hotter east and west sides to mitigate the extreme effects of the sun. These areas act as buffer spaces to minimize east-west solar gains and keep living spaces cooler



Top: North-south orientation is not opimal Middle: East west orientation is optimal Bottom: Vegetation can aid in reducing heat gain on east and west sides (State of Hawaii, Department of Education 17)

Building Form for Daylighting

Naturally lit spaces need to be located adjacent to an exterior surface in order to have access to daylight. Thus, maximizing the perimeter wall areas provides more opportunities to access daylight. Atriums, courtyards, or staggered forms create building shapes that promote daylighting. Clustering rooms around an atrium is a useful method for bringing light into the interior portions of a building while maintaining privacy. Open atriums offer an opportunity for natural ventilation along with natural lighting.



Complex building forms can increase the potential for daylighting (State of Hawaii, Department of Business, Economic Development, and Tourism 17)

Building Form for Solar Collection

The main concern for solar energy collection is to maximize the solar exposure of collectors. If collectors are placed upon the building, the building form should encourage and not inhibit solar exposure. If the surrounding buildings or landscape block the sun, increasing the height of a building can improve solar exposure to the roof, and hence solar collectors.

Building Form for Natural Ventilation

A building's shape affects it ability to naturally ventilate itself. The width and the height are especially important. Naturally cross ventilated buildings should have narrow cross sections to maintain ample air velocities and allow the penetration of breezes. Deep cross sections can not be adequately ventilated as the lack of ample air velocities permit air stagnation and heat build up.

The building height plays a critical role in the natural cooling of a building and the creation of the stack effect. In order for stack ventilation to be an effective in removing hot air and drawing in cooler air, a relatively high ceiling must exist. The ceiling must be high enough so that a temperature difference can occur. High ceilings generate better air ventilation and provide greater separation between hot and cold air. A room with a high ceiling can provide better thermal comfort than a room with a low ceiling. A relatively high ceiling (over 12 feet) or a large open space under the ceiling are recommended[15].

Although designs utilizing the combination of both stack and cross ventilation is considered to be the optimal situation, most residential buildings in Hawaii do not benefit from the stack effect due to their low building height and lack or roof top openings. Most homes have low sloped roofs, flat ceilings, and lack roof vents to minimize building costs. Thus, most homes in Hawaii must rely on cross ventilation and the proper orientation to winds with sufficient velocities.

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15. Louchak Chan. An Investigation of the Effect of Roofing Design on the Thermal Performance of Single Family Residential Houses in the Hawaiian Climate, thesis, University of Hawaii at Manoa (May 1980) 72.

2.10 ROOF DESIGN

The thermal design of a roof has a pronounced influence on indoor temperature, as it is exposed to solar radiation throughout most of the day. It is the prime source of heat gain for most low-rise buidlings in Hawaii, accounding for up to 70% of a building's total heat gain during peak sunlight hours[16]. Uncontrolled heat gain through a roof has a pronounced influence on indoor thermal conditions and the need for cooling.

Heat is transmitted though the roofing material in three different ways: radiation, convection, and conduction. Radiated heat from a roof has the largest effect upon human thermal comfort. The sun heats the roof, which radiates heat through the air and to the building occupants.

In Hawaii, night temperatures vary slightly from the daytime average. The relatively constant temperature requires a building to be cooled the majority of the time. Thus, heat gain to buildings, and especially the roof, should be minimized.

Large volumes of high density materials (i.e. concrete, concrete blocks) tend to store heat from the sun during the day and re-radiate it to the cooler air at night. Because the Hawaiian climate requires cooling during the night as well as day, radiated heat from thermally massive material is undesirable. Therefore, thermal

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16. Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 21.

mass should be minimized in both roof and wall materials; selected roofing material should be lightweight and able to minimize the absorbtion and storage of heat.

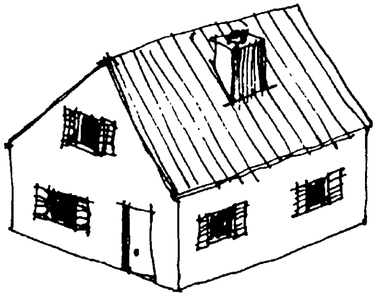
In higher elevations on the islands, temperature variations are more extreme and massive roofs and walls can be used in order to stabilize the building's interior temperatures. Solar heat gain stored in building materials are re-radiated to the building's interior during cooler night conditions.

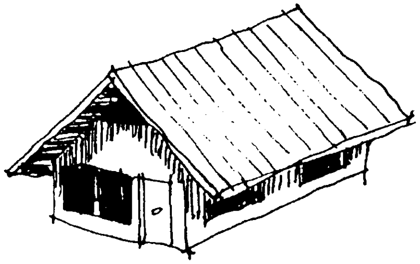
Roof Form

Roof Form for Solar Control

The roof form greatly influences a building's ability to naturally ventilate, shade, and collect energy. One of the major functions of the roof is to provide shade. Various roof forms utilized in Hawaii throughout the years have provided different degrees of shading. These are described below:

Missionary Gable The "missionary gable" roof did not have overhangs and therefore did not provide sun control for walls and windows. This roof was well-suited to the New England climate from which it was originated. Sunlight was welcome most of the year there, but these roofs were ill-suited to Hawaii's climate[17].





Top: Missionary gable roof
Bottom: Gable roof (Jim Pearson 12)

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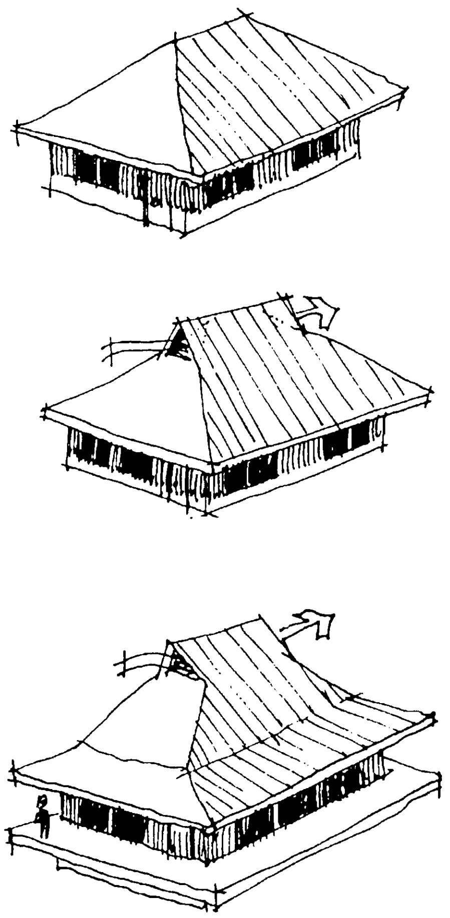
[17] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 12.

Gable roof The gable roof with overhangs provides sun control on only two sides and permits the warming and sun exposure on the other walls. The extension of overhangs on the gable ends have little effect as these overhangs tend to be too high above most windows to provide adequate protection from the sun and sky.

Hip roof The hip roof provides better low sun and rain protection on all sides and is well-suited to Hawaii's climate[18]. The modified hip roof (semi-gabled) can provide added ventilation for cooling the building.

Hawaiian roof The Hawaiian style roof, with its double slope, allows for steep roofs and a wide overhang that provides coverage with adequate headroom over lanais[19].



Top: Hip roof
Middle: Semi-gabled or modified hip roof
Bottom: Hawaiian style roof (Jim Pearson 13)

Roof Form for Solar Energy
When solar collection panels are placed upon the roof, south facing roofs are best for collecting the sun's energy. Sloped solar panels have a high solar exposure and can be easily supported and attached to these roof types. Panels can be efficiently placed adjacent to each other with little possibility of one panel shadowing another. Flat roofs are satisfactory for the placement of solar collectors. Horizontally placed panels are less efficient than slightly tilted panels (see Tilt efficiency figure on page 37). Here, collectors

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[18] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 13.

[19] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 13.

should be angled (this requires an additional support structure) to increase efficiency and spaced so that panels do not fall into the shadow of another.

Roof Form for Natural Ventilation

The roof form also influences a building's ability to naturally ventilate. High roofs with openings atop promote stack ventilation. The placement of roof openings on the leeward side of the roof also aid in drawing the warm air out of the building. In order to maximize stack ventilation, the height difference between the roof top outlet and the lower inlet should also be maximized. Roof top openings (outlets) should be at least equal or larger than inlet windows below[20]. Offset roofs with jalousie windows promote natural ventilation while allowing daylight deep into the space.

Roof Overhangs

Overhangs for Solar Control and Daylighting The appropriate architectural treatment for the roof can be determined from the sun angle chart (see page 26). North, south, east, and west sides have different sun exposures, thus a building's overhangs should respond to and reflect each sides needs.

The south facade will be exposed to various sun angles and intensities throughout the year. The most extreme exposure condition occurs on December 22nd, the winter solstice, when the sun's

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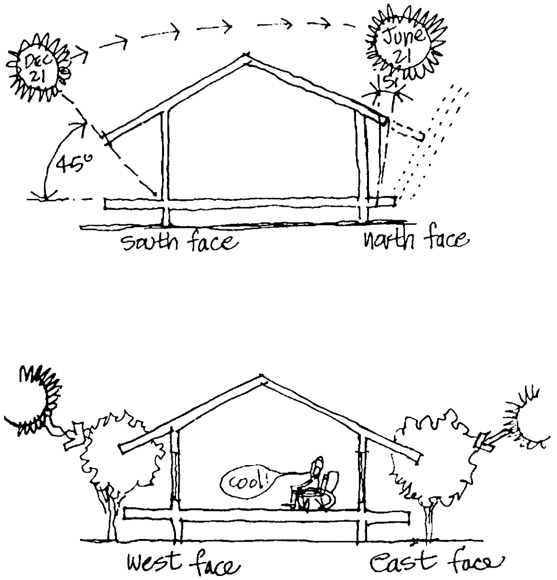
[20] Louchak Chan. An Investigation of the Effect of Roofing Design on the Thermal Performance of Single Family Residential Houses in the Hawaiian Climate, thesis, University of Hawaii at Manoa (May 1980) 79.

noon altitude is 45 degrees from the southern horizon. An overhang as deep as it is high will thus give complete protection from the direct sun within the living space of the home. Lanais are often used on the south side in order to utilize the shaded space beneath the wide overhang and are pleasant outdoor environments for Hawaii's climate.

The north facade, on the other hand, is only exposed to the sun during extreme summer conditions in June. This is the only time in which the sun actually enters the northern hemisphere of the sky. Thus, the north facade only needs a small overhang to protect openings in the wall from the June sun (3 degrees north of vertical at noon). The small overhang blocks out the direct June sun, yet allows ambient light from the north sky to naturally light the building's interior throughout the majority of the year.

The east and west facades receive the low early morning and late afternoon sun. Overhangs provide some shading for the higher sun angles. Protection from the sun at lower angles can be provided by horizontal shading devices or landscaping.



North, south, east, and west have different sun exposures and required different overhangs (Jim Pearson 17)

Overhangs for Natural Ventilation

Roof overhangs are not only desirable for shading, but also for cooling a building. Areas under the overhang are cooler than those exposed to the sun. As breezes past through these spaces the air is cooled before entering the building. Overhangs also aid in the process of natural ventilation by collecting, channeling, and directing breezes to inlets.

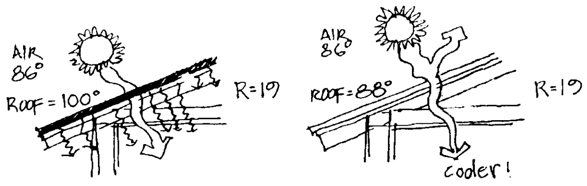
In order to be effective, roof overhangs should be low enough and wide enough to shade a window from direct solar exposure. Hipped roofs or the "Hawaiian roof" are the most effective at producing this effect.

Roof Color and Texture

When solar radiation strikes a roof surface, it is reflected, absorbed, or transmitted. The roof color, texture, and materials influence the proportion of radiation absorbed or reflected and thus the amount of heat gain within a home.

Increasing the reflectance of a roof reduces the amount of heat transmitted or absorbed by the roof and lessens the heat gain to a home's interior. Light colored materials or metallic surfaces have high reflectance factors and are effective at reducing heat gain. Because a metallic surface tends to lose shine over time with the collection of dirt and oxidation, light colored materials (white) are more effective than metallic materials[21].

The amount of radiation reflected is also dependent on the texture of a surface. In general, rough textured surfaces scatter radiation while highly polished surfaces reflect radiation. As a result, a rough textured surface generally absorbs more radiation than a polished surface.



The roof color greatly infuences the proportion of heat absorbed and reflected. Light colors are more reflective and reduce absorbtion (Jim Pearson 25)

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[21] Louchak Chan. An Investigation of the Effect of Roofing Design on the Thermal Performance of Single Family Residential Houses in the Hawaiian Climate, thesis, University of Hawaii at Manoa (May 1980) 47.

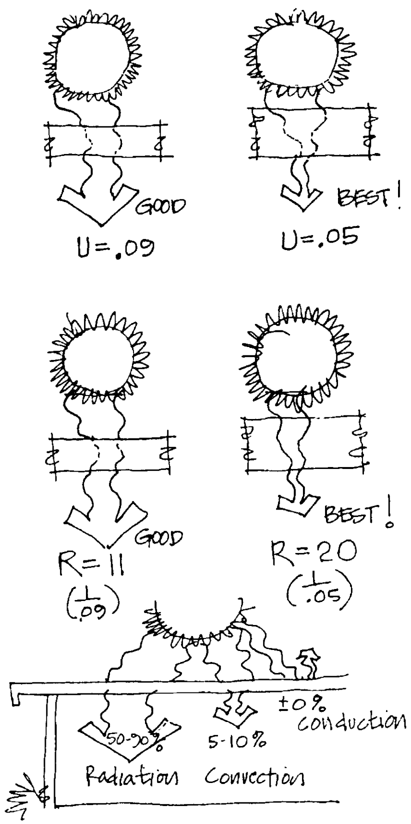
In hot climates such as Hawaii, one of the main objectives of the roof is to minimize heat gain to the building. Thus, homes in Hawaii should utilize light-colored roofing materials to reduce solar heat gain from the roof.

Roof Insulation

Another line of defense in preventing heat gain to a building is to insulate a roof. Uninsulated roofs result in large heat gains. Insulation decreases this heat flow through a roof and can be used to improve the thermal performance of an existing roof as well as a new roof.

In selecting insulation, the R (resistance) value determines the effectiveness of a material to resist heat flow. The higher the R value of an insulating material, the better its resistance to heat flow.

Insulation placed above a flat ceiling or within the sloped rafter space can greatly reduce heat gain within the space below. When insulation is used within a roof, an air space above it should be allowed in order to ventilate hot air and evaporate any moisture collected in the roof.



Top: High r-value insulation reduces the rate of heat radiation through the roof Bottom: Heat is transmitted through a roof by conduction, convection or radiation (Jim Pearson 21)

Radiant Barriers

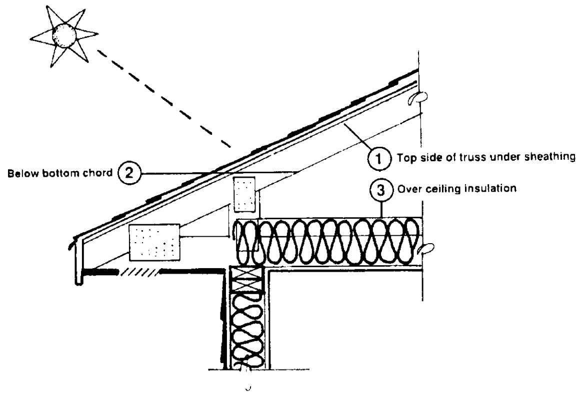
An addition to insulation, radiant barriers can also reduce radiant heat gain in a space. These barriers are an excellent solution for minimizing solar heat gains in new and existing homes. Radiant barriers are lightweight reflective materials that repel heat from the roof. Radiant barriers can be placed below the bottom of rafters, on top of rafters, or over ceiling insulation. Radiant barriers properly applied in several layers can be just as or more effective than bulkier, batt insulation.

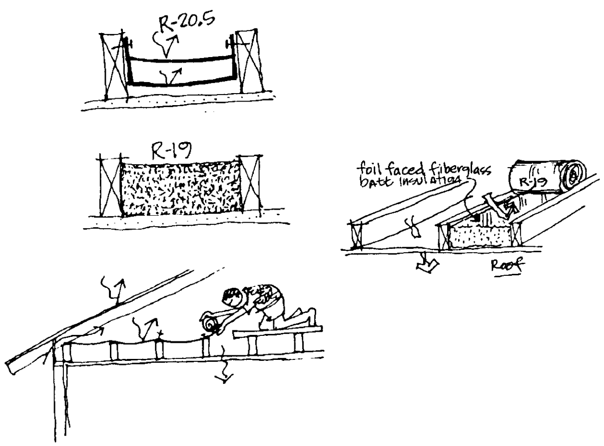
Radiant barriers work by reflecting radiant heat to the surrounding air which is then ventilated from the space. Ventilation can be achieved with soffit vents, ridge vents, gable vents, or hip vents using the natural buoyancy effects or pressure differences of air.

Products that combine batt insulation with radiant barriers can also be used. Because of the warm climate in Hawaii, the reflective foil side should face upwards to the airspace in order to be most effective.

Roof Openings and Vents
Roof openings with skylights or vents provide opportunities for daylighting and ventilation. Roof openings can be applied to both new and existing homes.

Roof Openings for Daylighting
Roof skylights are commonly used for daylighting. Skylights and skywells allow for the entry of daylight deep into interior spaces. Light provided from the skylight, like any other source of daylight, should be filtered, diffused, or reflected in order to avoid glare and bright spots that would otherwise cause human discomfort. Direct viewing of the skylight should especially be avoided in offices and other critical task areas. Clear skylights in Hawaii should be





Top: Section with three possible locations for a radiant barrier (State of Hawaii, Department of Business, Economic Development, and Tourism 42) Bottom: Properly installed radiant barriers can be just as effective as batt insulation (Jim Pearson 23 &24)

shielded from the direct sun as much as possible. A diffuse white skylight offers a large amount of light with little heat gain.

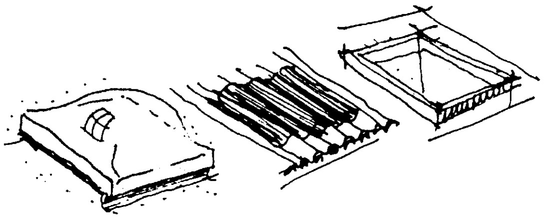
Roof Vents for Natural Ventilation

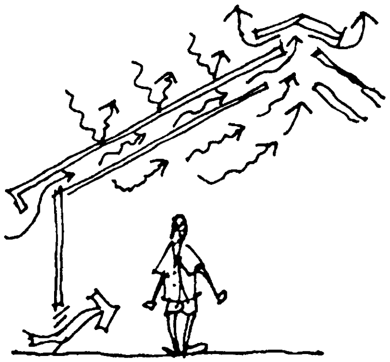
In addition to stack ventilation within the building space, ventilation between the roof rafters can also greatly reduce the accumulation of heat within a building. As mentioned above, roof vents and venting spaces are mandatory when insulation or radiant barriers are used. Attic vents at the peak of the roof and vents in the soffit allow air to circulate within the roof framing space and for warm air to escape. The circulation of air in this space also aids in evaporating moisture that can enter a roof space due to rain or high humidity levels.

Roof vents are manufactured in a variety of styles and shapes. These vents should be located as high on the roof as possible to take advantage of buoyancy effects of warmed air.

Gable vent Gable vents are often constructed out of metal or wood in various sizes and shapes. These are located on the gable ends and are more effective when faced normal to the direction of the tradewinds. Screens placed over the vents provide protection from birds and insects. In any case, vents must be protected from driving rains that could cause moisture problems in the roof.

Soffit vent Soffit vents can be either screened or louvered plates, continuous louver strips, or made by stapling screening over drilled or cut holes. Whatever the type of soffit vent, the function of these vents are to allow air into the attic space at the eaves to cool the



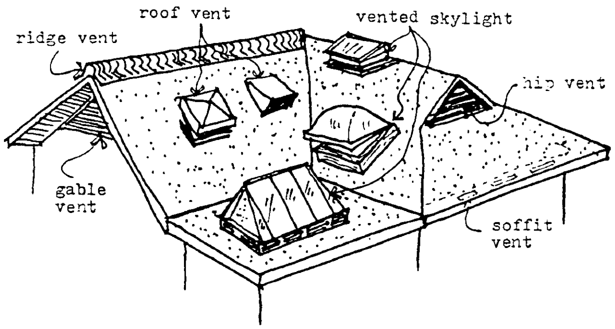


Top: Domed skylights, translucent corrugated fiberglass sheets, or flat skylights can allow daylighting (Jim Pearson 35) Bottom: Soffit vents and ridge vents aid in stack venting a roof (Jim Pearson 15) space between the roof and ceiling.

Hip vent A hip vent is actually a gable vent added to a hip roof (semi gable) by extending the roof ridge as a rain shield. Hip (semi-gabled) roof vents are common features of roofs in Hawaii.

Ridge vent Ridge vents are manufactured elements that attach to the ridge of the roof. They provide continuous hot air release that is protected from the rain.

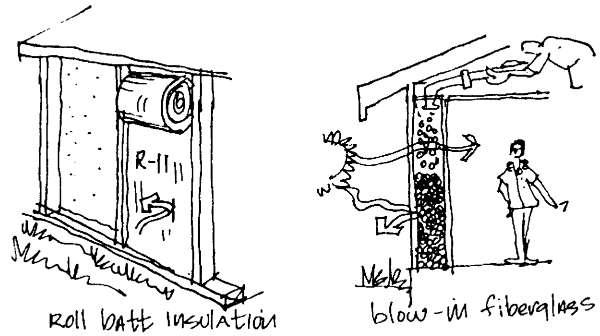
Vented skylight Skylights can provide both daylighting and natural ventilation. Fixed skylights do not allow for the warm air built up beneath it to escape. Vented skylights, on the other hand, allow for daylighting and venting. Most plexiglass skylights have vents to allow heat build-up to be released. Some are hinged so that they can be manually opened to let hot air escape.



Various types of roof vents (Louchak Chan 87)

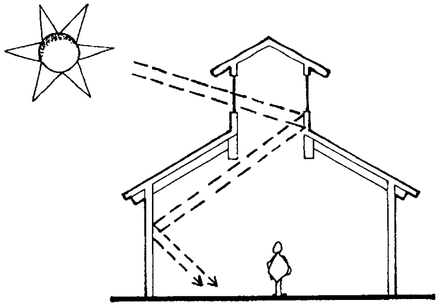
2.11 WALL DESIGN

Walls usually do not present as great problem of heat gain as the roof. Walls can be effectively shaded to mitigate the effects of the sun. Walls should act as barrier to the sun and heat, yet be open to breezes. Both single-wall and double wall types can be designed to minimize heat gain.



Wall Insulation

Double-wall construction offers the opportunity for insulating walls. The insulation of walls, although not as critical as the roof, can help mitigate the effects of the sun and increase thermal comfort. Insulation should be used in walls to prevent heat flow. Batt insulation or blown-in fiberglass insulation can easily be applied between wall studs. Because single-wall homes can not be insulated, shading of walls is essential to minimize heat gain.



Top: Roll batt insulation and blow-in fiberglass insulation (Jim Pearson 25) Bottom: Clerestory windows offer the lighting advantage of skylights with the control of heat gain and waterproofing (State of Hawaii, Department of Business, Economic Development, and Tourism 25)

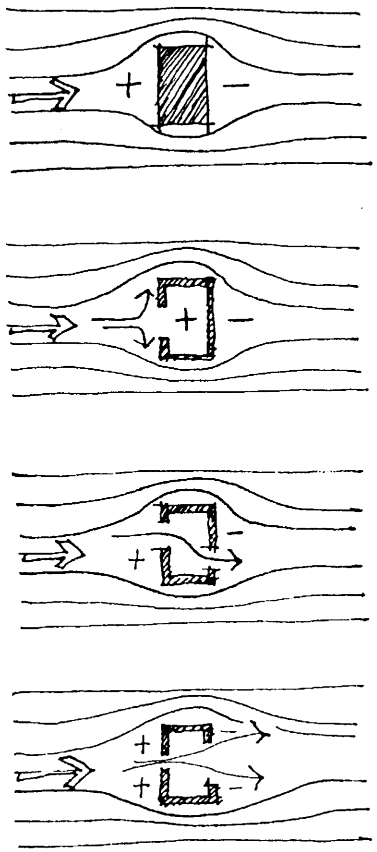
Wall Openings

Placement of Wall Openings for Daylighting

It is desirable to bring daylight as high as possible into a space to allow the light to penetrate deeper into the space. The proportion of a room, particularly the relationship between the ceiling height and room depth, is important to produce even lighting within a room. As a rule of thumb, the depth of rooms illuminated with openings on one wall should not exceed 2.5 times the height of the window wall[22]. The height of a window is more important than its width for maintaining an even distribution and quantity of light[23]. Offset roofs with clerestory windows or any type of highly placed windows are thus a good strategy for bringing light deep within a room. Clerestories offer the lighting advantages of skylights with the easier control of heat gain and waterproofing.

Placement of Wall Openings for Natural Ventilation

The movement of wind around a building will cause areas of varying pressures. Wind will cause a high pressure area (+) to develop on the windward side and a low pressure area (-) to develop on the leeward side. All habitable rooms must have two external openings (inlet and outlet) for cross ventilation to occur. If there is only one opening in a room, air generally will not flow into it. Differences in pressure are the driving forces in cross ventilation. The wind will flow faster through a space when the opening on the windward wall is smaller than the opening on the leeward wall.



Wind flow and pressures for various window placements (Jim Pearson 27)

Window types

The mild climate of Hawaii permits the use of wall louvers, jalousie windows, and single-pane casement windows.

Wall louvers and Jalousie windows

Wood or glass jalousies are common in Hawaii because they provide virtually 100% ventilation through a window. Because of the adjustable angle of each louver, breezes can be directed to various areas. Low level windows provide air movement across a seated

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22. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 25.
23. State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 25.

person or a bed. High level windows allow hot air to escape. Fixed screened metal louvers function in the same way, but do not have adjustable louvers and are less flexible.

Casement windows

Casement windows are generally not desirable in rainy tropical climate because they offer less rain protection than the jalousie window. The advantages of casement windows are that they provide virtually 100% ventilation through a window and have the ability to act as wind scoops.

Shading Devices

Shading Devices for Solar Control

In addition to the roof shape and overhangs, shading devices can also provide local solar protection of openings. Shading devices are advantageous where high walls (multi-story), inadequate overhangs, or extreme and various sun conditions occur. Devices for individual windows include both exterior and interior shades.

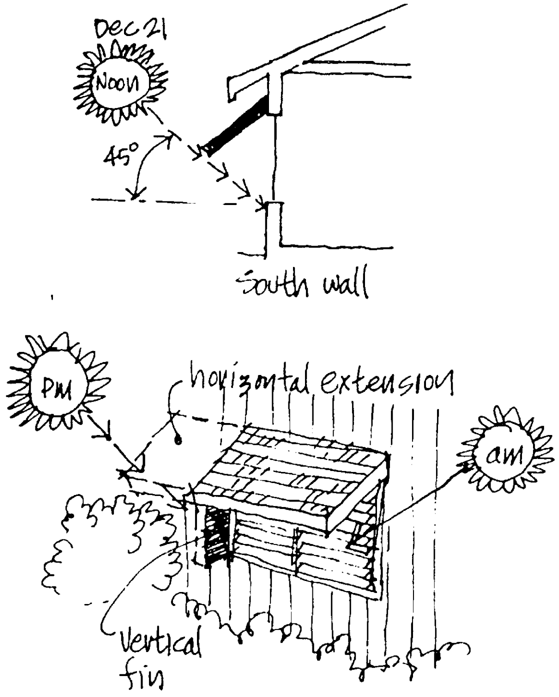
The effectiveness of a shading system is reduced as it moves from the building's exterior, to the glazing surface, to the building's interior. Exterior devices are the most efficient as it is more effective to intercept heat outside the building rather that inside. Exterior shading devices, glazing type, and interior devices can also enhance a building's character and architectural form.

Exterior Devices A variety of shading devices including horizontal, vertical and egg crate configurations can be used and should be appropriately designed to provide protection from the sun. Exterior shading devices block out the sun rays before they enter the building keeping the interior environment cooler and more comfortable.

The south facade is exposed to not only sun angles that are normal to it, but from a variety of side angles as the sun makes its daily path across the sky. Shading devices, such as a simple awning, on the south window can protect it from the 45 degree noon sun in December where overhangs are not adequate. There is also a need to protect against the morning and afternoon sun. This can be accomplished with the use of vertical fins that block the entrance of light from the side.

Openings on the north side, where other methods of sun control are not utilized, should be treated similarly to those on the south side. Because of the less severe exposure of openings on the north side, both vertical and horizontal shading devices should be smaller.

Shading devices are especially critical on the east and west sides. Ideally, openings on these sides should be minimized. These walls receive extended periods of exposure to the hot summer sun and are difficult to shade effectively. Here horizontal shading devices should be utilized in order to block out lower rays of the sun. Vertical fins also aid the block out the lower morning and afternoon sun.



Top: Exterior shading device to block low winter sun
Bottom: Horizontal or vertical fin shading devices (Jim Pearson 71)

<u>Interior Devices</u> Shading devices that can be categorized as inte-

rior shading devices include curtains, blinds, shutters, or drapes. Interior devices do little to stop the heat from penetrating the building. They reduce glare within the interior and in some cases (vertical and horizontal blinds) can redirect sunlight used for daylighting. The color of these devices is significant as a white blind is about 20% more effective in reducing heat gain than a dark blind[24].

Shading Devices for Daylighting

Shading devices should be used to filter daylight. Exterior shading devices, curtains and blinds can be used to produce more diffused and even light distributions. Venetian blinds, when properly adjusted, allow excellent control to reduce glare and distribute light. Light shelves adjacent to windows provide an effective overhang and reflecting surface that bounces light up to the ceiling and deep into the room space. Battens located in skywells also aid in filtering sunlight from the skylight above and can block direct views of the skylight.

Glazing Material

Glazing for Solar Control

In addition of the use of solar shading devices, special "high-performance" glass can reduce the amount of solar heat entering through an opening. A wide variety of glazing materials including heat absorptive, low emissive, reflective, and tinted glass can be

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[24] State of Hawaii, Dept. of Business Economic Development & Tourism. Hawaiian Design: Strategies for Energy Efficient Architecture, Publication (Hawaii: 1990) 21.

used to reduce heat gain to a space.

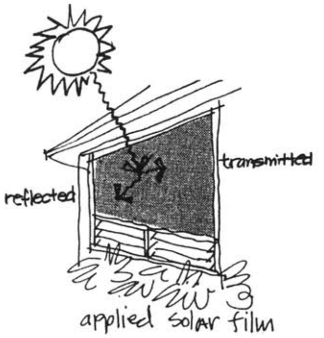
Heat absorbing glass is characterized by a dark tint and functions by partially absorbing solar energy which strikes the window and converting it to heat within the glass. This heat is then re-radiated from the glass to the building interior and exterior. The majority of the heat is released to the exterior resulting in a 20% to 35% reduction in solar heat gain[25].

Low-emissivity glass is coated with a layer that reflects infrared light without altering the transmission of visible light. The reflection of infrared light reduces heat gain to the space.

Reflective glazing and films are also effective in reducing solar heat gain. This type of glass incorporates a very thin film of reflective metal which acts like a mirror and reflects the sun's rays.

Glazing Materials for Daylighting

Transparent or translucent glazing can be used to provide daylighting. Transparent (clear) materials allow direct daylight to enter, glare problems, and views to the outside. Translucent (opaque) materials allow daylight to enter, a reduction in glare, and privacy. When either type of material is used their selection should be given special consideration. Color alterations caused by the materials can adversely affect the perception of interior spaces (i.e. tinted



Sunlight will be transmitted , absorbed, or reflected by glazing (modified drawing by Jim Pearson 20)

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[25] Jim Pearson. Hawaii Home Energy Book, (Honolulu: University Press of Hawaii, 1978) 20.

glazing can make a space look dark and gloomy). Common types of glazing materials used for skylights are plastic bubbles, translucent corrugated roofing materials and wired or safety glass.

2.12 FLOORS AND FOUNDATIONS

The design of the floor and foundation of a Hawaiian home does not need to consider solar daylighting needs as it is not exposed to the sun. An opportunity for natural ventilation exists in cases where houses are raised off the ground. Many homes in Hawaii were built this way. Raised floors are well-suited for the climate since it allows breezes to pass under the floor to naturally cool the home. Floor vents can also increase the air circulation in the home and bring the cooler air beneath the home into the building. Homes which sit on a footing or on a concrete slab do not have the ability for ventilation from below.

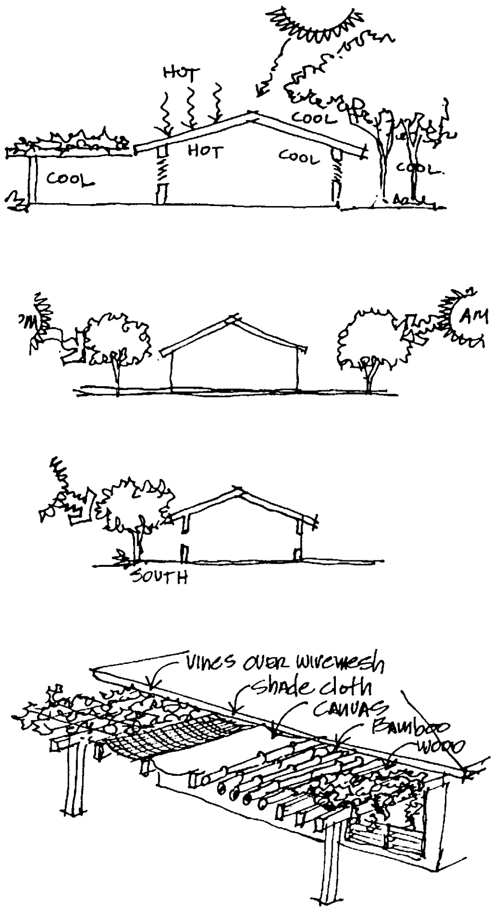
Floor vents

A raised floor can utilize floor vents as a means of natural ventilation. These adjustable floor register vents allow cooler air from under the house to move up into the living spaces.

2.13 LANDSCAPING

Landscaping for Solar Control and Daylighting

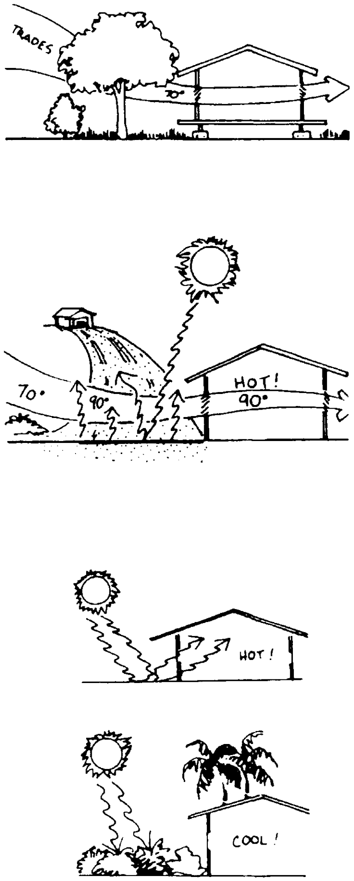
The landscaping surrounding a home can play a major role in energy conservation by providing shade, reducing heat and glare, and directing breezes. Trees, depending on their height, fullness, and distance away from the building provide different levels of solar control. Low height trees and shrubs are very effective means for protecting the east and west sides from the low morning and afternoon sun. Medium height trees placed a short distance from the east wall provide shade through the late morning by blocking the bright morning sun. Tall trees located adjacent to a building shade it from the high mid-day sun. Plants and shrubs located on the west and northwest provide protection from the intense afternoon sun. Vegetation can also reduce reflected glare. Trellises and hedges, and hanging plants can also be used to shade around openings where overhangs are inadequate.



Various landscaping strategically placed can reduce solar heat gains (Jim Pearson 108)

Landscaping for Natural Ventilation and Cooling

The surrounding landscape of the building can aid in directing and cooling the breezes before entering the building. Vegetation around a home may block tradewinds or serve to direct cooling ventilation to a home. A large tree will often direct winds downward, below its canopy and thus increase wind speeds. Trees and hedges can not only block undesirable wind conditions, but mitigate the effects of unpleasant noises and odors coming from the neighborhood and streets. Vegetation on the windward side will evaportively cool wind entering the building as the wind passes over the surfaces of its leaves. Vegetation adjacent to buildings can cool wind that has been heated by surrounding surfaces such as driveways, parking lots or other buildings. Thus, driveways and parking lots are better situated on the leeward side of a home.



Various landscaping strategically placed can evaporatively cool the natural breezes (Jim Pearson 108)

2.14 ENERGY EFFICIENT HOMES

The energy efficient home is a home that is responsive to the climate of Hawaii. Solar control, daylighting, solar energy collection, and natural ventilation are necessary design strategies for an energy efficient home. With the nation and the State of Hawaii in a precarious energy situation, energy saving for future homes is critical. The integration of energy considerations into the design can greatly increase energy savings in the future of Hawaii's homes that will benefit the people of Hawaii as well as the environment.

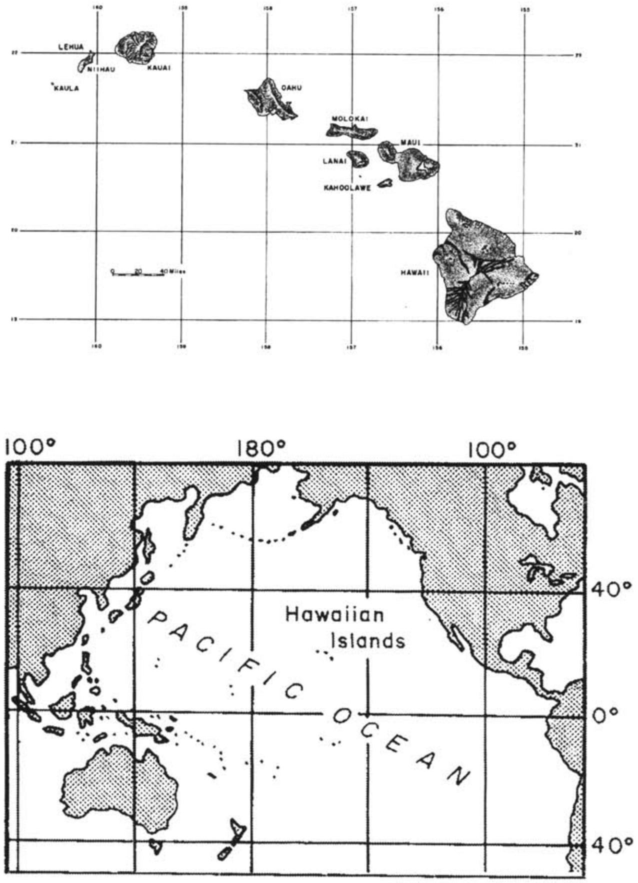
EARTHQUAKE RESISTANT DESIGN

3.0 EARTHQUAKE RESISTANT DESIGN

The designer of a Hawaiian home must also consider factors such as earthquakes, hurricanes, and termite attack. These problematic natural conditions are typical experienced by a home and are often overlooked in its design. Although these disasters are recognized threats to the people and buildings of Hawaii, only recently has the destruction caused by these natural disasters been documented and analyzed.

3.1 HAWAII'S VOLCANIC ORIGINS

The Hawaiian Islands exist as a group of volcanic islands in the center of the Pacific Ocean. The land area of the State of Hawaii is comprised of a chain of volcanic mountain tops that form the eight Hawaiian Islands. These islands, along with 124 islets, form a 1,500-mile crescent from Kure Island in the west to the Island of Hawaii in the east. They were formed by a hot spot (a magma plume) beneath the Pacific Plate. Geologists believe that this hot spot has slowly formed the islands over 80 million years (the Pacific plate slowly drifted over it in a northwesterly direction)[1]. Magma from beneath the earth's surface rose, and continues to rise, to form the Hawaiian Islands. The existence of the hot spot is proven by the relative ages of the islands, with the youngest island being Hawaii. Volcanoes are dormant except on the easternmost Island (Big Island) of Hawaii, where Mauna Loa and Kilauea remain as two of the most active volcanoes in the world.



Top: The eight islands of the Hawaiian Island chain (Harold T. Stearns 77) Bottom: The Hawaiian Island chain lies isolated in the middle of the Pacific Ocean where it is vulnerable to earthquakes and tsunamis (Gordon A. Macdonald & Agatin 4).

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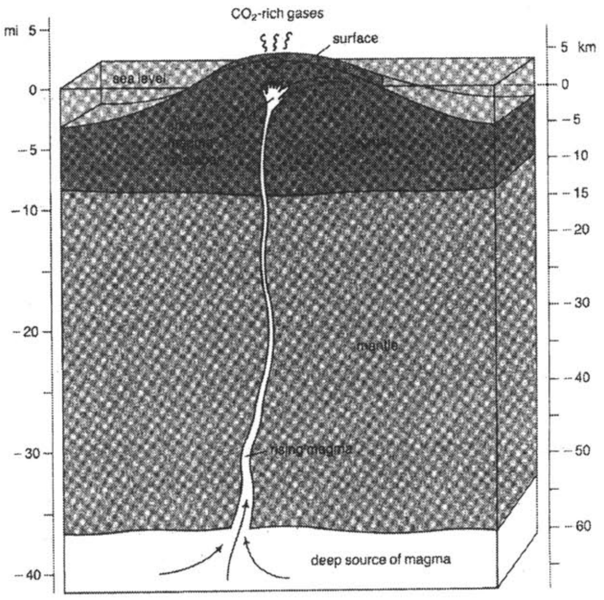
[1] "Volcanism", Encyclopedia Britannica v. 29 (Chicago 1990 Encyclopedia Britannica, Inc.) 521.

3.2 DEFINITION OF EARTHQUAKES

Earthquakes are caused by a variety of geologic events which include stress fractures within the earth's crust, volcanoes, and landslides. According to geophysical theory, the earth's crust consists of different plates floating on a semi-fluid core. These plates grind and scrape against each other creating stress when movements are restricted. Slow movements usually relieve this accumulated stress, but stress can sometimes accumulate causing the bedrock to fracture abruptly at fault zones. Abrupt fracturing of the ground produces ground vibrations commonly called earthquakes.

Fault zones do not solely occur at the edges of opposing tectonic plates, but also occur within the plate's boundaries. There is a web of numerous crustal breaks (faults) that result from the stresses of the plate collisions. These faults are all capable of moving and therefore can cause abrupt slippage that produce an earthquake. When the stresses of a fault are released in an earthquake, the highest intensity of vibrations is usually felt along the fault line nearest the point of slippage.

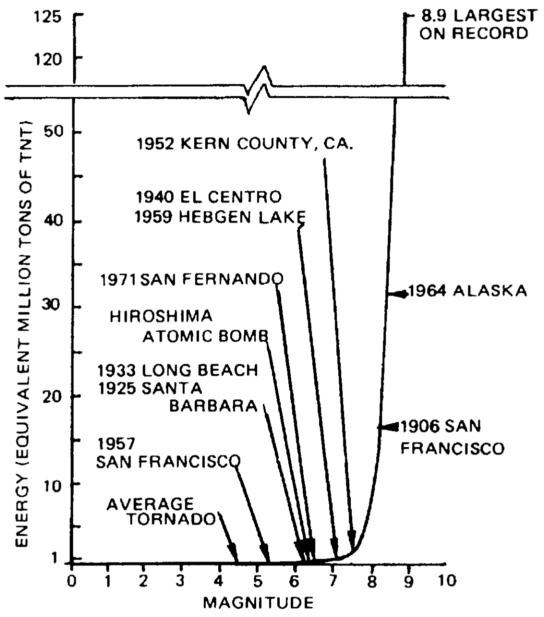
The strength of an earthquake can be measured in several ways. One commonly accepted measurement of earthquake strength is the Richter Magnitude scale. It measures the strain energy released when the bedrock fractures. The Richter scale, devised by Charles Richter, is a numbered scale with a value of zero at its lowest end and is open-ended at the upper end.



Section through a volcanic hot spot ("Volcanism" 515)

The scale of the amplitude of seismic waves increases logarithmically with each whole value on the Richter Magnitude scale. For example, an earthquake of Richter Magnitude 7 would have an amplitude of ten times and an energy increase of thirty times more than a Richter Magnitude 6 earthquake. Damage expected to be caused by earthquakes of different magnitudes are summarized as follows[2]:

An earthquake of Richter Magnitude in the range of 1 to 2 probably would not be felt or noticed. An earthquake of Richter Magnitude 4 to 4.5 would be felt and cause slight damage to poorly designed or seriously deteriorated buildings. An earthquake of approximately Richter Magnitude 4.5 to 5 would be expected to cause minor damage such as cracked plaster and cracked masonry in ordinary buildings and more severe damage to poorly built or deteriorated buildings and buildings with poor resistance to lateral forces. When a scale value of 6 or more is reached, building damage will be noticeable, relatively widespread in the area of the earthquake, and in some cases the damage may be significant. At a scale of approximately 7, serious building damage will be widespread, and there will be some collapsed structures. At a scale of 7.5 to 8, building damage would be widespread, severe, with numerous collapses, even including buildings designed with seismic resistance. The duration of the earthquake also affects the amount of damage.



Graph illustrating the exponential energy of earthquakes of different Richter magnitudes (Peter Yanev 41)

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[2] Stanley W. Crawley & Delbert B. Ward, Seismic and Wind Loads in Architectural Design: An Architect's Study Guide, (Washington D.C.: The American Institute of Architects, 1990) 81.

3.3 EARTHQUAKES IN HAWAII

The volcanic origin of the Hawaiian Islands and existence of fault lines account for seismic activity experienced throughout the islands. The islands have frequent volcanic activity and a continual recurrence of earthquakes. Although most of Hawaii's earthquakes have occurred in the southern half of the islands (the Island of Hawaii was among the highest risk areas to earthquake activity in the U.S.), they are not restricted to this area[3]. Earthquakes of large magnitudes have occurred throughout the entire island chain.

Since the majority of earthquakes are attributed to Hawaii's volcanic activity, they tend to be small in magnitude relative to earthquakes that occur along fault lines. Those associated with volcanic activity are frequent and have maximum magnitudes of 4 or 5 on the Richter scale[4]. Larger magnitude earthquakes are located farther away from active volcanoes and have no connection to volcanic activity. The earthquakes' centers are typically located along fault lines. However, most fault lines are not visible from the surface because of the lava flow covering. There are maps that trace the faults that cross the Hawaiian Islands and distinguish potentially hazardous areas.

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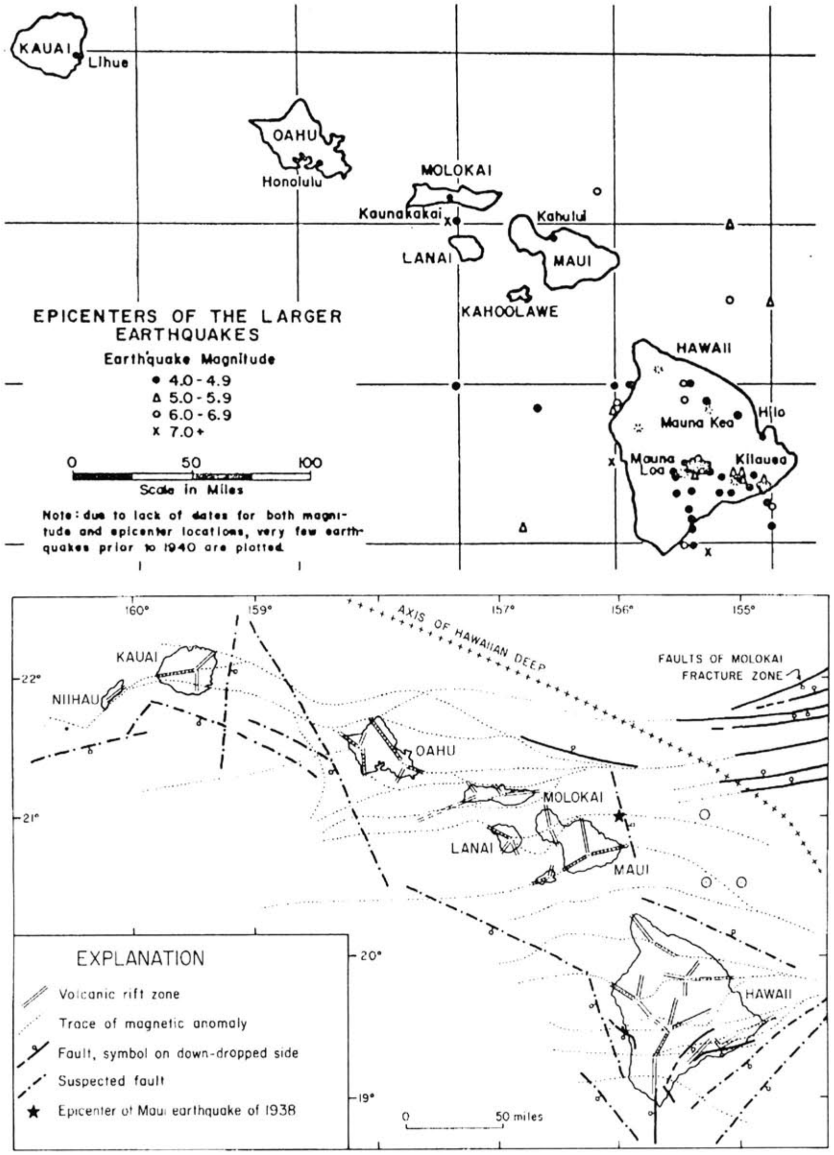
3. David Benaroya Helfant, Earthquake Safe: A Hazard Reduction Manual for Homes (Berkeley: Builders Booksource, 1989) 8.

4. U.S. Geological Survey Hawaiian volcano Observatory, Common Sense in Earthquake Country (http://www.soest.hawaii.edu/hvo/1995/95_03_10.html).

EARTHQUAKE RESISTANT DESIGN: EARTHQUAKES IN HAWAII

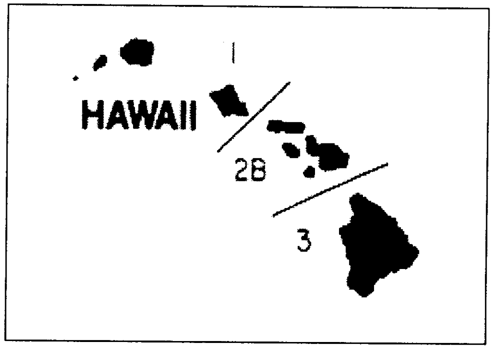


Top: Epicenters of Larger earthquakes in Hawaii (Bernadette Maria Paik 44) Bottom: Faultline Maps in Hawaii (Gordon A. Macdonald & Agatin 281)

Major earthquakes in Hawaii are relatively infrequent, yet their damaging effects cannot and should not be overlooked. If buildings are to provide safe dwellings for people, buildings must be seismic resistant.

3.4 TSUNAMIS IN HAWAII

Earthquakes exceeding 6.5 on the Richter scale can generate large ocean waves commonly known as tsunamis[5]. These seismically generated waves are potentially the most catastrophic of all ocean waves. In the past, they have caused severe destruction and loss of lives. The waves of a tsunami can strike within minutes or several hours after an earthquake, depending on the location of the earthquake. Very large earthquakes located in other remote areas of the Pacific can generate tsunamis that are potential threats to the islands. These waves can travel long distances at speeds of up to 500 mph[6]. When they reach shallow water, tsunamis can rise to devastating proportions and forces. They are particularly a threat to low-lying coastal areas, where serious destruction and flooding will occur.



Hawaii seismic zones (modified from Uniform Building Code 194)

During this century, there have been 13 significant tsunamis impacting Hawaii. These tsunamis were generated by earthquakes occurring along the geologically active margins of the Pacific basin[7]. On the Big Island there have been several signifi-

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[5] Oahu Civil Defense Agency, What is a Tsunami? (http://www.hgea.org.e911/tsunami1.htm).

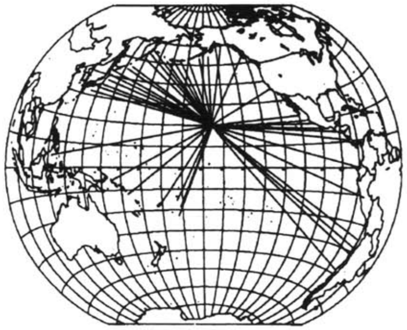
[6] Greg Barrett, "Hilo Town Awash in Memories of Tsunami." Honolulu Advertiser (March 31, 1996): A1-A2.

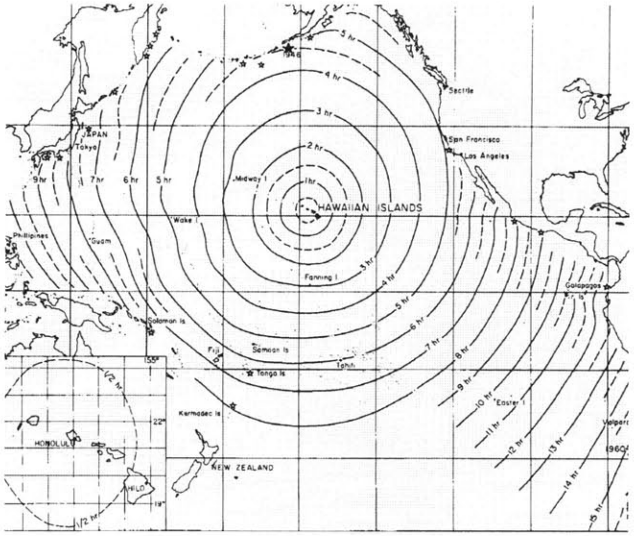
cant tsunamis resulting from local earthquakes or submarine landslides.

3.5 SEISMIC ZONING AND RISK

Earthquakes, their strength or their duration, cannot be accurately predicted by modern seismology. Earthquake prediction and seismic risk assessment relies on the probabilities of earthquake occurrence based upon the seismic history of an area. Estimates of seismic risk are represented in seismic risk maps. Such maps are based mainly on a statistical analysis of the number and intensity of earthquakes actually recorded in the areas since observations began. These evaluations are what determine the earthquake hazard zonation of different regions.

Seismic risk maps contain information about the relative levels of risk from damaging earthquakes in the area, but they do not and can not predict when such earthquakes will occur. Recent mappings by seismologist and engineers working with the International Conference of Building Officials have categorized four major areas by their risk of earthquake activity. Zone One presents itself as minimal to zero hazard earthquake activity. Zone two as a low to moderate risk of damage, Zones three and four present the most risk. Zone four areas are characterized by known active faults[8].





Top: Tsunamis recorded in Hawaii (Natiional Geophysical Data Center and World Data) Bottom: Tsunami distance in hours (Gordon A. Macdonald & Agatin 260)

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7. Hilo Tsunami Museum : Frequently Asked Questions (http://planet-hawaii.com/tsunami/faq.htm).

8. David Benaroya Helfant, Earthquake Safe: A Hazard Reduction Manual for Homes (Berkeley: Builders Booksource, 1989) 8.

Seismic zones range across the island chain with the highest seismic risk on the youngest Island of Hawaii. The Island of Hawaii is presently rated as a Zone three seismic risk zone although recent evaluation of the history of earthquake activity indicates that Hawaii falls well into the criteria for Zone four and should be rezoned[9].

The problem of predicting the time and location of earthquakes has become the subject of intensive study. Currently no forewarning can be given to the populace when a major earthquake occurs. The only defense against injury and property damage is to build earthquake resistant structures and to educate the public about earthquake safety. Earthquake property damage can be reduced considerably by the use of improved design, siting, and construction procedures.

3.6 DAMAGE CAUSED BY PAST EARTHQUAKES

The occurrences of early earthquakes in Hawaii have been documented, yet details of their strength and location are uncertain. It wasn't until the middle of the twentieth century that details of earthquakes were recorded. Little is known about earthquakes prior to this time because of the lack of documentation equipment. Damages described in this section have been acquired from reports of Hawaii's earthquakes in Kona (1951), Honomu (1973), and Kalapana (1975 and 1989).

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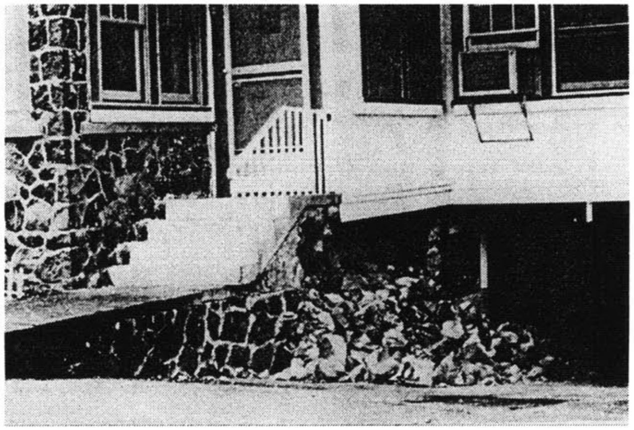
[9] U.S. Geological Survey Hawaiian volcano Observatory, Common Sense in Earthquake Country (http://www.soest.hawaii.edu/hvo/1995/95_03_10.html).

Reports indicate that wood framed structures generally performed well during earthquakes. Minimal damage occurred to well-built homes due to the short duration of the shaking action. However, not all homes were reported to have withstood the earthquake. As described earlier, many of the "plantation style" homes were constructed on post-and-pier or post-and-footing foundations. Wooden posts, inadequately fastened to the precast concrete footing or piers, often slipped. Many homes experienced permanent torsional deformations which made it difficult or impossible to close windows and doors. Differential settlement occurred in long narrow buildings and caused uneven displacement of buildings. Building material and joint failure also resulted.

Some homes experienced total collapse. In these cases, the collapse of houses appears to have been caused by inadequate bracing or poor underpinning material. In some cases, this was aggravated by insecure footings. Soil failure induced the collapse of structures as the ground that supported the home failed. Retaining rock walls and rock wall foundation failures were also common occurrences in earthquakes.

The Honomu earthquake of 1973 (6.2 Richter Magnitude) caused approximately 6 million dollars of damage. Although the earthquake's epicenter was located on the Island of Hawaii, tremors were felt approximately 350 miles away on Kauai. On this island, unreinforced lava rock walls failed and houses were shifted off their foundations.



Damage to lava rock masonry foundation walls during the Honomu earthquake (N. Norby Nielsen 9)

EARTHQUAKE RESISTANT DESIGN: DAMAGE CAUSED BY PAST EARTHQUAKES

The 1975 Kalapana earthquake (7.2 Richter Magnitude) caused widespread variety of damage including shattered plate glass windows, house and garages shifting from foundations, distortion of doors and doorways, leaks in roofs, and collapse of stairways and brick fireplaces. Cesspool cave-ins, collapse of stone walls and fences, and plumbing damage also resulted. The earthquake produced a tsunami which further added to the destruction. Damages caused by the major earthquake alone are estimated at 2.7 million dollars[10].

In the past, houses have performed well. Simple frames and the short duration vibrations are factors that likely contributed to the success of these designs. A large proportion of serious damage in previous earthquakes has resulted from poor construction or inappropriate materials such as unreinforce masonry.

Earthquake vibration damage has been quite minor. This is attributed to the fact that most large magnitude earthquakes occur on the Island of Hawaii where building developement is quite small in relation to the amount of land. If an earthquake were to strike the more densely developed Island of Oahu, damage would be more extensive.

Newer houses are more complex and many modern house fea-

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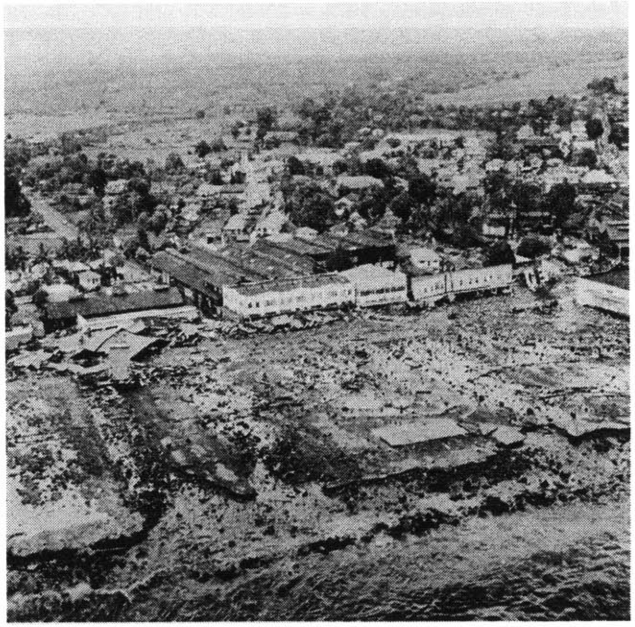
[10] United States Department of Interior, Robert I. Tilling, et al. Earthquake and Related Catastrophic Events Island of Hawaii, November 29, 1975: A Preliminary Report, Geologic Survey, (Arlington: 1975) 3.

tures are inappropriate for a seismically safe building. The following section offers some design options that would to increase a building's chances of withstanding an earthquake.

3.7 DAMAGE CAUSED BY PAST TSUNAMIS

Tsunamis generated from local and remote earthquakes have caused extensive damage and loss of lives. On April 1, 1946 the Island of Hawaii was hit by an eight wave tsunami. Three primary waves struck the town of Hilo with the last and largest wave cresting at over 50 feet and sweeping half a mile inland[11]. An earthquake on the ocean floor off the Aleutian Islands of Alaska, 2,300 miles away, generated the tsunami five hours earlier. This tsunami has been called the state's worst natural disaster. The tsunami struck at dawn and left 159 people dead and 1,421 homes damaged[12]. There were no warning systems at this time as little was known about the origins of tsunamis. Tsunami watches and civil defense sirens were non-existent. Huge waves snapped wood framed houses from their foundation and left them as piles of debris. Rows of wooden houses that lined the coastal area splintered and crumbled under the forces of the tsunami. Homes were either ripped off their foundations by the immense hydraulic forces or left badly damaged by the flooding waters.



Hilo town waterfront, devastated by the tsunami of April, 1946 (Gordon A. Macdonald & Agatin 257)

The 1975 Kalapana earthquake triggered a series of events includ-

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[11] Greg Barrett, "Hilo Town Awash in Memories of Tsunami." Honolulu Advertiser (March 31, 1996): A1-A2.

[12] Greg Barrett, "Hilo Town Awash in Memories of Tsunami." Honolulu Advertiser (March 31, 1996): A1-A2.

ing a tsunami, massive ground movements, hundreds of aftershocks, and a volcanic eruption. The tsunami reached a height of 40.0-47.9 feet above sea level. The earthquake, together with the tsunami, caused severe property damage to the Island of Hawaii. Estimates of damage approximated 4.1 million dollars[13]. The tsunami also caused two deaths.

The tsunami hit the sparsely populated areas of the southeast coast of Hawaii. There would have been considerably more property damage, injuries, and deaths had the tsunami hit a more populated area.

Although watch and warning systems for tsunamis currently exist, there is little that can be done to withstand the immense hydraulic forces of a tsunami. Residents are usually given early enough warning to allow for the evacuation with some belongings. After the people evacuation, homes within these coastal evacuation areas are left to withstand the tsunami and in the past many have been destroyed.

3.8 SEISMIC EFFECTS ON BUILDINGS

The main purpose of earthquake resistant design is to prevent loss of life and personal injury, and only then to minimize damage to property. In determining the seismic requirements for a new home, various factors need to be considered:

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[13] United States Department of Interior, Robert I. Tilling, et al. Earthquake and Related Catastrophic Events Island of Hawaii, November 29, 1975: A Preliminary Report. Geologic Survey (Arlington: 1975) 1.

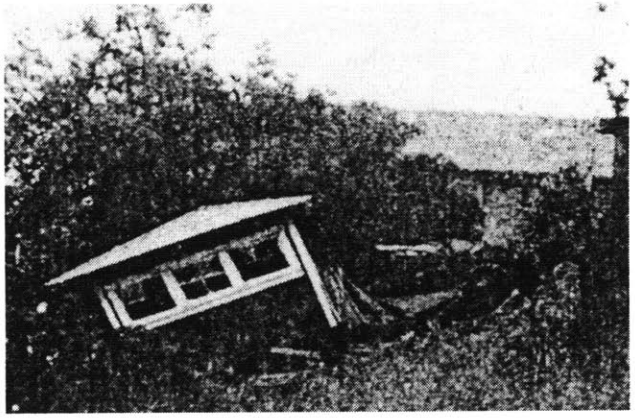
a) the probability of occurrence of a strong earthquake on site
b) the characteristics of site and surrounding soil
c) the building configuration and material
to be utilized

Overall, when designing for an earthquake or hurricane in Hawaii, the prime consideration is to build a structure that can withstand lateral forces.

3.9 SITE PLANNING TO REDUCE RISK

Careful site planning can reduce a building's risk from potential seismic related hazards such as floods, landslides, and tsunamis. Areas in close proximity to fault lines, areas with soft soil, and areas with unstable soil conditions are especially susceptible to damage from the vibration of the earth. Thus, as a part of site planning, it is critical to determine soil behavior in response to seismic action. Careful geotechnical investigation of a site's soil properties, proximity to known fault lines, and slide zones should be conducted in high-risk areas.

Buildings located on hillsides face problems of localized landslides. Natural geologic deficiency or man-made problems can make a site more prone to landslides. Unstable soil conditions, heavy rains, the slope of the land, and the occurrence of earthquakes are all factors that can lead to landslides.



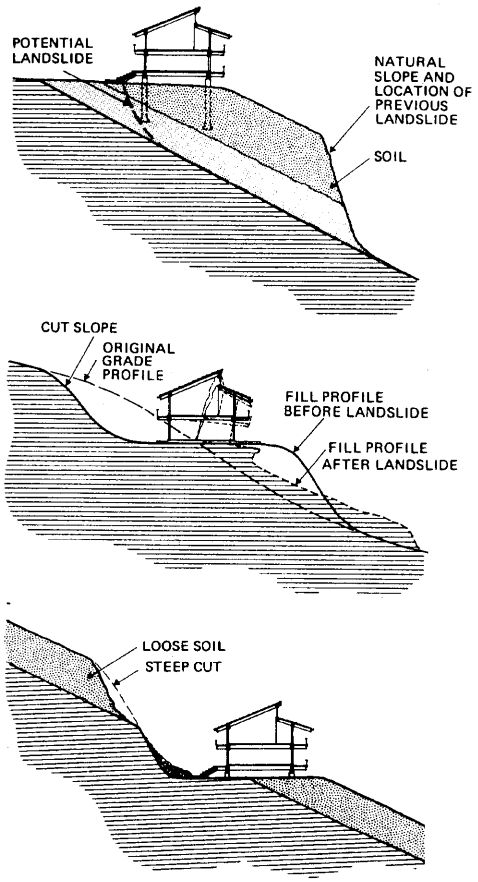
Top: Demolished home Punaluu Hawaii caused by earthquake related tsunami 1975 (Robert I. Tilling 13) Bottom: Post-and-footing failure caused total collapse of the structure (Gordon A. Macdonald & Wentworth 275)

Stable soil conditions can be made unstable because of careless or poorly engineered grading or landfill. Heavy rains or earthquakes can easily induce landslides in these areas. When slopes are cut, it is important to ensure the design and integrity of retaining walls and good drainage conditions on sites. Well-designed retaining walls and drainage systems reduce the chance of sliding induced by earthquakes. In areas where slopes are regraded with added fill, the nature of the fill and its placement are key issues. Typically a properly filled site utilizes materials that have granular or sanding components. These encourage good drainage and are less subject to shrink and swell from water saturation. Fill should be placed in layers and compacted to 90% of its ultimate compacted state so land subsidence does not occur[14].

Coastal areas are especially susceptible to damage from tsunamis. Cliff sides are pounded and low-lying coastal regions are plowed and flooded by these huge waves. Thus, as a part of site planning, it is critical to recognize the threat of tsunamis to these areas.

Soil Conditions

Foundation soil knowledge is essential to earthquake-resistant design. Soil conditions and subsurface soil structure can dramatically affect the amount of vibration that is transferred to a building during an earthquake. Soil profiles have recently been reclassified



Building site prone to a land slide Top: Soft soils make this site prone to sliding Middle: Naturally stable ground has been disrupted by improper grading and compaction making the ground prone to settlement of sliding Bottom: Steep cuts are prone to sliding (Peter Yanev 98 & 99)

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[14] Uniform Building Code 1991 Edition (Whittier: International Conference of Building Officials, 1991) 1000.

into four basic categories, S1-S4.

Table: Soil Types[a]

TYPE	DESCRIPTION
S1	A soil profile with either: a) A rock-like material characterized by a shear-wave velocity greater than 2,500 feet per second or by other suitable means of classification b) Stiff or dense soil condition where the soil depth is less than 200 feet.
S2	A soil profile with dense or stiff soil conditions, where the soil depth exceeds 200 feet.
S3	A soil profile 70 feet or more in depth an containing more than 20 feet of soft to medium stiff clay but not more than 40 feet of soft clay.
S4	A soil profile containing more than 40 feet of soft clay characterized by a shear wave velocity less than 500 feet per second.

a. Uniform Building Code 1991 Edition (Whittier: International Conference of Building Officials, 1991) 184.

In the Hawaiian Islands most of the soils have been formed by the decomposition of lava rock[15]. In other areas in Hawaii, deposits of volcanic ash lie over the lava rock. Soil depth varies in different locations throughout the islands. Beneath the soil is beds of lava rock.

Soil types and water table levels also influence the type of seimic-

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[15] Gordon A. Macdonald and Agatin T. Abbott, Volcanoes in the Sea: The Geology of Hawaii (Honolulu: University of Hawaii Press, 1970) 155.

ground movement. Soft soils tend to amplify the effects of ground shaking. In a comparison of damaged areas with different soil types during the 1973 Honomu earthquake, indicated that more damage was sustained by buildings located on deep volcanic ash rather than those on beds of lava rock. Volcanic ash is found throughout the islands as layers of ash were deposited in the final stage of volcanic activity. The Island of Hawaii still has areas where little ash is present due to its still active volcanoes.

Sandy soils with high water tables are vulnerable to liquefaction, tne of the most disastrous types of ground movements resulting from the vibrations of an earthquake is liquefaction. This is a phenomenon in which soil turns to quicksand when an earthquake suddenly vibrates areas with sandy clays and a high water table. Hawaiian volcanic ash has a high moisture content and liquefies even under the vibrating loads of construction vehicles[16]. Surprisingly liquefaction of ash has not occurred during previous earthquakes. Vibrations of longer duration could cause liquefaction, but whether or not the Hawaiian ash will liquefy under heavier shaking of longer duration is unknown.

High water tables or saturated soils caused by poor drainage produce immense hydrostatic pressure on a building's foundation or retaining walls. Hydrostatic pressure augmented by earthquake motion can cause extreme damage. Special consideration must

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16. N. Norby Nielsen and Augustine S. Furumoto, The Honomu, Hawaii, Earthquake (Washington D.C.: National Academy of Sciences 1977) 16.

be given to the structural integrity of foundations and retaining walls and the drainage of water around them.

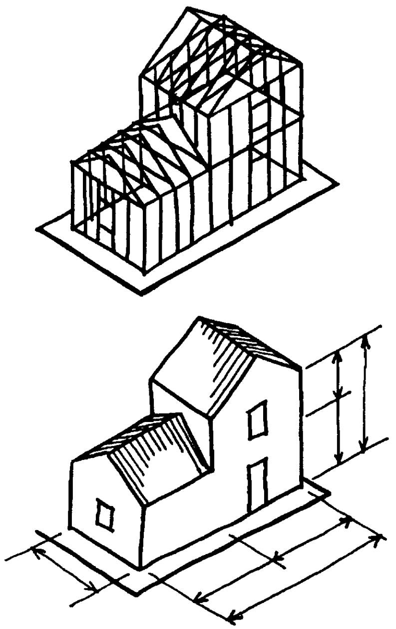
3.10 BUILDING CONFIGURATION FOR SEISMIC DESIGN

Even during the early schematic stage of design, decisions about a building's configuration, materials and detailing play a major role in determining the seismic resistance of a home. Research on building performance in earthquakes indicates that a building's geometry and the arrangement of its components have a major effect on the distribution of earthquake forces thus its structural behavior. In plan, elevation and section, certain configurations can positively influence a building's seismic performance.

Configuration of Plan

The configuration of a floor plan plays a significant role in determining a home's seismic resistance. The arrangements of the composite elements, the relative shapes, and proportion influence the seismic behavior of the building.

Simplicity The analysis of the effects of earthquakes has repeatedly demonstrated that the simplest structures have the greatest chance for survival[17]. Simple configurations such as squares and circles are most desirable. These structures have an advantage over more complex forms, for it is easier to predict their behavior in an earthquake. Simpler configurations tend to consist of straightforward structural systems and details. These buildings types con-



Aspects that influence building configuration: size and shape of building; nature and size of structural and non-structural elements

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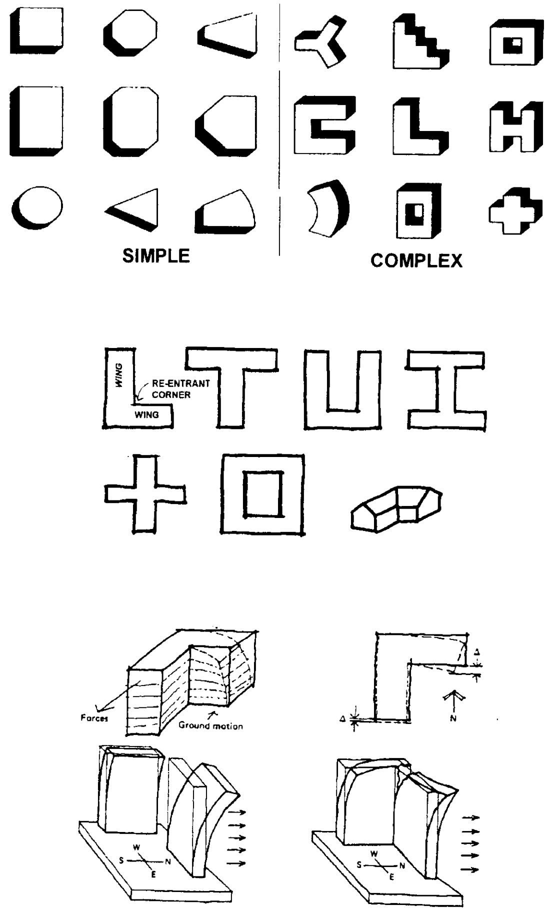
[17] D.J. Dowrick, Earthquake Resistant Design. (London: John Wiley & Sons, 1977) 81.

tain fewer connection points, which are also vulnerability. More complex building plans such as T, L, and H shapes should be avoided. These shapes are typified by wings and re-entrant corners where seismic stresses concentrate and failure is likely to occur. Buildings with such complex plans should be carefully detailed and constructed at building connections to withstand the different reaction forces of the wings.

Symmetry Structural symmetry can also enhance a building's seismic resistance. Symmetry is the basic design principle that contributes the most to the reduction of torsional (twisting) stresses. Asymmetry will almost inevitably lead to torsion and stress concentrations. As a building becomes more symmetrical, its torsion and stress concentrations are reduced. True symmetry in both directions or in all directions (as in a circular plan enables a building to resist forces equally from all directions.

Past studies of building performance indicate that even the slightest deviation from symmetry can drastically affect a building's performance. However, buildings can exist with an asymmetrical plan yet have a resistance system that acts in a symmetrical way due to the distribution of interior components. Conversely, a "false symmetry" can exist when a building appears to be symmetrical yet interior components such as stairwells or closets are unevenly distributed and produce stiff elements that increase the probability of torsion[18]. The building will tend to rotate and twist around this cen-



Top: Simple versus complex building plans (Christopher Arnold 232) Middle: Complex shapes with re-entrant corners of concentrated forces (modified Stanley W. Crawley 120) Bottom: Differing motions of wings produce reentrant corner (Chirstopher Arnold 88)

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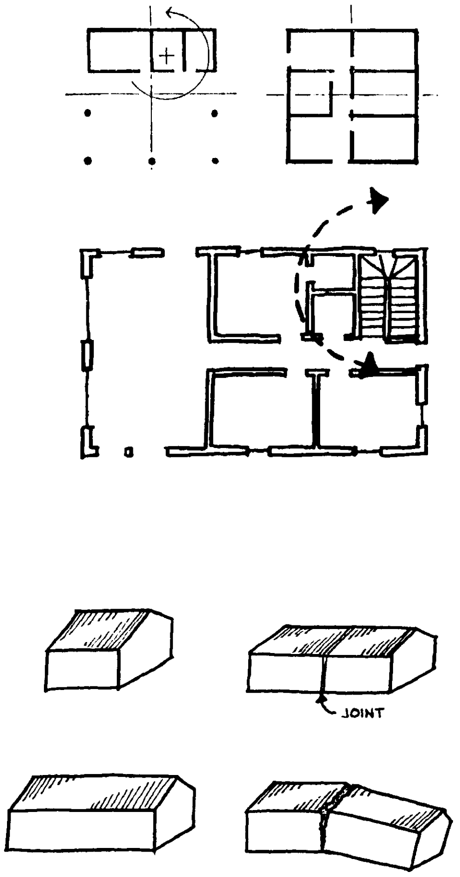
18. Christopher Arnold, Building Configuration and Seismic Design. (New York: John Wiley & Sons, 1982) 60.

tral area of stiffness.

Compactness Compactness of a building plan allows for a building to respond as an entire unit in an earthquake and resist forces equally in all directions. When a building plan lacks compactness and becomes extremely large, it has trouble responding to seismic forces as an entire unit. A home that has a long extended plan will have a greater chance of experiencing different earthquake movements simultaneously. Horizontal displacements are more likely to take place with these potentially various forces acting on the building which would produce disastrous results. A solution to this problem of elongation would be to break the home into two separate structures, which allows both parts to move independently from one another.



Top: The center of gravity and stiffness should be placed as close as possible to avoid twisting (David Oakley 63) Middle: Closets and stairs produce stiff areas around which rotation occurs Bottom: Compact buildings are desirable. Elongated plans are susceptible to differing settlement types.

Configuration of Building Elevation

Another crucial factor that should be considered in the seismic design of a building is the form of the elevation. The design of the vertical configuration should be a compromise of uniformity, continuity, and proportion.

Continuity & Simplicity The vertical configuration of a building should be as continuous as possible. Drastic height changes of a building's elevation results in re-entrant corners and areas of concentrated forces. When the vertical configuration is discontinuous, large vibrating motions take place in some areas and special detailing must be used where these abrupt changes occur. Examples of building elevations with abrupt changes are split level homes or homes with exterior walls of various heights.

Proportion In seismic design, the proportion of a building, rather than its absolute size, is more significant[19]. Buildings with large slenderness ratios (height to width) will have large lateral displacements whe subjected to earthquake and wind forces. This is not a major problem for homes in Hawaii, as most are one or two stories in height and large slenderness ratios are not common. As one can imagine, a building with a small floor plan and two stories high will be more easily overturned than a low lying building with the same floor area.

Top left: Simple building elevation with continuity Top right: Complex elevation with soft story and large windows Bottom left:: Elevation with a large slenderness ratio Bottom right: Elevation with a small slenderness ratio

Configuration of the Building Section

There are several strategieswhich increase a home's chance of survival during an earthquake. Structural discontinuities should be avoided at all times. Columns and beams should be appropriately sized and securely connected. Openings in floors, roofs and shear walls should also be avoided. Overall, the structure should be as continuous, redundant (have several alternate load paths), and monolithic as possible[20].

Continuity Sudden changes in the vertical distribution of stiffness and strength should be avoided. Soft stories, cantilevers, and heavy roofs should be avoided. Soft stories, although helping to absorb small lateral forces, can cause the entire building to collapse under larger forces. Stiffness and strength can be adjusted

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[19] Christopher Arnold, Building Configuration and Seismic Design. (New York: John Wiley & Sons, 1982) 55.

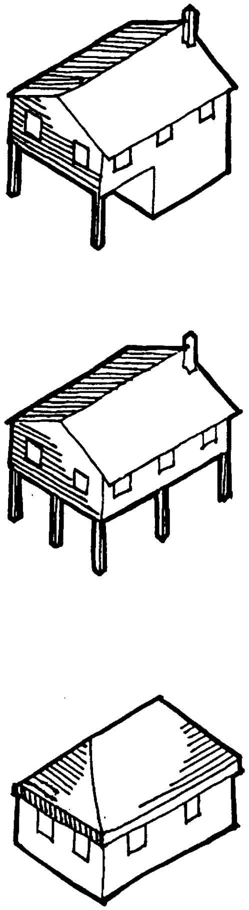
[20] D.J. Dowrick, Earthquake Resistant Design. (London: John Wiley & Sons, 1977) 83.

by increasing the size of columns and/or bracing in the soft stories. Cantilevered floors cause reentrant corners. The column and wall supported areas will experience different motion types and create large stresses at the corner connections. The most efficient seismic configuration would provide the greatest intensity of vertical resistant elements at the base where they are most needed and thus a substantial building foundation should be employed[21].

A heavy roof or any other type of concentrated mass elevated above ground can amplify earthquake motion. A building will act similar to an inverted pendulum as the elevated mass increases the effects of the earthquake.

Principal members that change section suddenly, as well as columns or walls that are not continuous or vertically aligned, can also cause major problems during an earthquake. These abrupt changes in a building section are common points of failure during an earthquake. Detailing these areas also becomes very difficult.

Uniformity Uniformity in column and beam sizing is important to the seismic reaction of the building. Columns and beams of similar width promote good detailing and aid in the transfer of moments and shear forces at connections. When columns of various sizes and height are used on a single story, shorter columns and beams are stiffer. It is in these, rather than in longer members, that the stresses are concentrated. Thus, shorter columns and beams are



Discontinuities in a building section Top: Cantilevered floor Middle: Soft story Bottom: Massive, heavy roof

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[21] Christopher Arnold, Building configuration and Seismic Design. (New York: John Wiley & Sons, 1982) 61.

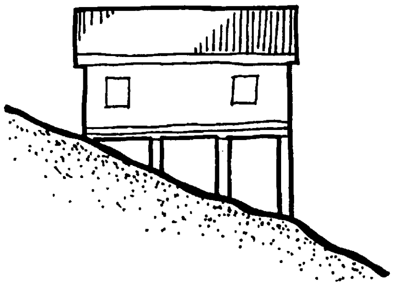
the first to fail during an earthquake [22].

Avoidance of Large Openings Large openings in floors, roofs and shear walls in the form of atriums or doorways should be avoided. These are weak points in the structure where failure is likely to occur. Openings in floors and roofs and walls should especially be avoided near the perimeter of the building.

Redundancy Structural redundancy is very important in a section. A well-connected, well-supported structure allows for alternate load paths that enable forces to reach the ground in a variety of ways. Redundancy is especially helpful in light-framed wood construction where material is minimized. High redundancy is desirableso that local failures do not induce the total collapse of the structure.

Overall Building Configuration for Seismic Resistance

Overall, the shape and proportion of a building has a major impact on its seismic performance. According to various building codes written over the past years buildings that are "regular" in form are more ideal than those that are "irregular"[23]. The design of irregular buildings entails complicated analysis and detailing methods. The 1988 Uniform Building Code defines the conditions of building irregularity and contains special provisions for their design.



Discontinuity in building section; Columns lack uniformity

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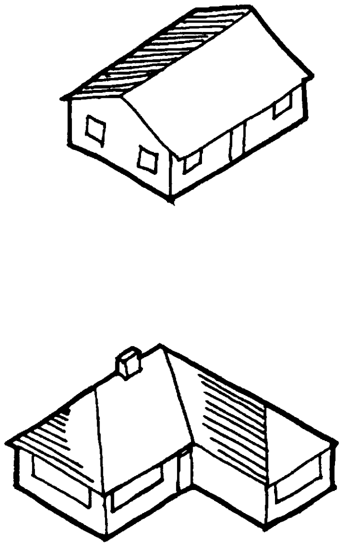
[22] Monoru Wakabayashi, Design of Earthquake-Resistant Buildings. (New York: McGraw-Hill Book Company, 1986) 228.

[23] Stanley W. Crawley & Delbert B. Ward, Seismic and Wind Loads in Architectural Design: An Architect's Study Guide. (Washington D.C.: The American Institute of Architects, 1990) 105.

Regular vs. Irregular Regular building configurations are classified as systems that show uniformity of elements and symmetry in both directions. Crawley, the author of *Seismic and Wind Loads in Architectural Design* states "The ideal form of a building for seismic performance would have a symmetrical plan, short spans, direct load paths, low unit stresses, a broad base, and symmetrically reducing plan size [24]."

The ideal building configuration to resist earthquake forces is as symmetrical as possible in plan and elevation. Such configurations allow for the most even and balanced distribution of earthquake forces. Irregularities, such as setbacks and re-entrant corners cause stress concentrations and twisting (torsion) that is difficult to analyze and resist. Overall, the building design should be simple, continuous, straight forward, and repetitive. Poor choices of the configuration of a building will create a poor structural form that could prove disastrous during an earthquake.

Although regular building configurations are ideal, most buildings are irregular for aesthetic and other practical reasons. Irregularities can not always be avoided, but should be avoided when possible and detailed in such a way to ensure safety and performance.



Top: Regular building configuration
Bottom: Irregular building configuration

3.11 MATERIAL CONSIDERATIONS

During an earthquake, ground motions caused by seismic waves

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[24] Stanley W. Crawley & Delbert B. Ward, Seismic and Wind Loads in Architectural Design: An Architect's Study Guide. (Washington D.C.: The American Institute of Architects, 1990) 107.

are transmitted to structures through their foundations. The type of construction, geometry, mass distribution and the stiffness properties influence the distribution and relative intensities of seismic forces within a structure to a large extent. In general, heavier elements in a building develop greater "direct" forces while stiffer elements receive a larger share of forces transmitted through connected elements. Lateral forces tend to concentrate at the roof and floor levels where mass is more concentrated[25].

Structural systems react differently during an earthquake due to the various properties of the materials and the type of connections used. Because of this difference in reactions, it is recommended that the combination of structural systems (i.e. both masonry and timber walls) be avoided.

Certain building materials perform better than others under earthquake forces. Generally, wood and steel construction are preferred because these materials are relatively light and because the materials are flexible and can deflect with the motion of the earth without cracking or breaking[26]. Rigid materials such as concrete, concrete-block and other types of masonry do not perform as well in an earthquake. Buildings utilizing these materials can also be made reasonably safe with proper reinforcing and detailing. Rein-

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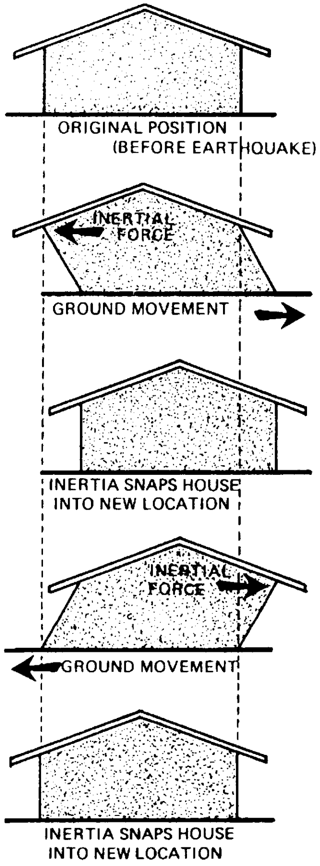
[25] U.S. Department of Commerce, National Bureau of Standard, Design Siting, and Construction of Low-Cost Housing and Community Buildings to Better Withstand Earthquakes and Windstorms, Publication 48 (Washington: GPO, 1974) 13.

[26] Peter Yanev, Peace of Mind in Earthquake Country (San Francisco: Chronicle Books, 1974) 135.

forced concrete and masonry performs well.

Light-framed wood construction is predominantly used in Hawaii because of it cost and availability. It is also popular because the minimization of materials and their light weight has made this type of construction relatively low in cost and easy to construct. The efficiency of materials eliminates structural redundancy within the structure and thus every element of the building plays a critical role in the performance of the structure.

Since most of the homes in Hawaii are made of wood, they are ideally resistant to earthquake damage whe nproperly designed and constructed. Timber structures are highly flexible and deformable due to the discontinuities in the wood members. The nailed joints are also able to dissipate earthquake energy. Still, past earthquakes have demonstrated that timber homes often do fail as the result of inadequate detailing. A house must be appropriately attached to its foundation and the components of its structure need to be tied together in order to make the house as safe as possible. Elementary reinforcing details applied to light-framed wood homes are not difficult to provide during construction and can greatly improve a home's chance of survival during an earthquake.



A building experiences lateral and vertical movement caused by earthquake forces (Peter Yanev 130)

3.12 CONNECTIONS

During an earthquake, a building experiences chaotic, irregular horizontal and vertical shaking motions. Sudden ground motions cause the building to be pushed and pulled in various directions.

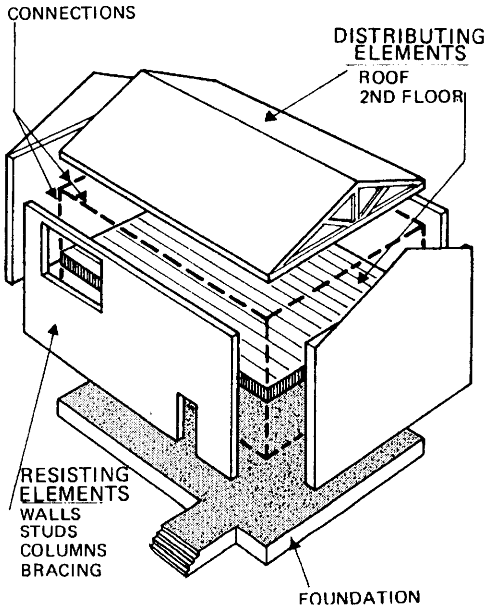
The structure must resist these abrupt movements and the bending and swaying actions of the building.

The superstructure of any building is designed chiefly to distribute and carry the weight of the building and occupants. Because buildings are, by their very nature, designed for vertical loads, vertical shock waves can be effectively resisted by most structures. The horizontal movement, however, can easily exceed the lateral strength of a structure. Conditions where earthquake-induced lateral forces are of special concern in buildings are[27]:

a) Connections of roof and floor systems to walls or other vertical members of the structure
b) Connections of walls to load-carrying frames or to foundations
c) Connections of partitions to floor and ceilings
d) Connections of cabinets and shelving to walls and/or floors

3.13 DESIGN FOR TIMBER-FRAMED BUILDING COMPONENTS

There are several means of protecting a structure from excessive earthquake damage. A structure can either be flexible or rigid. The choice of using either system is dependent upon local conditions, building materials, and other economic factors. On rocky ground, a flexible structure is generally recommended, whereas a rigid structure is more desirable on soft deformable ground[28]. Greater rigid-



Each building component has a critical role in distributing earthquake loads (Peter Yanev 129)

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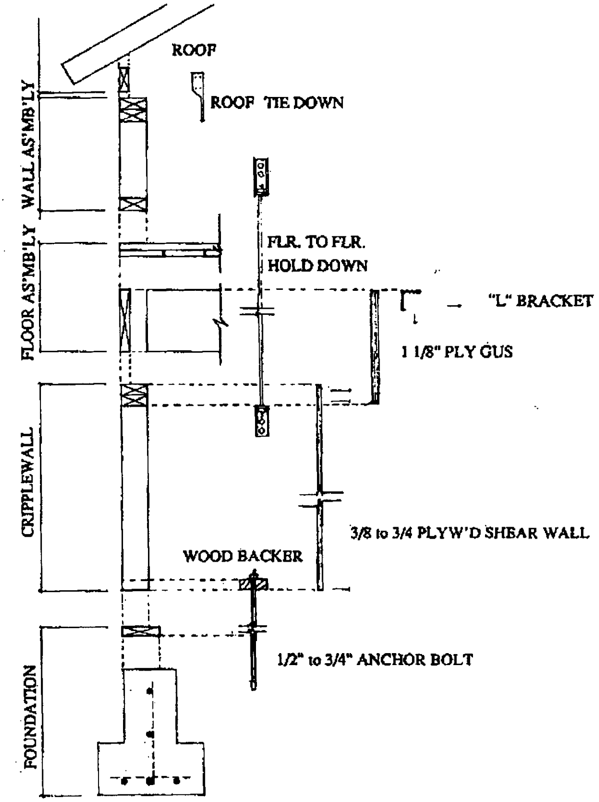
[27] Crawley, Stanley W. & Delbert B. Ward. Seismic and Wind Loads in Architectural Design. (Washington D.C.: The American Institute of Architects, 1990) 30.

ity generally results in higher costs, but it provides a more comfortable living environment (less shaking) for humans. In general, a building with good resistance to earthquakes should have: a vertical structure capable of withstanding horizontal forces; rigid horizontal diaphragms at each floor that transmit the lateral forces to vertical elements; and foundations designed to receive and transmit the shear forces generated between the foundation soil and the building[29]. Each building component plays a critical role in transmitting seismic forces.

When architects, engineers, and builders design a home to resist seismic motion, an often-stated principle of design is to "tie the building together." This enables a building to react as a unit to the seismic loads. It also addresses the need for each and every component to be secured to the next in order to create a continuous load path. This principle should be applied to both the superstructure (the part of the building above ground) and the substructure (the part of the building above ground below ground).

As mentioned earlier, well-detailed wood structures are ideal in an earthquake-prone region. The highly flexible timber members and joints, with the ability of its to dissipate energy, perform well in earthquakes. The design of their components and connections are



Typical recommended connections for a wood framed home (David Benaroya Helfant 41)

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28. United Nations, Department of Economic and Social Affairs, Low-Cost Construction Resistant to Earthquakes and Hurricanes. (New York: 1975) 74.

29. United Nations, Department of Economic and Social Affairs, Low-Cost Construction Resistant to Earthquakes and Hurricanes. (New York: 1975) 76.

critical in determining the seismic resistance of a home.

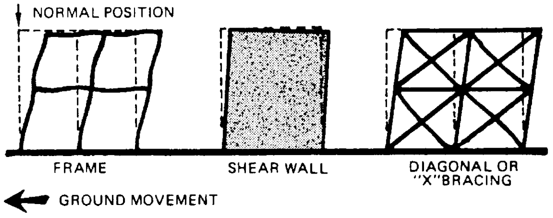
Walls, Frames, and Openings

During an earthquake lateral loads cause the walls of a building to sway and bend. Thus, the walls and columns in a home must be capable of withstanding horizontal forces produced by earthquakes. Walls transfer loads to and from the roof and foundation and thus proper connections to both the roof and foundation are critical. Walls should be properly anchored to the foundation with metal straps or bolts.

Shear Walls and Diagonal Bracing

Many light-framed timber constructed homes rely upon shear walls of sheathing to provide lateral support for the building. Shear walls are defined as "solid continuous walls of plywood or reinforced poured concrete serving either as the main bearing wall or as a second backing wall attached to the framing of the building.[30]" It provides a solid surface for the easy transfer of the earthquake forces back to the foundation and provides structural rigidity to resist lateral forces upon the structure.

Because ground movement due to earthquakes can be from a multitude of directions, shear walls should be incorporated into a building design to resist lateral seismic forces from as many directions as possible. The greater the intensity of the earthquake and the



Various types of lateral resisting elements (Peter Yanev 133)

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[30] Peter Yanev, Peace of Mind in Earthquake Country (San Francisco: Chronicle Books, 1974) 133.

longer the duration of vibrations, the greater the damage potential and the more shear force resistance is required. Shear walls act as a "stiffening panels" that resist movements in both the horizontal and vertical directions. Shear wall requirements should consider the soil conditions, seismic risk zones, building weight, and the framing design of the home. Homes on unstable soils, adjacent to known seismic zones, or with massive and/or tall forms require more lateral resistance and shear walls[31].

Diagonal bracing is another form of lateral bracing. It is the most common technique used for providing lateral resistance in a wood-frame house and other small buildings[32]. Diagonal bracing consists of a strip of lumber or a special strap of steel nailed at an angle across studs. Diagonal and "x" bracing (created when diagonal bracing is placed in the other direction) stiffen the framing of the building against excessive deformation and provide a direct path for the transfer of earthquake forces to the foundation. Diagonal bracing is less effective than shear walls, but if it is well design and detailed it can protect a home from substantial earthquake damage[33].

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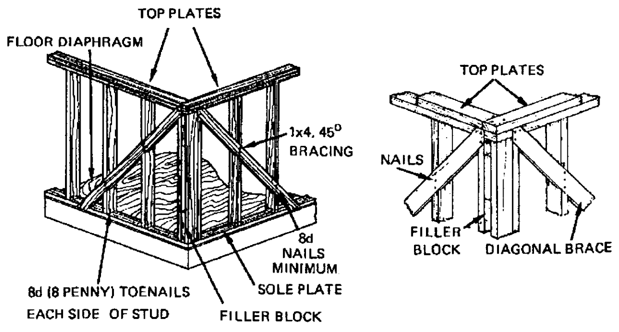
31. David Benaroya Helfant, Earthquake Safe: A Hazard Reduction Manual for Homes (Berkeley: Builders Booksource, 1989) 33.

32. Peter Yanev, Peace of Mind in Earthquake Country (San Francisco: Chronicle Books, 1974) 133.

33. Peter Yanev, Peace of Mind in Earthquake Country (San Francisco: Chronicle Books, 1974) 133.

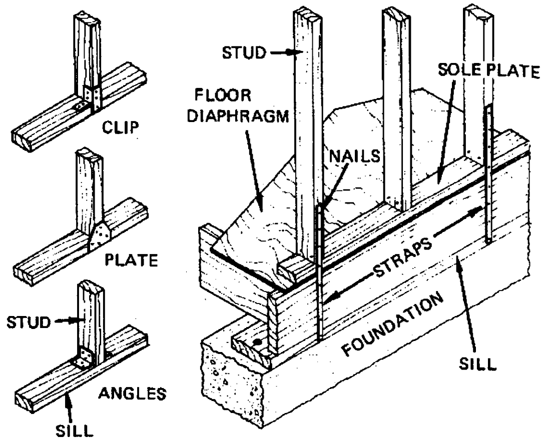
In addition to incorporating shear walls or diagonal bracing as lateral resisting elements, exterior walls should be prevented from separating at the top corners. This can be done by providing adequate connections that can accommodate tensile forces acting on the upper peripheral junctions of the walls. The tops of walls should be securely connected so that the all the walls can resists lateral loads as a unified whole. This can be done with the alternation of overlapping of top plates and proper connectors. Internal and adjacent walls should also be appropriately connected to external walls with the alternation of overlapping top plates and proper connections.



Balancing of Wall Elements

The seismic resistance of walls can be improved considerably by increasing the "balance" of the walls and ensuring reliable connections. The arrangement of walls, partitions and openings should be made in a balanced manner to obtain as uniform stress distribution in the building as possible. Areas with concentrated stiffness (i.e. with a cluster of walls) or large openings create unbalanced walls and should be avoided.

The location and size of openings can significantly impair the structural resistance of walls. To a certain extent, it is possible to strengthen walls by using smaller openings and by providing equal spacing between openings or between an opening and vertical edge of the wall. This creates a "balanced" wall. Large windows and windows placed at or near the corners of buildings should be avoided.



Top: Top plate connections should overlap (Peter Yanev 140) Bottom: Wood stud and wall connections need to be anchored with metal ties and plate (Peter Yanev 150)

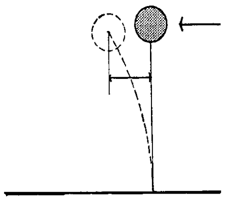
The failure of plate glass windows were a common occurrence in past earthquakes in Hawaii. In earthquake prone areas, large openings should be avoided for these are areas of discontinuity and likely to fail. Safety glass should be used in large openings to minimize bodily harm.

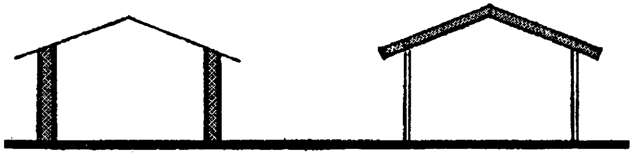
Floors and Roofs

Floor and roofs play an essential role in the seismic resistance of a home. Well-designed and constructed floors and roofs are rigid diaphragms. These rigid diaphrams distribute lateral forces throughout the floor and to the many vertical resistive elements of the building. Rigid diaphragms, consisting of timber joist or beams and sheathing, should be located at every floor in any earthquake resistant building.

Reducing the floor or roof weight can also improve the seismic performance of a building. Heavier roofs and floors produce areas of concentrated mass, which tend to amplify the dynamic motion of the building. Reduction of the floor and roof weight can be achieved by using shorter spans and the use of load-bearing interior partitions. Roofs can be lightened without the loss of strength by substituting lighter-weight materials for roof coverings in lieu of heavier, bulkier types. This reduces the both the lateral and vertical forces that need to be carried by the walls.

Roof rafters and trusses should be well connected to the top plates and reinforced with metal ties (hurricane ties). Continuous block-





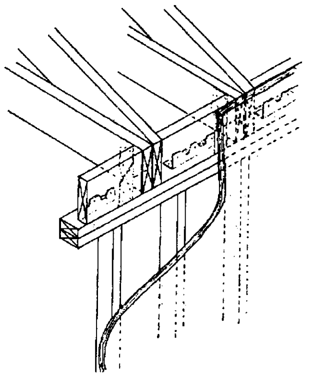
Top: Mass concentration at roof can amplify earthquake vibrations and cause the buidling to act like a pendulum (David Oakley 62) Middle: Mass concentration in walls is more desirable than in the roof (David Oakley 63) ing in between rafter and trusses and anchoring the blocking to the plate with metal fasteners will further increase the strength of the roof.

Where roof geometry is complicated ("L", "T", and "H" -shapes) or where hips and valleys occur, the intersections between the roof components must be fastened securely in order to retain the overall structural integrity of the roof.

Foundations

During an earthquake, the foundation of a building is subjected to varying stresses, frequently of an alternating nature. Accordingly, the foundations of earthquake-resistant buildings must be carefully designed to withstand shearing, twisting, and bending in addition to gravity loads. Foundations and connections of components fastened to foundations must be designed to resist both lateral and vertical forces. Earthquake energy is transferred from the foundation to the building and back to the foundation. Ultimately the function of the foundation is to transmit loads to the ground. Thus, a strong, well-designed, and properly connected foundation is essential in areas prone to earthquakes.

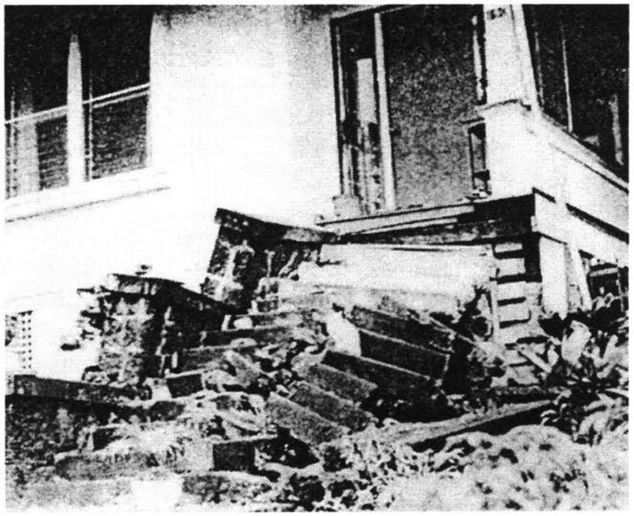
In order to make a home more earthquake resistant, the building foundation should allow the entire building to move as a unified whole. The base of the foundation should be below superficial or "top soil" level. Footings should be firm and upon stable ground. Foundations should be designed as continuous as possible in order to minimize differential settlements and avoid relative dis-



Continuous blocking between rafter and trusses and the anchoring of blocking with metal plates increase roof strength (David Benaroya Helfant 41) placements and local damage to the walls. Continuous wall footings should extend under the entire length of the wall and sufficient vertical dowel reinforcement should be provided between the wall and footing to create continuity and capacity for integral movement. Continuous footings also create more uniform distribution of bearing pressure upon the soil.

The separation of a building foundation should be considered in areas where variable displacement could occur. When different types of soil conditions exist under a home, foundations should be kept separate so they can be structurally independent of each other in the case of different types of shaking conditions. The foundations of elongated building should also be divided into segments to accommodate variable ground movement. For a building foundation sunk to different depths (stepped foundations), each segment should be designed as a separate unit to accommodate different types of ground movement.

The foundation material is also affect the seismic response of a building. Brick, lava rock, unreinforced concrete, and wood post-and-pier foundations are materials and construction types that are prone to earthquake failure.



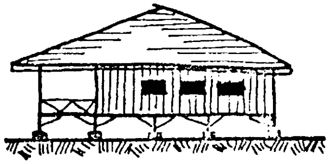
Lava rock foundation wall and concrete stair failure (Robert I. Tilling 7)

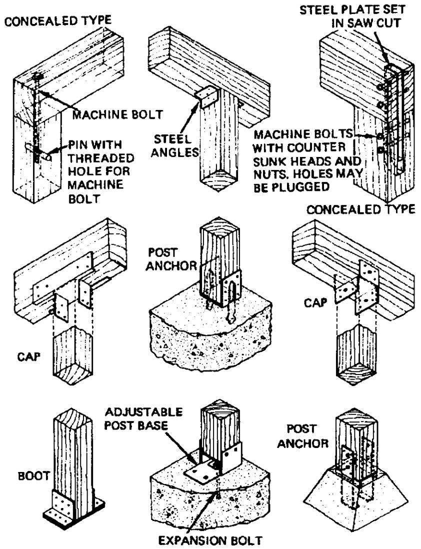
Frequent failures of unreinforced masonry walls have proven that they are inadequate as building foundations. Masonry walls and indigenous lava rock walls used for building foundations should always be reinforced with metal bars for greater strength and resistance. Unreinforced masonry wall failures are due to the difficulty of bolting to unreinforced masonry and the low strength of mortar.

Steel reinforced concrete or reinforced masonry foundations performed well in earthquake motion and remained connected to their walls. Their success was due to the strength of the materials as well as their ability to provide strong connections. Although reinforced concrete has performed well in the past, poor quality of concrete could compromise the integrity of the foundation. Porous, crumbling concrete due to poor construction practices can result in spalling and weak connections. Anchor bolts or connectors for metal straps would simply loosen and shear out of the weakened concrete.

The foundations of older "plantation style" homes as well and newer homes failed during previous earthquakes in Hawaii. Post-and-pier and post-and-footing foundations were commonly used in "plantation style" homes and were often areas of failure. Houses have shifted from several inches up to several feet from their original positions. Homes with posts that are one story tall are particularly vulnerable to earthquake vibrations. Careful attention should be given to the material and sizing of these posts so an appropriate seismic resistance foundation is provided.

Fastening of the posts of post-and-pier foundations with foundation bolts will significantly reduce earthquake risk in older homes. Underpinning of foundations and post should be sound and ade-





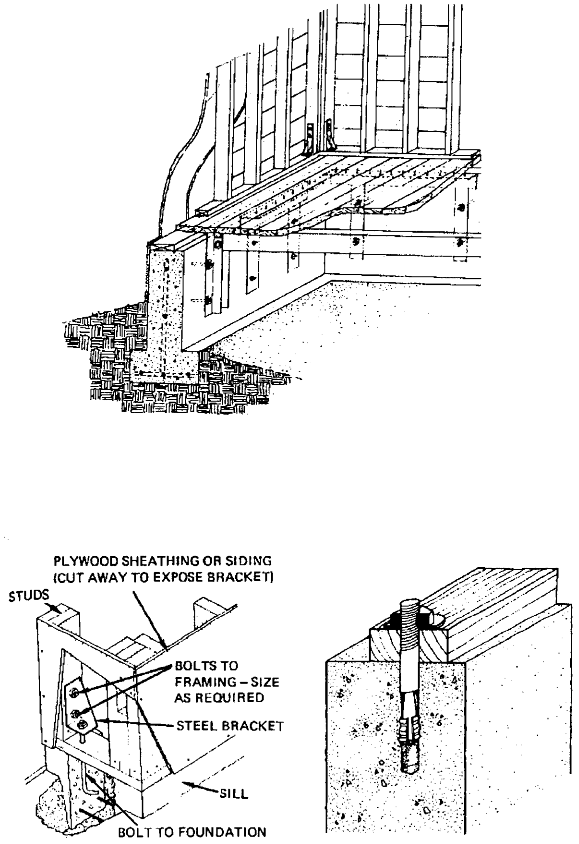
Wood-frame column connectors

Top: Elevation of typical plantation wall home with post-and footing foundation (Bernadette Maria Paik 20) Bottom: Wood framed column and post connections (Peter Yanev 198) quately cross-braced in all directions[34]. Details to reduce seismic damage for post-and-pier foundations are shown.

Wood framed walls should be tied to their foundations to prevent shifting. Existing buildings with insufficient wall-to-foundation connections can be strengthened with epoxy-set expansion bolts. Anchor bolts or structural steel plates can be used to connect the mudsill to the foundation. Rebar that comes up from the concrete through the mudsill and is bent over is not an adequate mudsill anchor[35].

Water saturated soil surrounding a building increases the effects of lateral forces upon the building during an earthquake. Thus, it is important that good drainage occur around a building's foundation. It is recommended that the ground water level be at least one meter below the foundation level when possible[36].

The appropriate placement of utilities, such as water pipes and drains, should also be considered when designing a building for seismic resistance. Improper design of these utilities can cause breakage during an earthquake. Water leakage can cause direct damage to the foundation or indirect damage through altering the



Top: Wall-foundation connections with metal straps and connectors (David Benaroya Helfant 38) Bottom: Proper anchor bolted connections of wood walls to concrete foundations (Peter Yanev 187)

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[34] Gordon A. Macdonald & Chester K. Wentworth, "The Kona Earthquake of August 21, 1951, and Its Aftershocks." Pacific Science (October 1952): 278.

[35] David Benaroya Helfant, Earthquake Safe: A Hazard Reduction Manual for Homes (Berkeley: Builders Booksource, 1989) 28.

[36] Department of Economic and Social Affairs, Low -Cost Construction Resistant to Earthquakes and Hurricane (New York: United Nations, 1975) 87.

surrounding soil's conditions and bearing capacity. Proper design, installation, and placement of pipes to drain water away from the foundation can prevent damage of this type.

Chimneys

The failure of brick chimneys is not commonly seen in Hawaii due to the overall rarity of chimney construction. Chimneys have been common areas of failure in other earthquake prone areas and offer some lessons in proper chimney construction. Inadequate and separate foundations of chimneys and poor or non-existent structural connections to the building allowed the chimney to move independent of the building. Chimneys detached, rotated, or settled. Thus, in designing chimneys, foundations and connections should be properly engineered and constructed. Chimney foundations should be deepened, and constructed of steel-reinforced concrete. Chimneys should be strapped to the home at floor and roof levels to brace it to the frame of the building, help strengthen the chimney, and keep it vertical[37]. In addition the design of the chimney, conditions around the foundation must be designed for proper drainage of water.

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[37] David Benaroya Helfant, Earthquake Safe: A Hazard Reduction Manual for Homes (Berkeley: Builders Booksource, 1989) 40.

3.14 RECENT SEISMIC CODE DEVELOPMENTS IN HAWAII

The failure of buildings due to slippage from their foundations was a common mode of failure in older homes during previous earthquakes. Older homes were built under less stringent codes than those of today and these post-and pier and post-and-footing foundations were extremely vulnerable during large earthquakes.

The newly adopted 1991 Uniform Building Code requires that new homes be built on, and secured to a solid foundation. Overall, stricter, more comprehensive earthquake design codes have been developed over the years as earthquake continually test the integrity of homes. The implementation and enforcement of the requirements outlined in building codes can reduce damage to homes in the event of future earthquakes[38].

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[38] Hawaiian Volcano Observatory, Earthquakes: Lessons from Kobe (http://www.soest.hawaii.edu/hvo/1995/95_01_20.html)

3.15 EARTHQUAKE RESISTANT HOMES

An earthquake resistant home is able to withstand the extreme lateral forces and chaotic motions that occur during an earthquake. The owner and designer's selection of building configuration, materials, design, and detailing contribute to the success of a building's seismic resistance. The thoughtful integration of earthquake design strategies will provide the residents of Hawaii with safer buildings in the future.

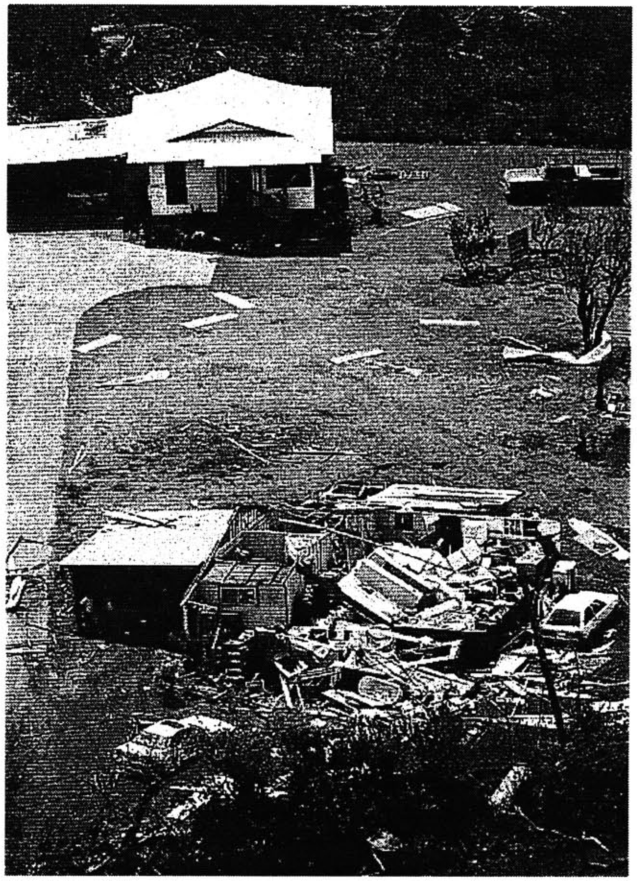
HURRICANE RESISTANT DESIGN

4.0 HURRICANE RESISTANT DESIGN

Hurricane resistant design must also be incorporated with energy efficient and earthquake resistant design when striving to design homes appropriate to the Hawaiian climate. Hurricanes threaten the Islands of Hawaii nearly every year. The extensive damage to buildings from past hurricanes has proven that the majority of light-frame wood homes in Hawaii are inadequate to resist these extraordinary forces. In order to build safe homes, hurricane resistance is mandatory.

4.1 DEFINITION OF TYPES OF TROPICAL CYCLONES

Tropical cyclones in the form of hurricanes, tropical storms, and tropical depressions threaten coastal areas every year. Tropical cyclones are low-pressure systems of air that originate over the tropical oceans. Hurricanes, also known as typhoons, are the most severe types of tropical cyclones and pose the largest threat with their strong winds and intense rain conditions. In order to understand the progression of a tropical depression to a hurricane, the various tropical cyclones are defined as follows[1]:



A Kauai home withstands Hurricane Iniki while its neighbor is completely demolished (Jim Borg)

Tropical Depression:

A tropical depression is an area of developing rotating wind circulation (clockwise in the Southern Hemisphere or counterclockwise in the Northern Hemisphere) that may include localized rain and thunderstorms. It is characterized by maximum sustained winds up to

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[1] Oahu Civil Defense Agency, Hurricane Information Page: Hurricane Information. (http://www.hgea.org/E911/hurrl.htm).

38 m.p.h. (33 Knots). The National Weather Service assigns it a number.

Tropical Storm:

A tropical storm is a well-defined area of circular rotating wind of 39-73 m.p.h. (4-63 knots). It usually includes rain and thunderstorms. It is assigned a name.

Hurricane:

A hurricane is a severe tropical cyclone with sustained winds of 74 m.p.h. (64 Knots) or greater. It is capable of rapid movement and erratic motion. Hurricanes are typified by hazards including high winds, heavy rainfall, flooding, storm surge and high surf. If a hurricane develops from the strengthening of a tropical storm, it retains its assigned name.

Hurricane winds revolve around a relatively calm center called the "eye" of the hurricane. Hurricanes are, in essence, giant whirlwinds that spiral around a low-pressure center. They are large storm systems with high winds that can extend outward 20 or 30 miles from the edge of the eye. Winds near the eye of the hurricane can reach gusts of 200 m.p.h.[2]. Hurricane winds are driven by strong thermal circulating currents with rising warm air near the center of the storm and sinking cooler air outside. Hurricanes are large storm systems that dominate the ocean surface and lower atmosphere over tens of thousands of square miles. Because hur-

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[2] Oahu Civil Defense Agency, Hurricane Information Page: Hurricane Information. (http://www.hgea.org/E911/hurrl.htm).

ricanes affecting Hawaii are located in the Northern Hemisphere, winds circulate in a counterclockwise direction.

Most Central Pacific hurricanes originate near the costs of Central America or southern Mexico. They move with the westward-flowing trade winds of the tropics. Hurricanes begin as relatively small tropical cyclones that increase in size, speed, and intensity under particular atmospheric conditions. The heat released by the condensing water vapor of the warm ocean and external mechanical forces drive these storms[3]. Once the system moves over land, it is cut off from the water and heat energy of the warm ocean and is slowed by the friction caused by the terrain.

The Hawaiian hurricane season begins in June and lasts through November. Hurricanes are extremely destructive because they combine violent winds, torrential rains and abnormally high waves and tides. Hurricanes vary in their intensities and can be categorized by the Saffir/Simpson Scale according to their amount of potential damage and wind speeds.

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3. Oahu Civil Defense Agency, Hurricane Information Page: Hurricane Information. (http://www.hgea.org/E911/hurrl.htm).

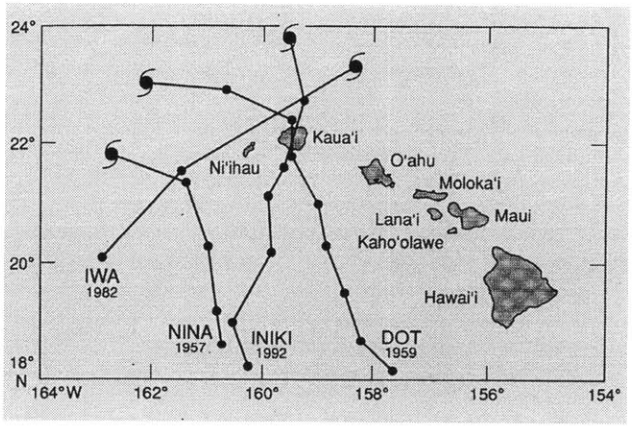
Table: Saffir/Simpson Scale and Previous Hurricanes[a]

	DESCRIPTION OF DAMAGE	WIND SPEEDS (MPH0	STORM SURGE (FEET)	EXAMPLES
1	Minimal	74-95	4-5	Iwa, 92 MPH, Nov. 1982
2	Moderate	96-110	6-8	None
3	Extensive	111-130	9-12	Uleki, 128 MPH, Sep. 1992
4	Extreme	131-155	13-18	Iniki, 145 MPH, Sep. 1992
5	Catastrophic	>-155	>-18	Emilia & Gilma, 161 MPH, Jul 94, John 173 MPH Aug. 1994

a. Oahu Civil Defense Agency, Hurricane Information Page: Hurricane Information (http://www.hgea.org/E911/hurrl.htm).

4.2 HURRICANES IN HAWAII

Hawaii, as with many other parts of the United States with large coastal areas, is exposed to the serious threat of tropical cyclones for approximately six months each year. Hawaii is located in the Tropics and is threatened by the possibility of a hurricane nearly every summer season. In the past Hawaii has experienced four major hurricanes. In 1992 the people of Hawaii had a "wake-up call" to the inadequacy of the construction of their homes when Hurricane Iniki passed over the island of Kauai and caused extensive damage to the island's buildings. According to a survey conducted by the Red Cross, 14,350 buildings on Kauai were destroyed or damaged. Of these, approximately 1,421 of the homes in Kauai were destroyed, and another 5,152 suffered major damage. The remaining 607 buildings sustained damage or were destroyed in other parts of the State[4]. Indeed this was a revealing test of the strength of housing construction on Kauai and modern construction typical of the entire chain of Hawaiian Islands[5]. Structural and architectural design and detailing, building code enforcement, workmanship, and commonly used building materials were all tested by severe winds and storm surge. In many cases they failed.



The four major hurricanes to hit Hawaii (Structural Engineers Association of Hawaii, A Survey of Structural Damage Caused by Hurricane Iniki 6)

Tropical cyclones pose a particular threat to the Hawaiian Islands.

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4. Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, (Honolulu: University of Hawai'i at Manoa, 1995) 5.

5. NAHB Research Center. Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki. (Marlboro: U.S. Department of Housing and Urban Development, September 1993) 69.

Hawaii is especially isolated when hit by a storm. Because of the Island's location in the middle of the Pacific Ocean, little can be done to escape from the wrath of these storms. When there is a need to evacuate coastal area or areas in risk, the people of Hawaii do not have the option of evacuating inland to avoid the storm's fury. Instead, adequate sheltering is the most viable option and the residents of Hawaii rely strongly upon their homes to provide storm protection. Unfortunately, many homes in Hawaii are not capable of withstanding a storm like Iniki. Throughout all the islands, there exists a need to build safer homes that provide protection from these natural disasters.

Winds

The most damaging factor of a hurricane is its high winds. Because of the revolving nature of hurricane winds, a single location can experience strong winds from opposite directions proceeding and following the hurricane eye. Minimal sustained wind speeds of 75 m.p.h., and strong gusts of winds have blown over and through the islands causing loss of life and immense destruction.

Storm Surge & Wave Action

The eye of the hurricane is accompanied by storm surge. This dome of water moves with the storm and when the eye of the hurricane reaches land, the surge sweeps across the coastline. Because of the islands do not have a continental shelf to amplify the storm surge, the effects of the surge are not as devastating in comparison to conitnental coastal area. Still, storm surge does cause high tides and coastal flooding. High tides and waves flood and pound the coastline.

Floods and Rain

Heavy rains of a hurricane can cause water accumulation and the flooding of low-lying areas. Areas adjacent to hillsides, rivers, or streams are especially vulnerable to flooding due to excessive water runoff and overflow.

4.3 INADEQUACY OF EXISTING STRUCTURES

Residential construction in Hawaii is generally not engineered; many homes are poorly designed and constructed. Single family houses are predominately constructed of light-framed timber construction, the most severely damaged construction type during Hurricane Iniki. This is mainly due to the relatively low cost of wood as a building material and the flexibility and ease of construction of this type of building system. Typically houses in Hawaii are one or two stories high.

Older wood framed houses typically are of single-wall construction (plantation style homes). Roofs are framed with timber members and covered with non-structural corrugated metal roofing. Lower floors usually consist of wood plank floors that rest on timber framing. Timber posts sit on precast concrete or concrete masonry footings that elevate the floor above grade. Newer houses (less than 20 years old) typically have concrete slab-on-grade foundation, wood stud walls (double wall construction), wood roof framing with plywood sheathing, and metal or asphalt roofing materials. Both old and new homes were damaged during Hurricane Iniki. Damage was caused by poor detailing of structural connections and inadequate fastening of materials Many damaged wood homes were already weakened by dry rot and termite damage.

In reponse to the damaged caused by Hurricane Iwa, the County of Kauai adopted the 1985 Uniform Building Code in 1988. The 1985 UBC defined a more stringent 80 m.p.h. design wind speed for the Island of Kauai. At the time, the County of Kauai amended its building codes to allow the continuation of single-wall light frame timber and post and precast concrete block footing construction. Requirements for metal hurricane fasteners for connecting roof trusses or rafters to the top plates of exterior walls were also included.

Building codes and guidelines are based upon research and human postulations. It is not until an actual natural disaster occurs that a building's strength is ultimately tested. Although Hurricane Iniki brought damage, destruction, and the loss of lives, it also presented an opportunity for learning from mistakes. Thus, the majority of the suggestive guidelines presented in this section are a result of findings from Hurricane Iniki.

4.4 DAMAGE CAUSED BY PAST HURRICANES

Many hurricanes and tropical storms have come into close proximity with the Hawaiian Islands during the last 50 years, but only three have directly impacted the islands. In all three cases, Kauai was the hardest hit, although Oahu also suffered significant damage. Many o Hawaii's lightly built homes and other structures have proven inadequate by both Hurricane Iwa (1982) and Iniki (1992)[6].

Hurricane Iniki hit Kauai on September 11, 1992. It was by far the most destructive storm to strike Hawaii in recorded history. It left widespread wind and water damage exceeding an estimated 2.2 billion dollars and 14,350 homes destroyed or damaged in its wake. Approximately 90% of the island's wood-frame buildings sustain some measure of damage through the direct impact of Hurricane Iniki on the island of Kauai.

Wind Damage

The majority of damage to the buildings and structures during Hurricanes Iwa and Iniki was from high winds and occurred primarily to light wood frame construction. Damage to these structures ranged from minor to total destruction. Most of the damage was light to moderate and primarily to windows and roofing material. Approximately 10 % of the wood-framed structures had moderate to major damage[7]. Surveys conducted after Hurricane Iniki indicated that

Roof loss was a common occurrence during Hurricane Iniki (Jim Borg)

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[6] Sam Monet, Aloha 'Aina Hydro Farms Inc.: Hurricane Iniki. (http://Hawai'i-shopping.com/~sammonet/iniki1.html).

[7] Hurricane Iniki. (http://www.ege.com/publications/iniki/iniki.htm).

building envelope and structural connection failures were common.

Building envelope damage (window, door, roofing,and roof sheathing) accounted for most of the damage. Hurricane winds lifted objects ranging from lawn furniture to roof shingles, transforming them into flying missiles. Flying debris contributed to initiating an exacerbating damage to roof and building cladding.

Hurricane Iniki destroys the framing of the a home under construction (Jim Borg)

Poor structural connections were also the cause of failure. Many of the homes that failed in Hurricane Iniki were not equipped with hurricane ties since these were not required until after the Hurricane Iwa hit Kauai and the 1985 edition of the U.B.C. was implemented. At the time Hurricane Iniki hit, the Kauai building code still followed the guidelines set forth in the 1985 U.B.C. Because both old and new buildings failed, it is obvious these prescriptive building codes were inadequate for a storm of Iniki's magnitude and desperately require reexamination and revision.

Hurricane Iniki brought with it sustained winds of up to 97 m.p.h. with gusts up to 143 m.p.h.[8]. This, by far, exceeded the 80 m.p.h. design standards. Hurricane Iniki produced winds well in excess of acceptable levels or risk established by the existing building code requirements and U.S. design standards[9].

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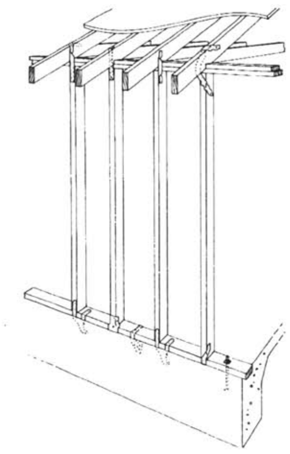
8. NAHB Research Center. Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki. (Marlboro: U.S. Department of Housing and Urban Development, September 1993) 69.
9. Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 520.

Roof Damage

The loss of roof systems and the resulting rain and wind infiltratration were major contributors to property damage from Iniki. There were numerous cases of partial or total loss of a roof structure due to insufficient uplift resistance and an incomplete load path. This was either due to the absence of metal hurricane fasteners or the inadequacy of nailed sheathing. Common points of failure were at the connections between roof purlin to girder or wall; girder to wall or column; or column bases[10]. These connections were typically toe-nailed which proved to be inadequate. Whenever a load path was established and carfully detailed, the building's structure performed well.

Large overhangs or open lanais experienced high winds and highly concentrated pressures. These areas were particularly vulnerable and often the initiation point of roof failure. In most instances the loss of the roof led to the progressive failure or total collapse of a home.

Gabled roof forms experience significantly higher wind loads than hipped roof. Gabled roofs did not perform as well as hipped roofs, as structural problems were most evident in the former. Damage to gabled roofs and walls was attributed to the weak joints between the wall and cripple wall studs above. Failures occurred at the ceiling level where joints between primary studs and cripple studs



Top: Typical wall connections with hurricane straps (Southern Building Code Congress International 80) Bottom: Excessive roof overhangs and poor connections led to roof loss (United States, Federal Emergency Management Agency 43)

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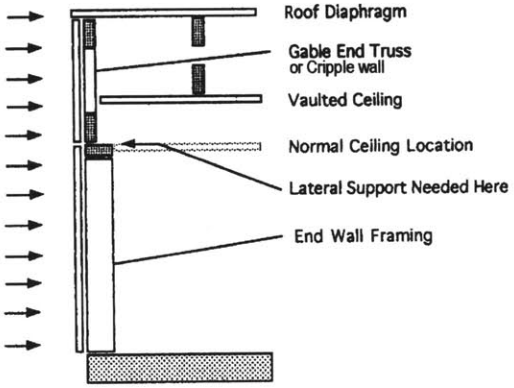
[10] Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, University of Hawai'i at Manoa (Honolulu, 1995) 53.

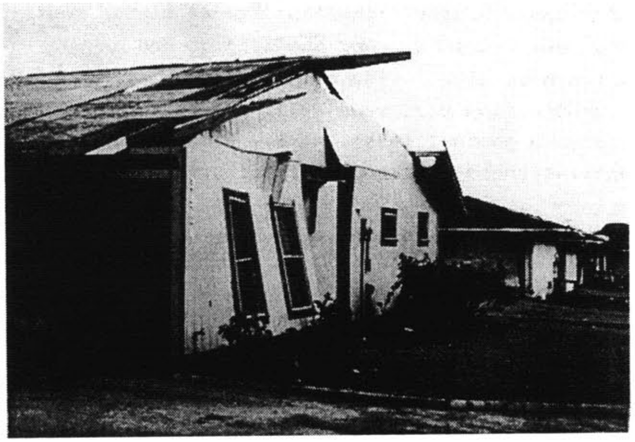
lacked adequate bracing and blocking. Steeply sloped roof systems often failed at the ridges or gable ends while low slope roof systems were damaged primarily at roof corners

Investigations found that building codes and standards were not followed in failed buildings. Nails were fewer in number and shorter in length than required and staples were used in place of nails. Common types of failed attachment details were: nailing of roof covering to sheathing; stapling of plywood; nailing of metal roofing to battens; nailing of purlins to trusses; and nailing and splicing of tongue-and-groove decking[11]. Excessive spacing between nails and staples, or the failure of staples or nails to strike rafters, trusses, or purlins were common reasons for roof sheathing failure. Excessive corrosion of inadequately protected nails or staples also weakened sheathing connections[12]. Extensive loss of roof coverings including wood, fiberglass, or asphalt shingles, sheet metal, and concrete or clay tiles also occurred because of inadequate connections.

Wall Damage

Overall there was minor wall failure in comparison to roof failures. Deficient design and construction was prevalent in cases where walls failed. Wall failure often occurred once the roof was gone and there was nothing left to brace them. Wall types sustaining





Top: Gable end walls were especially vulnerable at the cripple wall studs (Ronald A. Cook and Mehrdad Soltani 517) Bottom: Gable roof end wall failure (Structural Engineers Association of Hawaii, A Survey of Structural Damage Caused by Hurricane Iniki 30)

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[11] Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, University of Hawai'i at Manoa (Honolulu, 1995) 53.

[12] United States, Federal Emergency Management Agency, Federal Insurance Administration, Building Performance: Hurricane Iniki in Hawaii (March 1993) 47.

damage included: conventional wood framing, masonry, heavy timber, and single walls. Failures were due to the lack of continuous load paths or inadequate connections between the wall and the foundation. Wall damage was also amplified by local topography in areas with high winds.

Termite resistant building materials in use at the time of Hurricane Iniki included metal studs and stucco finishing. Typical damages to these building materials were tension cracks due to the bending induced by wind pressures. Buildings of this sort performed better when plywood sheathing was located between the lath and stud[13].

In almost all cases, shear walls incorporated within buildings fared well and increase the home's ability to withstand wind forces. Internal partitions also acted as shear walls.

Damage to Windows and Openings

Glazed areas and garage doors were weak points in homes. There was extensive damage to glazing due to wave forces, windborne debris, and high wind pressures. Large unprotected plate glass windows and sliding doors were especially vulnerable.

Flying projectiles shattered glazing upon impact. The failure of these openings created additional internal pressure resulting in an

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[13] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 515.

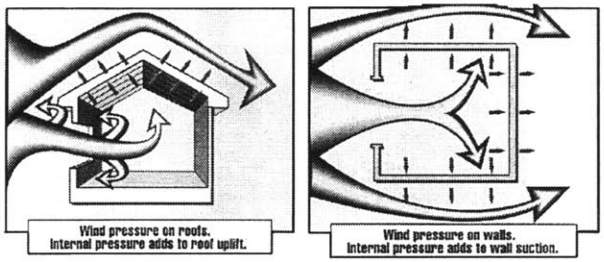
increase in the uplift on roofs and blowing out of walls. The combined effects of wind pressure and improper installation of windows or doors (inappropriate attachments of window frames to structural wall elements and weak connections of sliding doors) increased the probability of building failure. Breaches in the openings resulted in wind and water damage to building interiors. Protective glazing devices (shutters or plywood) reduced the occurrence of glazing and building envelope failure.

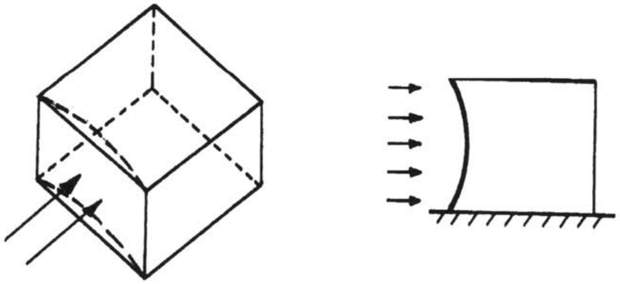
Foundation Damage

Foundation failure due to high winds was infrequent. However, failure at the connection of the superstructure to the foundation was common. Uplift and lateral forces caused by the high winds were often powerful enough to lift and shift buildings horizontally from their foundations. This was a common occurrence with building whose posts sat upon precast concrete footings. Buildings were often displaced by 3 to 5 feet and in one extreme case by 15 feet[14]! Unreinforced masonry piers failed due to shear slippage (blocks slip and are offset). Slab-on-grade foundations away from the coastal areas performed well[15].

Damage to Building Additions

Architectural additions, such as carports or lanais, were often constructed of lighter building materials than the main structure, and





Top: Loss of opening protection allows wind entry and increases internal pressures (United States, Federal Emergency Management Agency 56). Bottom: Wind pressure upon a wall will cause bending (National Bureau of Standard, Design, Siting, and Construction 31)

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[14] Structural Engineers Association of Hawaii, A Survey of Structural Damage Caused by Hurricane Iniki, September 11, 1992, (March 1993) 26.

[15] NAHB Research Center. Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki. (Marlboro: U.S. Department of Housing and Urban Development, September 1993) 88.

inadequately connected to the main structure. The failure of these "appendages" contributed to the amount of windborne debris.

Storm Surge & Wave Action Damage

Hydrodynamic forces caused by the repetitive pounding of waves were accompanied by impact from water-borne lava rocks and boulders. Scouring of building foundations occured but the damage was minimized due to retrofits and improved foundation types implemented after Hurricane Iwa in 1982. Foundations that experienced little damage were anchored to the deeper bedrock rather than resting on loose, unstable sand. Although foundations performed well and were not undermined, little could be done to prevent the flooding of lower floors. All oceanfront properties experienced some damage due to flooding of the first story.

Floods and Rain Damage

Heavy rains caused property damage in Hawaii. Heavy rains upon steep hillsides caused landslides, severe flooding, and stream overflow. Building envelope failure allowed rainwater to enter and damage homes. Rainwater accumulations in low-lying areas have also caused damage. Rivers and streams overflowed with the abundance of rainwater and flooded surrounding areas. Homes not elevated above the ground suffered extreme water damage.

4.5 OVERALL LESSONS AND FINDINGS FROM INIKI

Homes in Kauai experienced extreme damage during Hurricane Iniki despite the updated codes and preventative measures taken. Post-disaster investigations and damage reports were made to discover and document the reasons for building failure . The findings from structural assessments made by SEAOH (Structural Engineers Association of Hawaii) after the strike of Hurricane Iniki are summarized as follows[16]:

- Structures that had metal hurricane fasteners and a positive load path to the ground sustained significantly less structural damage. Those with complete load paths sustained minimal structural damage

- Buildings with precast concrete footings lacked adequate lateral resistance. Some structures were shifted sideways off their foundations by wind or wave forces.

- Building features that are vulnerable include long eave overhangs, gable end buildings, high open beam roofs, large glass windows and sliding doors.

- Wind penetration through a building's envelope due to window or cladding failure creates increased internal pressures. When combined with the external (suction) pressures progressive failure of the structure could occur.

- Topographical features can increase the wind speeds. Structures built along ridges are exposed to more severe wind envi-

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16. Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, University of Hawai'i at Manoa (Honolulu, 1995) 76.

ronments and many buildings here sustained severe damage. The combined funneling effects (Venturi effect) on wind through gaps in mountainous terrain can increase wind speeds and create hostile wind situations.

- Flying debris from damaged structure or unsecured items can inflict damage to other buildings and structures downwind. Debris included wind-borne tree limbs or parts, as well as loose gravel from rooftops.
- Oceanfront homes suffered damage from both wind and waves. Structures were exposed to the hazard or impact from wind and water-borne debris.
- Heavy timber frames and roofs performed better than light framing even in high wind exposure areas.
- Reinforced concrete or masonry buildings performed well structurally. Overall they suffered little or no structural damage although there were many instances where the loss of roofing or glazing occurred. Damage to concrete houses occurred to mainly roofing materials.

4.6 LEARNING FROM THE PAST: OVERALL SUGGESTIVE GUIDELINES

Hurricane Iniki tested the integrity and safety of Hawaiian homes. With approximately 90% of all structures on Kauai sustaining some measure of damage, it is clear that the design and construction of many homes in Hawaii are vulnerable to natural disasters such as

Hurricane Iniki[17]. The building industry of Hawaii must learn from its mistakes. Damage and structural assessments following Hurricane Iniki serve as resources that suggest improvements that can upgrade old buildings or can be incorporated into future buildings. General recommendations are[18]:

a) Provide Resistance to Forces of Uplift
b) Provide a Complete Load Path
c) Update Applicable County Building Ordinances
d) Consider the Topographic Effect on Wind Velocities
e) Provide Verification/Inspection of Construction
f) Evaluate Roof Overhangs and Materials
g) Evaluate Exterior Envelope Elements
h) Establish Appropriate Basic wind Speeds with Microzonation Maps

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17. Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, University of Hawai'i at Manoa (Honolulu, 1995) 1.

18. Arthur N.L. Chiu, et al. Hurricane Iniki's Impact on Kauai, University of Hawai'i at Manoa (Honolulu, 1995) 124.

4.7 HURRICANE EFFECTS ON BUILDINGS

The main purpose of a building is to provide protection for the building occupants in the event of a hurricane. Homes must be resistant to wind, rain, and wave forces. In determining the hurricane resistance for a new home, various factors need to be considered:

a) The wind, surge, flood exposure of a site
b) The type and quality of building form and material to be used
c) the type of and quality of building construction

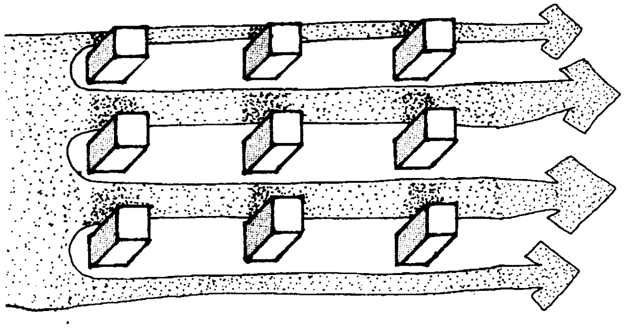
4.8 SITE PLANNING TO REDUCE RISK

A building's site determines the type of forces a building is exposed to. The effects of wind, storm surge, and flooding are often exacerbated by site conditions. Upon deciding where to site a building, investigative studies of flood maps, high tide lines, storm surge, and wind should be made. Where adverse site conditions exist, accommodations in the building design should be made.

The complex topography found on the Hawaiian Islands greatly impacts wind patterns and speeds. The effects of the local terrain augment high-speed winds. Wind speeds increase in higher elevations over mountain ridges or through the valleys and result in severe wind environments. Structures on exposed ridges or those situated to the lee of mountain passes are especially vulnerable to damage.

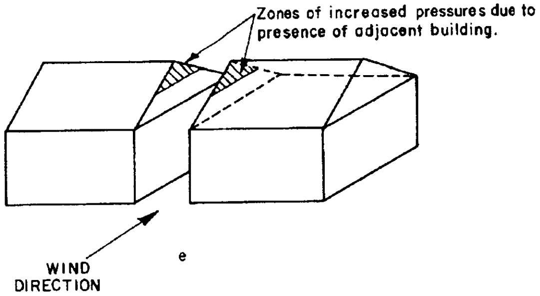
Homes located near large open areas or directly on the coastline are subjected to high wind speeds. The relatively open surroundings allow wind speeds to accelerate and impact the building with increased velocities. Coastal regions are also susceptible to high forces caused by wave action and storm surge and are also prone to flooding.

Homes located in low-lying areas or valley floors are prone to flooding, but subjected to less severe wind conditions than home in higher elevations. Buildings on the leeward side of closely spaced buildings can benefit from the wind shadows of the upwind build-



Buildings on the leeward side of closely spaced buildings benefit from the wind shadow of the up-wind buildings. (State of Hawaii, Department of Business, Economic Development, and Tourism 30) ings. On the other hand, adjacent buildings normal to the wind direction can experience increased zones of pressure when high winds are funneled between them.

Slopes with unstable soil conditions are vulnerable to landslides caused by heavy rainfall. Low-lying areas adjacent to these steep hillsides are susceptible to damage caused by landslides and severe flooding. Flooding is also common in areas adjacent to rivers and streams.



Increased zones of pressure on adjacent building (National Bureau of Standard, Design, Siting, and Construction 30)

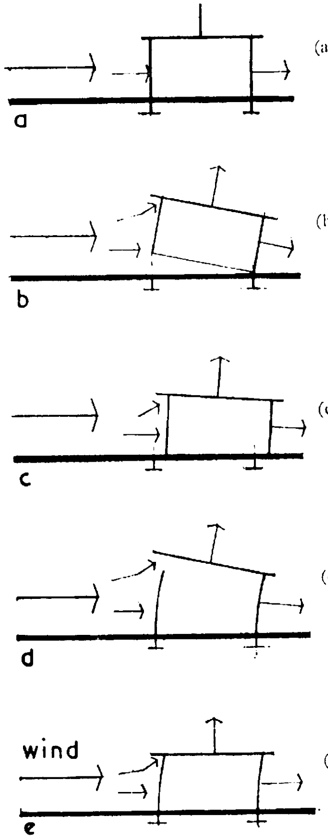
4.9 DESIGN FOR HURRICANE RESISTANCE

A building's design determines its survival chances during a hurricane. A well-designed, hurricane-resistant home is designed with consideration to hurricane forces on a building's overall form and each building component.

Building Form

The building form has a significant impact on a building's ability to withstand extraordinary hurricane wind forces. Wind flow around a building produces the pressures that act upon its structure. Wind produces positive pressure on the windward side ofl walls normal to the direction of the wind. Air flowing past a building creates negative (suction) pressures on side walls and leeward facing walls. Different building configurations and various roof slopes alter the pressure magnitude upon building faces.

Aerodynamic building forms minimize the wind forces upon a building and are the most efficient forms to withstand high winds. Single story homes are usually more aerodynamic than two story homes. Taller forms have large wind exposures and require additional framing connections that make it more susceptible to the effects of high winds. Two story homes in high wind prone areas (coasts and crests) are also more damage prone than single story homes[19]. Round plans are also more aerodynamic than rectilin-



(a) Properly designed walls resist wind forces as beams supported both ends

(b) Insufficient weight or anchorage to foundation to prevent overturning

(c) Insufficient anchorage or foundation too weak to resist shearing force

(d) Roof not properly anchored to walls. Roof blown off walls act as cantilever beams

(e) Roof or floor not properly designed or anchored to transmit lateral loads to end walls

Types of failure under wind loads (David Oakley 70)

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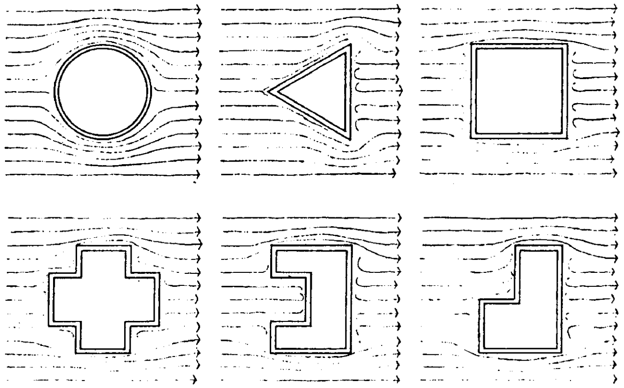
[19] NAHB Research Center. Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki. (Marlboro: U.S. Department of Housing and Urban Development, September 1993) 75 &103.

ear forms.

Building framing

The overall goal of the building structure is to provide adequate means and methods of load transfer. The building frame must resist uplifting and lateral wind forces. This requires continuous and clearly defined load paths from the roof down through the foundation. Hurricane clips and straps are key elements that help ensure proper framing connections of a structure. Metal fasteners (hurricane clips) and straps must be adequately sized, properly installed, and covered with a protective coating. Toe-nailing does not provide a complete load path and should not be used in lieu of metal hurricane straps[20].

Although a building depends on its primary structure (framing) to transfer and withstand wind forces, every architectural element on a building must also resist the same wind forces. The failure of roofing materials or wall cladding can result in wind and water damage or compromise the integrity of the primary structural system. Special attention must be given to construction methods and code prescriptions for nailing and attachment of roof sheathing, roof cladding, windows, and doors to minimize building envelope failure.



Effect of building shape on wind flow. Round forms and corners oriented toward the wind (i.e. the triangular plan above) are the most aerodynamic (Stanley Crawley 38)

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[20] United States, Federal Emergency Management Agency, Federal Insurance Administration, Building Performance: Hurricane Iniki in Hawaii (March 1993) 34.

Building Maintenance

Many of the buildings that suffered damage in Hurricane Iniki were poorly maintained prior to the strike of the storm. Weakened materials, corroded roofing and nails, and termite damage to structural members all compromised the integrity of these building. Routine maintenance including the repair and replacement of damaged elements should be conducted annually to minimize weak, damage-prone areas in the structure.

4.10 ROOF DESIGN

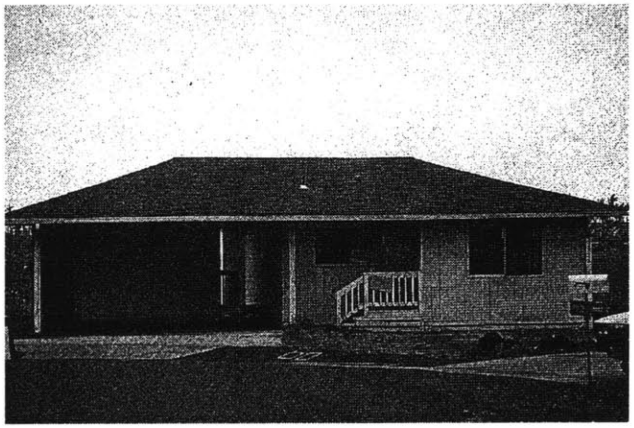
As roof damage accounted for 70% or more of the structural damage in Iniki, it is clear that more attention must be focused on the roof form, framing, details, and materials[21]. Roof failure allowed for wind and water damage to the building interiors.

Roof Form

Wind loads can lift roofs and cause localized pressure increases on surfaces at locations of discontinuity (corners, eaves, overhangs, etc.) Aerodynamic roof forms allow wind to flow around the roof more easily. Thus, roof designs that are aerodynamic are recommended for hurricane or high wind prone areas.

Hip Roof Surveys conducted of damage by Hurricane Iniki show that hip roofs performed better than gabled roofs. Roof form studies indicate that hipped roof can carry over 50% more wind load than a gabled roof with the same amount of material[22]. The form both reduces wind turbulence and pressure, and possesses more structural resistance. Low-pitched hipped roofs are aerodynamic an are appropriate minimizing the forces caused by high winds.

The hipped roof is structurally better suited than a gabled roof because the framing at the ends of the building are better tied. Lower eaves of the hipped roof also provide protection from the



Low-lying hip roofs are more aerodynamic and performed well during Hurricane Iniki (United States, Federal Emergency Management Agency 42)

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[21] NAHB Research Center. Assessment of Damage to Single-Family Homes Caused by Hurricanes Andrew and Iniki. (Marlboro: U.S. Department of Housing and Urban Development, September 1993) 77.

[22] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 153.

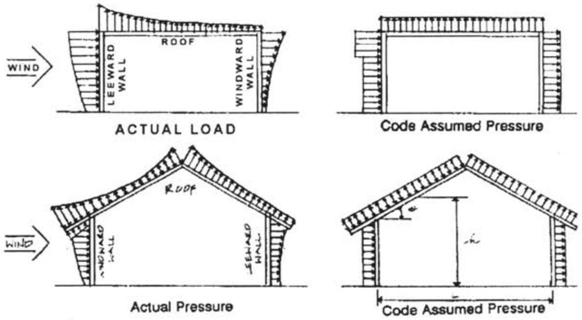
heavy rains brought forth by hurricanes.

Gable Roof The performance of gable roofs in high winds is inferior to hipped roofs. Gabled roofs are less aerodynamic, resulting in areas of concentrated pressure. Gable end walls can detach from the roof because of negative (suction) wind pressure upon leeward and side walls allowing wind and water infiltration. In turn, wind entering the building creates positive pressure on the walls and remaining roof. This positive pressure, coupled with the negative pressure above the roof, create extreme uplift forces. High sloped gabled roofs are especially vulnerable to high winds due to higher wind pressures on steeply sloped roofs. The high overhangs of gabled ends provide less protection from heavy rains than the low overhangs of hipped roofs, making them unsuitable to Hawaii's climate.

Semi-Gabled Roof Semi-gabled roofs are a combination of both the hip and gable roof. They have the low overhangs of hipped roofs for rain and wind protection while allowing for natural ventilation through small vented gables. Semi gabled roof are nearly as aerodynamic as hipped roofs.

Offset Roofs Offset roofs are potential problems in areas experiencing high winds. The offset in the roof provides a geometric discontinuity, which results in greater localized pressure.[23]

Arched Roofs Since ideally the roof in wind prone areas should be



Top: Actual and code assumed pressures for a flat and sloped roof (Stanley W. Crawley 248) Bottom: Offset roof damaged during Hurricane Iniki (United States, Federal Emergency Management Agency 42)

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[23] United States, Federal Emergency Management Agency, Federal Insurance Administration, Building Performance: Hurricane Iniki in Hawaii (March 1993) 42.

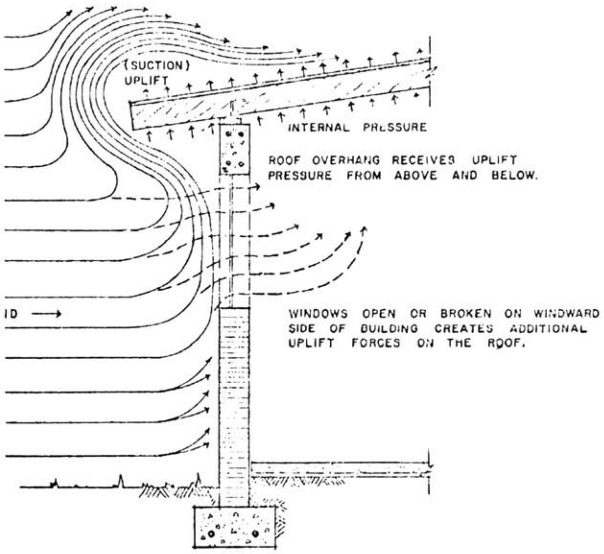
as aerodynamic as possible, an arched shape with a continuous membrane roofing would be more ideal than all the previously discussed roof forms[24]. It offers few discontinuities and a gradual transition of forces from the windward to leeward surfaces. Although this form may be ideal for high wind prone areas like Hawaii, one must note that most building materials are imported to the islands. Special manufacturing of curved laminated wood, or metal arches would cost significantly more than standard lumber trusses or rafters.

Overhangs

Strong winds exert excessive uplift forces on overhangs. Overhangs should be 3.0 feet or less and have adequate soffit and ridge vents. Overhangs exceeding 3.0 feet are exposed to large uplift forces and should be engineered for adequate uplift resistant connections.

Roof slope

The wind load upon a roof is significantly affected by its slope. In general, flat roofs and low sloping roofs (less than 20 degrees) experience the highest uplift forces. On sloped roofs, peak uplift pressures occur on the windward corners and edges of the roof. Negative pressure at corners close to the upstream roof edge may be double the uplift force on a 30-degree roof slope. Uplift pressure on the windward roof slope decreases as the roof slope increases. The average uplift pressure on the windward slope of a



Wind forces upon overhangs and roof (United Nations, Department of Economic and Social Affairs 167)

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[24] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 661.

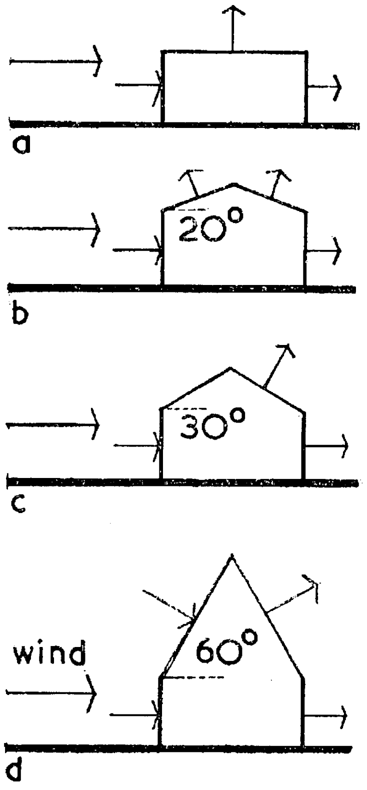
roof approaches zero when the slope approximates 30-degree. Positive or inward pressure results from slopes over 30 degrees[25]. The uplift or suction forces act on the leeward side of all roofs pitches .

Roof Framing

Hurricane Iniki has proven that structures with metal hurricane fasteners and a continuous load path to the ground have significantly less structural damage. Framing must be well and completely fastened: purlin to truss. In addition, hurricane ties should be placed at joist/girder, joist/wall, and top plate/rafter or truss connections. Heavy duty bolted steel straps at post/beam connections and post / footing connections must also be used (i.e. at large openings such as carports). Steel hurricane straps and connectors are recommended to create rigid and strong connections that aid in ensuring load transfer.

Roof trusses should be engineered and framed with minimum of 2x6 sized members[26]. Gang nailed or metal plate inter-truss connections are highly recommended.

Hurricane fasteners need to be consistently applied from the rafters down to the foundation. In hurricane prone areas such as Hawaii, connectors with rated uplift values should be utilized. Connectors must be properly installed in accordance with the manufac-



Wind pressure on various roof slopes (David Oakley 69)

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[25] Oakley, David. Tropical Houses: A Guide to their Design. (London: B.T. Bastsford Ltd., 1961)73.

[26] Sam Monet, Aloha 'Aina Hydro Farms Inc.: Hurricane Iniki. (http://Hawai'i-shopping.com/~sammonet/iniki1.html).

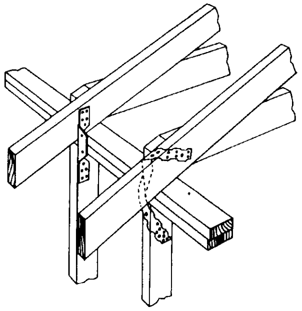
turer's instructions in order to maximize their performance. Misalignment and improper orientation are common mistakes during installation that compromise the ability of the fasteners to resist uplifting forces properly.

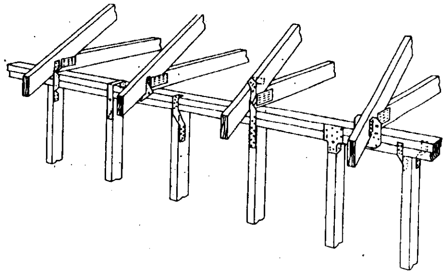
During a hurricane, the elements and connectors resisting the wind forces are of vital importance to a structure's survival. A weak link in an otherwise appropriately reinforced structure may cause serious damage or ultimately total building failure. Thus, it is strongly recommended that special inspection of wind-resisting elements and connectors be conducted by qualified structural engineers for buildings prone to high wind conditions.

Gable Roof Framing

The poor performance of gabled roof forms during Hurricane Iniki was largely due to framing discontinuities. The following are suggestions for improving gable roof framing[27]:

a) Utilize metal strap ties at connections between gable end overhang and top plate
b) Utilize metal strap ties at connections between gable end cripple stud and stud below or continuous stud from bottom plate to top of gable (balloon framing)
c) Brace gable end cripple walls at the base of the cripple wall





Top: Rafter to top plate to stud connection Bottom: Truss to top plate to stud connection (Southern Building Code Congress International 106)

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[27] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 622.

In wood framed homes, the roof framing predominantly carries gravity loads while sheathing resists and distributes lateral loads. Truss bridging, system wide lateral bracing, adequate cross bracing at gable end trusses, and the stiffening of gable ends can provide additional structural support and supplement the sheathing diaphragm for lateral support[28]

Roof Sheathing and Materials

The selection of roofing material and sheathing greatly affects a building's hurricane resistance. Many homes depend on the sheathing to provide lateral support, and so failure or damage to roof sheathing may compromise the structural integrity of the entire roof. Effective sheathing and the proper attachment and fastening of roof elements are critical for hurricane and earthquake resistance.

Sheathing serves as a diaphragm to distribute wind loads to the framing members and walls below. The stiffness and strength of the sheathing material must not be compromised by the exposure to sunlight or precipitation. Plywood, tongue-and-groove decking, and metal decking are appropriate sheathing types when attached properly.

Hurricane Iniki demonstrated the importance of adhering to sheath-

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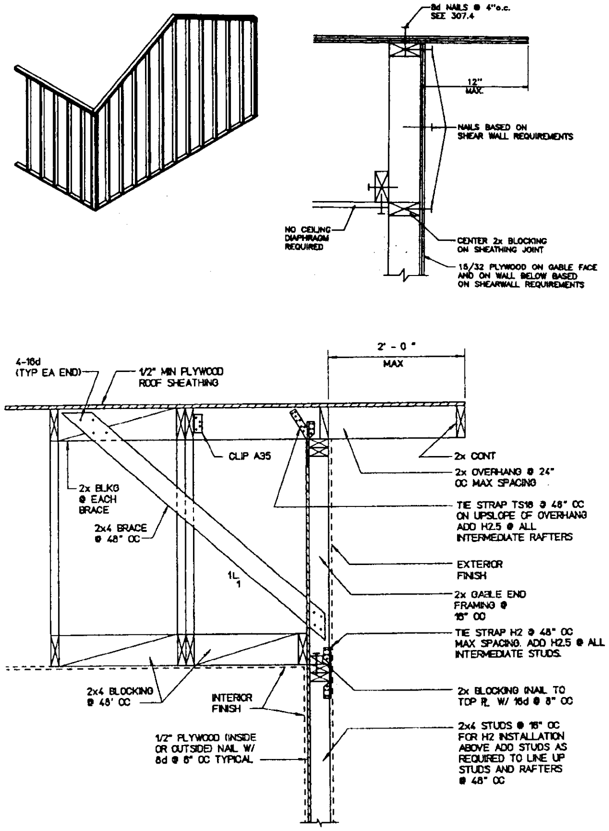
28. United States, Federal Emergency Management Agency, Federal Insurance Administration, Building Performance: Hurricane Iniki in Hawaii (March 1993) 47.

ing fastening requirements. As a result of Hurricane Andrew (Florida) and Iniki, the American Plywood Association (APA) developed stricter recommendations for attaching plywood sheathing. Revised prescriptions call for nails spaced six inches on center at panel edges, ends, and all intermediate supports[29]. Roofing materials should also be securely fastened to prevent loss and potential flying projectiles.

Roofing material must resist damage from projectiles, heavy rain, and excessive winds. Common roof coverings utilized throughout Hawaii include corrugated sheet metal, wood or asphalt shingles, and concrete or clay tiles. Properly attached corrugated metal sheets and asphalt composition shingles performed well in hurricane wind and driving rain conditions

Metal roofing is widely used throughout the islands because of its relatively low cost and availability. Metal roofing, when properly installed over roof sheathing is particularly appropriate to the climate of Hawaii because of its low thermal capacity, high reflectance or variety of colors, and its ability to quickly shed water[30]. Still, the most common type of damage in Hurricane Iniki was the loss of metal roofing[31]. This was due mainly to inadequate con-



Top: Balloon framing is preferred over cripple walls (Southern Building Code Congress International 83) Bottom: Section through gable end wall showing recommendations for framing and bracing (Structural Engineers Association of Hawaii, Tips on Improving Wind Resistance 12)

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29. Paul Tarricone, "The Winds of Change?" Civil Engineering (January 1994): 44.
30. Richard Foust, "Up on the Roof: Metal Meets Hawaii's Unique Demands." Hawaii Architect (August 1990): 15-16.
31. Structural Engineers Association of Hawaii, A Survey of Structural Damage Caused by Hurricane Iniki, September 11, 1992, (March 1993) III-28.

nections or the corrosion of the roofing material as well as its connectors. Composition shingles are also widely used on roofs in Hawaii and have performed well in past hurricanes.

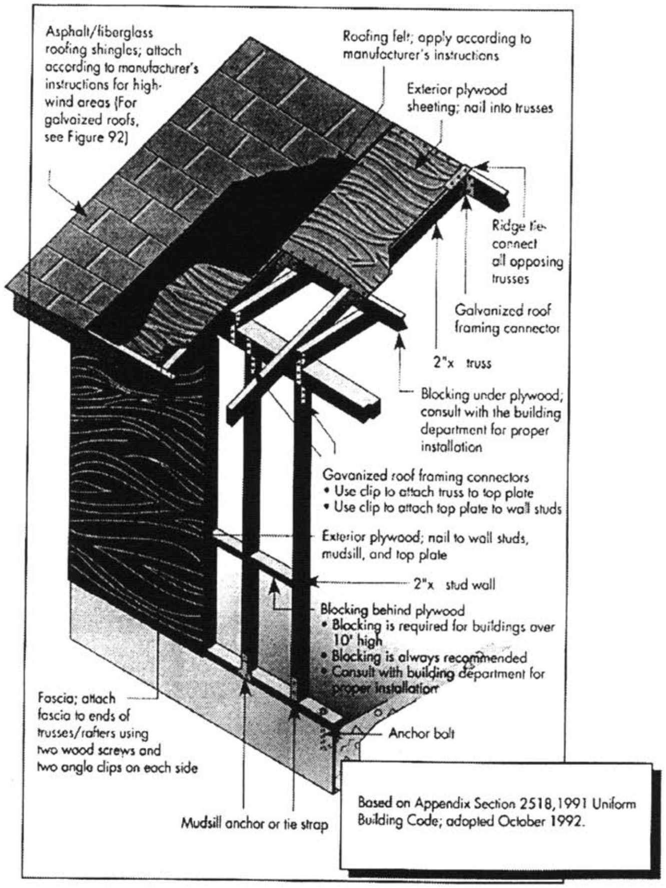
4.11 WALL DESIGN

Walls provide enclosure and are the connection elements between the roof and the foundation. The proper design of walls and their connections are important in ensuring the overall integrity of a building.

Wall Framing

Walls must be securely attached to both the roof and the foundation to ensure the survival of the building. Metal fasteners at these connections help to provide strong connections. Additional structural ties at the ceiling line between large exterior walls and interior partition walls must be used in order to maintain the structural integrity in the event of the loss of roofing. The wall members themselves must also be well connected. Wall openings are discontinuities in the framing and must be reinforced with metal connectors and plates (see Framing recommendations for openings figure on page 169) .

Internal walls should be designed to act as shear walls to provide lateral support. Interior walls should have diagonal framing components or use plywood sheathing beneath (see Shear wall section on page 137). Internal walls should be securely ties to each other and to external walls. Internal walls perpendicular to the wind direction and securely attached to exterior walls provide resistance to strong wind forces on long or large exterior walls.



Based on Appendix Section 2518,1991 Uniform Building Code; adopted October 1992.

Recommended wood-frame construction (United States, Federal Emergency Management Agency 81)

Exterior Wall Sheathing

In light-framed timber constructed homes a building's lateral support is provided by its sheathing and shear walls. In recent years particleboard, and oriented strand board have been used extensively on exterior walls. The strength of these materials are often compromised when exposed to moisture or fastened improperly. In comparison to these types of sheathing, plywood is much stronger. Stucco does not provide lateral support and has a higher performance when backed with plywood.

Shear Walls

In addition to providing lateral resistance to earthquake motion, shear walls and diagonal bracing also resist lateral wind and wave forces. Buildings located in areas prone to high winds, wave action, or earthquakes need to have shear walls or diagonal bracing to resist lateral forces. Shear walls and diagonal bracing were previously described in the earthquake section (see page 92).

Because wind can blow from any direction during a hurricane, lateral resisting elements oriented in several directions are recommended. In coastal residences, shear walls should be oriented normal to the beach line in order to b ethe most effective against wave and surge forces.

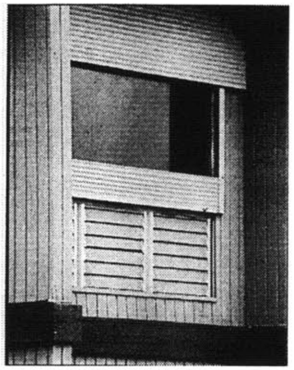
When retrofitting single wall construction homes. Corner and diagonal bracing should be added to provide lateral resistance to single wall homes.

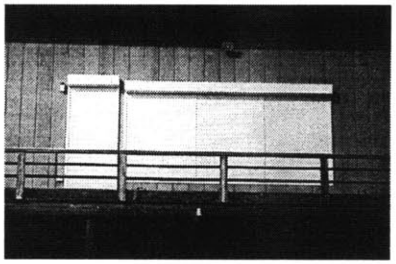
Windows and Openings

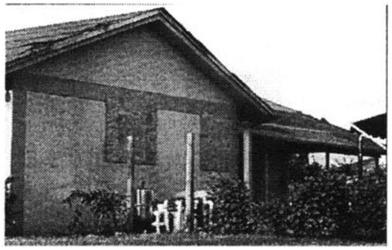
Hawaii's climate promotes the widespread use of natural ventilation and thus encourages large openings in the walls and roofs. This produces a high percentage of glazed areas in walls and large vulnerable areas during a storm. An opening on the windward walls as small as 5% of the wall area will produce full internal pressurization. This condition can effectively double the pressures acting to lift the roof and push side and leeward walls outward[32].

Windows are vunerable areas in a building envelope and should be protected. The best treatments for window openings are to avoid orientating them toward sources of high wind pressure, to minimize the size of open spans and provide rigid coverings to protect openings from wind forces and projectiles.

In order to help prevent undesired pressurization caused by missile penetration, it is recommended that openings be covered and protected to reduce building damage and human injury. Areas in need of protection are windows, doors, garage doors, skylights, and fixed lights where glass is present and may be penetrated by flying debris. Window protectors can be made of wood or metal and be affixed or removable window protection. Attached shutters can be locked shut in the event of a hurricane. Sheets of plywood nailed over a window are also sufficient.







Top: In-place protective devices provide window protection Middle: prefabricated storm shutters Bottom: Plywood used as opening protection (United States, Federal Emergency Management Agency 60, 92, 93)

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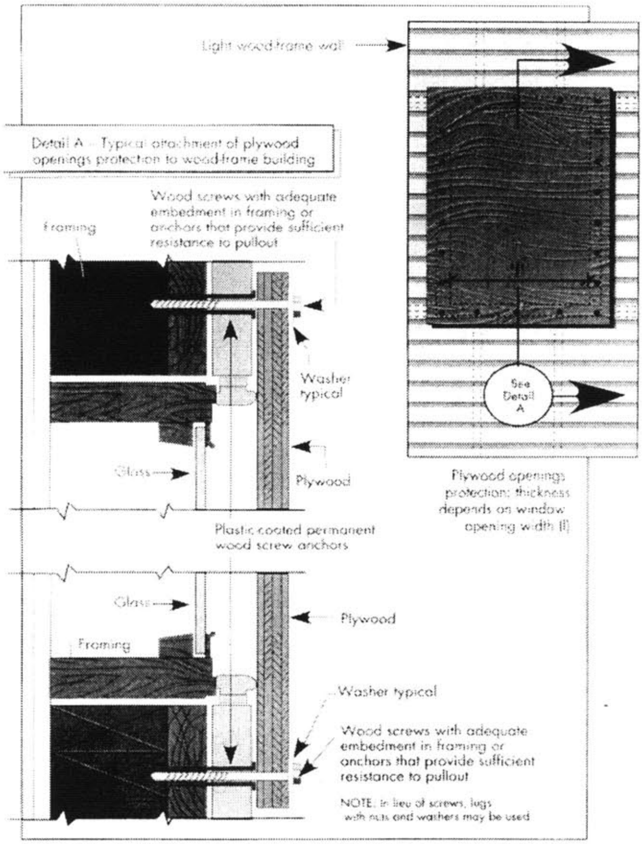
[32] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 477.

Different types of glazing can also prevent human injury or the penetration of the building enclosure. Tempered glass (safety glass) can be used to reduce the chance of human injury. It breaks in so that flying pieces don't cause injury, but easily shatter under impact loads. Laminated glass contains an intermediate film that holds the glass together and reduces the potential of building penetration. In the case where special glass is not used, windows must be taped before a storm to help reduce the risks of shattering.

One should note that U.S. codes and standards ignore the possibilities and implications of damage induced by windborne projectiles in their design requirements. They allow designers to assume that windows will neither be open nor be broken although these conditions are likely to occur in hurricane prone regions. During hurricane winds, openings in the building envelope subject the building to full internal pressurization and potential explosion of walls. Thus, buildings in hurricane prone areas need to either be designed for full internal pressurization or have impact resistant glazing along with external protection devices (shutters)[33].



Typical installation of plywood opening protection for wood frame building (United States, Federal Emergency Management Agency 94)

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[33] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 482.

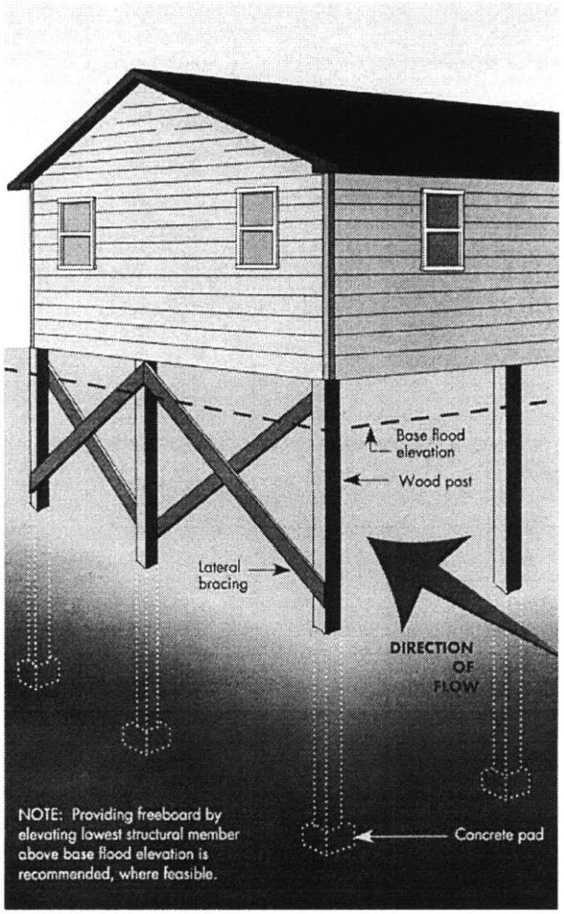
4.12 FOUNDATION DESIGN

The lateral forces transmitted to a building during a hurricane are ultimately resolved and resisted by the building's foundation. A proper foundation system especially along the perimeter of a structure is needed to resist all horizontal shear and uplift forces.

In coastal areas, building footings must be extended to rest upon lava rock rather than the unstable sand. Piers, posts, and columns need to be embedded deep into unconsolidated sediment or preferably keyed into natural lava rock deposits, so the foundation can not be undermined. Keyed footings minimize lateral movement when foundations are exposed to hydrodynamic forces. In areas prone to flooding, special consideration must be given to the depth of the structure's foundation relative to maximum potential depth of erosion caused by flood waters.

Timber-framed structures in coastal regions should be elevated above flood levels to allow waves to pass under. Elevation of the lowest structural member above the base flood elevation is recommended where it is feasible. Lateral bracing of the foundation piers, posts or columns should be oriented parallel to the anticipated flow of water.

Where reinforced concrete foundations or walls are used in coastal areas, metal reinforcement must be adequately covered with concrete. In these areas corrosion-resistant reinforcements and anchor bolts should be considered to prevent the rusting of these



NOTE: Providing freeboard by elevating lowest structural member above base flood elevation is recommended, where feasible.

Foundations should rest on bedrock. Lateral bracing should be oriented parallel to anticipated flow path (United States, Federal Emergency Management Agency 94) elements due to exposure to the salt conditions. Metal fasteners and other hardware should be galvanized to resist corrosion.

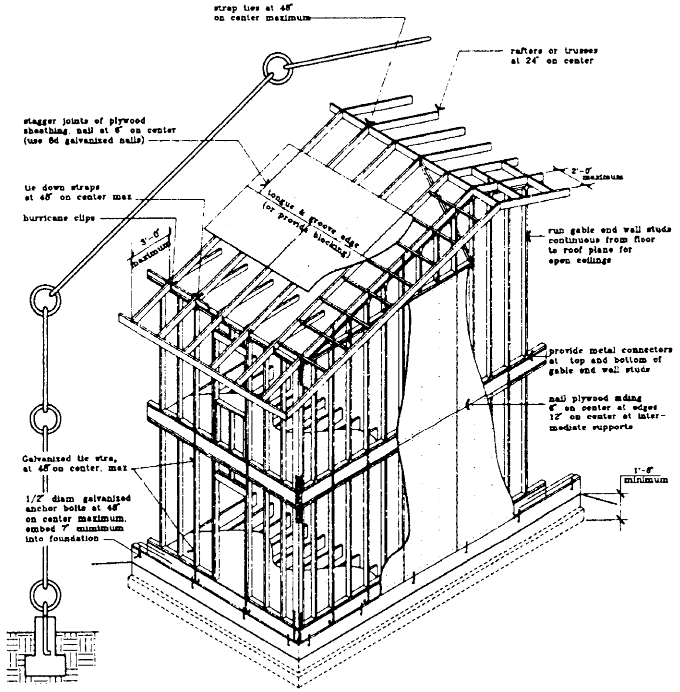
4.13 LANDSCAPING

Trees and landscaping have both positive and negative effects on buildings during the high wind conditions. Landscaping provides sheltering from high winds and blocks strong winds that will otherwise be incident upon the building. At the same time landscaping and tree parts are sources of windborne debris. Tree branches and coconuts are potential projectiles that cause window or cladding failure. During Iniki, airborne coconuts on Kauai caused more damage than all other projectiles combined. By picking coconuts or trimming branches at the beginning of each hurricane season (June), the possibility of these becoming dangerous flying projectiles can be reduced.

4.14 OTHER OPTIONS FOR HURRICANE PROTECTION

Optional Hurricane Accessories

Non-conventional external tie-down systems that anchor the entire building to the ground have proven to be successful alternatives to reinforcing framing connections. These tie down system consists of steel cables, chains and turnbuckles, or nylon ropes. The cables and ropes are attached to eye bolts located on the structure's overhanging rafters or were strapped across the entire width of the roof. Cables and ropes are then attached at ground level to concrete anchors, tree stumps, steel pegs, or tied to the floor girders beneath the house. Although somewhat crude in nature, this system performed well in Hurricane Iniki by resisting uplift forces. Buildings that implemented these systems sustained minimal structural damage.



Typical tie-down details (Nick Huddleston 18)

Protected Areas within a Home

During Hurricane Iniki people, upon the collapse of parts of their homes, took refuge in their bathrooms. Several evaluations of light framed wood homes suggest that wood structures have at least one safe haven (the bathroom for instance) that has reinforced concrete or masonry walls and protected openings[34]. Walls of this area can also be constructed of wood framing with proper connections and with plywood sheathing in place of dry wall. Plywood sheathing enables a wall to provide additional lateral resistance and perform like a shear wall.

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[34] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 724.

Alternative Building Materials

In principle, any type of construction material (i.e. wood, masonry, reinforced concrete, steel, etc.) can be properly designed to withstand high winds and wave forces generated by hurricanes. Still, previous disasters such as Hurricane Iniki have demonstrated that certain types of construction fare better.

This document has focused on the improvement of lightweight timber framed homes because the majority of homes in Hawaii, including those in high wind prone areas, are constructed of wood. Hurricane Iniki has demonstrated that homes constructed out of reinforced concrete or masonry are beter able to withstand hurricane forces. Damage to concrete houses was limited to roofing material and framing (usually of light framed wood construction). Both reinforced concrete and block walls were resistant to missile impact damage. Concrete and heavier material allow for redundancy in a design (several load paths) versus light frames (wood and metal) where mistakes have significant effects due to the minimization of materials[35].

One may also note that in Guam, another Pacific Island that often experiences hurricanes, homes are predominately constructed of reinforced concrete. In comparison with Hawaii, damage to homes in Guam is significantly less.

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[35] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 517-518.

Concrete has become the building material of choice in Guam because of it is resistant to typhoons and because wood and termite problems exist. One should also note that buildings in Guam are required to be able to withstand super typhoon wind speeds of 155 m.p.h. while homes in Hawaii only have to withstand 80 m.p.h. as prescribed by the U.B.C[36].

Whether there is a preferred material for housing in hurricane-prone regions, or if success is simply a function of good construction is the big question. James W. Sheffield, a regional engineer with the International Conference of Building Officials' Austin Texas office, surveyed the building damage after Hurricane Iniki and emphasized construction techniques utilized on Kauai. In his report, he concluded that "properly constructed housed and buildings of both light framed wood and concrete are extremely effective in resisting typhoons and hurricanes" and that light-framed wood homes "performed well structurally when careful attention was paid to details in their construction, especially in fastening roof, wall, and floor components[37]. Indeed, both material and good construction are requirements for hurricane resistance.

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[36] Ronald A. Cook and Mehrdad Soltani, ed. Hurricanes of 1992 (New York: American Society of Civil Engineers, 1993) 448.

[37] Paul Tarricone, "The Winds of Change?" Civil Engineering (January 1994): 43.

4.15 NEED FOR ADOPTING NEW WIND DESIGN CODES

Shortly after Hurricane Iniki, Kauai County adopted an appendix to the 1991 edition of the U.B.C. It clarified and specifically addressed design and construction of light frame buildings in high-wind areas. The new section is very explicit in its requirements and contains graphical presentation not contained in older versions of the code. Compliance with these codes will enable buildings to better withstand the next hurricane that hits Hawaii.

Currently all counties of Hawaii have their own building codes and each county uses the U.B.C. as the presiding guideline. Jurisdiction of building constructions throughout the State of Hawaii falls under local building authority. Because hurricanes are a threat to all islands, a statewide building code should be adopted. A statewide code would provide greater consistency among design professionals and contractors throughout the state as well and require all homes in Hawaii to be designed for wind resistance. Because of the similar residential building construction throughout the islands, the immense destruction that Hurricane Iniki inflicted on Kauai serves as an example to what could happen to other islands in the future.

Traditionally, residential construction in Hawaii has not been engineered. The immense damage caused by Hurricane Iniki raises the question of whether homes should be engineered. Building failures suggest that the design of these buildings should involve a structural engineer or an architect proficient in structural design.

4.16 FUTURE HURRICANES AND HOME CONSTRUCTION

Because of Hawaii's location in the middle of the Pacific Ocean, it is occasionally in the path of devastating hurricanes. Weather forecasters predict that the frequency of hurricane in this region of the Pacific will increase due to changes in weather patterns and global warming trends. Hurricanes in the middle latitudes are likely to become more frequent and destructive[38].

A home is a costly lifetime investment and human life is priceless. As people rely upon their homes for shelter in fair and foul weather, homes should be able to withstand natural disasters such as earthquakes and hurricanes. Further hurricane preparation measures need not only include specification of reinforcing materials and hardware at design and construction stages, but also the retrofitting of existing structures. The future of the building construction industry in Hawaii should not only learn from the failures of previous hurricanes like Iniki, but should act upon lessons learned and design safer homes. Hurricane Iniki has demonstrated the imperative need for design professionals, contractors, and owner builders to incorporate wind resistant engineering in all new construction in Hawaii.

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[38] Sam Monet, Aloha 'Aina Hydro Farms Inc.: Hurricane Iniki. (http://Hawai'i-shopping.com/~sammonet/iniki1.html).

APPROPRIATE RESIDENTIAL DESIGN

5.0 ADDITIONAL DESIGN FACTORS

5.1 TERMITE PROBLEM

Hawaii's warm moist climate is optimal for the proliferation of termite colonies. Buildings in Hawaii experience the most severe termite problems in the entire United States. This termite problem is another designissue that homes in Hawaii need to address.

Two types of termites are generally found in Hawaii; subterranean termites and dry wood termites. Subterranean (ground) termites are more active and cause significantly more damage than dry wood termites. The destructive subterranean termites thrive in moist decaying wood at certain temperatures (usually between 75 and 90 degrees Fahrenheit). Termites are especially partial to warm coastal areas[1].

In a matter of a few months, termites can seriously weaken a structural member or in severe cases, incapacitate an entire structure. Termites penetrate timber structures though cracks in the masonry or timber which contact the ground or through holes which they bore in the timber. Once inside the wood, termites need to remain in contact with soil or moisture in order to survive.

There are several things that a home owner can do to defend a home against termite infestation. The first level of protection is to

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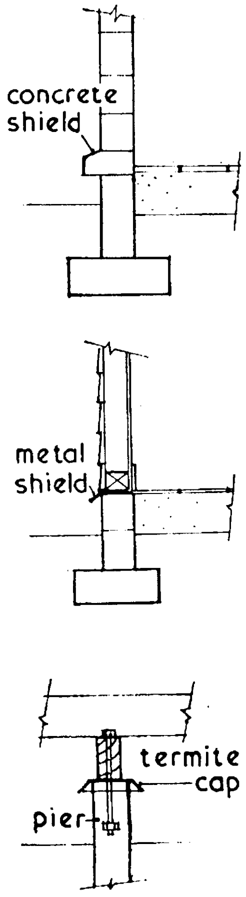
[1] Bernadette Maria Paik, Building Single Family Residences within Hawaii's Environment, thesis, University of Hawaii at Manoa, (Honolulu: May 1975).

create a barrier in the soil under and around the structure to keep termites away from the building. This is done by protecting soil with insecticides or by installing basaltic termite barriers beneath the slab before the slab is poured. In addition to termite treating, effective drainage on a site also discourages termite nesting close to the building.

The next step to defend against termite infestation is to keep termites away from the wood portions of the structure. This is achieved by ensuring that timber components are not placed near to or in contact with the ground. Wood members should be located as far from the ground as possible. Termites will find their way though any crack or opening to get to wood. Open areas in concrete slabs located at drains, pipes and cables are possible entry paths for termites and should be filled with epoxy grout and basaltic termite barriers.

Continuous, welded sheet metal guards placed along the upper portion of foundations prevent termites from accessing the wood above. Termites will not eat through metal so metal barriers placed between foundations and the wood structure force termites to expose themselves. Routine inspections of areas near metal shields can alert owners to termite problems and prevent severe and extensive termite damage from occurring.



Typical termite sheet metal termite shields provide another line of defense against termite infestation (David Oakley 80)

The third step for defending against termites is to deny termites food by using pressure treated lumber, or non-nutritious materials such as concrete masonry or steel. “Termite treated” wood, which has been impregnated with a preservatives, kills termites. Preservatives also prevent the growth of fungi, worm and other organisms that weaken timber.

5.2 SALT CORROSION

Buildings located in coastal regions have to contend with the additional problem of salt corrosion. In coastal areas corrosion resistant materials must be used to maintain the integrity and warrant the life of a structure. Concrete, wood, vinyl, and certain metals perform well in these types of environments.

Concrete structures are suitable for coastal areas, but the metal reinforcing is prone to rust and corrosion. Thus, where reinforced concrete is used, metal reinforcing must be adequately covered with good quality concrete. Careless construction practices can produce poor quality concrete, that is prone to cracking or spalling. When the concrete cover fails, metal reinforcing is exposed to the salty air and it corrodes. In coastal areas the use of special corrosion-resistant reinforcement and anchor bolts should be considered. These types of reinforcement do not rust from salt exposure and maintain their structural integrity when the surrounding concrete fails. Metal fasteners and other hardware should also be galvanized to resist corrosion or should be made of corrosion resistant materials such as stainless steel.

The building form of coastal home should discourage salt and water accumulation. Ledges or crevices should be minimized to reduce the chance of salt collection and corrosion.

6.0 APPROPRIATE RESIDENTIAL DESIGN IN HAWAII

The design of the appropriate house in Hawaii combines energy, earthquake, and hurricane strategies while resisting damage from termites and corrosion. Design guidelines for each of the approaches have been presented, but the issue of the “ideal home” for Hawaii still remains to be defined.

This study has shown that there are many factors that can, or should, influence the design of a home. Site specific characteristics largely determine the appropriateness of a home design. The programmatic demands, spatial requirements, and the availability and cost of materials and construction costs are also key determinates of the “appropriateness” of a home for both the site and owner. Personal preferences and aesthetic opinions further complicate the definition of the ”ideal home.”

There is no single solution to the “ideal home,” but the following guidelines offer suggestions that will increase the energy efficiency and structural stability of a home and make it more appropriate for Hawaii. This comparative study indicates that some, not all, design strategies remain consistent and optimal for all design approaches. In times where discrepancies exist, the architect or owner must decide the which factors take priority.

6.1 SITE PLANNING

The choosing of a site and the location and orientation of a building are the first decisions that will determine the performance of a home. The site and climatic influences are never the same for any two homes. Each site has its own unique topography, views, soil structure, sun exposure, trade wind patterns, wind exposure, and seismic risks. These factors can combine in an infinite variety of ways and thus the development of a single characteristic building for Hawaii is impossible. Thus, every site requires careful site investigation and analysis. The determination of site features and potential risks can aid designers and builders in creating homes that are appropriate for each site.

Zoning maps are available at local County Planning Offices. These maps identify hazard areas, evacuation zones for floods and tsunamis, and seismic risk for earthquakes. Tsunami evacuation zones are published in the front of the telephone directories for each Hawaiian Island. Owners and designers should attain information about these various site factors prior to designing.

Many designers and owners may consider site surveys to be a tedious or unnecessary step in the design process of a residential home. However, in order for designers to build homes appropriate to a site, they must be aware of all the site factors and features.

Hazard Prone Areas

Site features can make an home susceptible to high winds, landslides, floods, tsunamis, and high surf.

High wind-prone Areas

Topography greatly influences wind patterns on each site. Hilltops, windward facing slopes, and cliffs can experience extremely high and potentially damaging winds. In theses areas, on-site investigations must be conducted to identify potential high wind hazards.

Landslide-prone Areas

Although hilltops, mountain sides, hillsides, and cliff tops offer the most spectacular views, these sites are also prone to landslides caused by earthquakes or heavy rainfall.

Flood-prone Areas

Areas prone to flooding include low-lying areas adjacent to hillsides, rivers, or streams, and valley floors. These areas are especially vulnerable to flooding due to excessive water runoff and overflow. Heavy rains can result in severe flash flooding and the overtopping of streams and ditches. In lowlands and other poorly drained areas, water from rainfall and runoff may accumulate to depths of several feet.

Tsunami and High Surf-prone Areas

Generally, all coastal areas throughout the Hawaiian islands are vulnerable to tsunamis and high surf. Evacuation zones for tsunamis and high-surf identify areas of high risk. To determine the risks for specific areas, owners and designers must refer to zoning and evacuation maps.

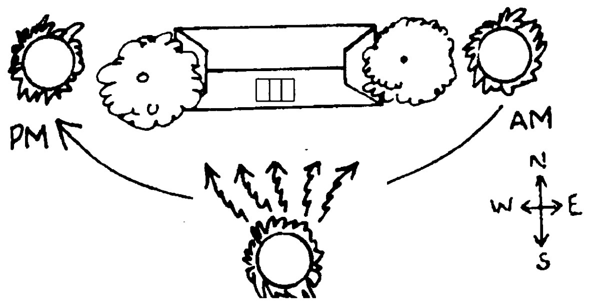
6.2 BUILDING ORIENTATION

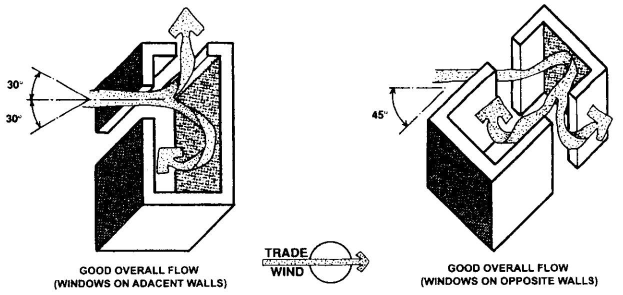
The orientation and configuration of a building is very important in determining its solar control, daylighting, and natural ventilation capabilities. The ideal building orientation is site specific. Solar exposure, wind patterns, and existing vegetation are factors that should guide the building's orientation.

The ideal building orientation for solar protection and solar collection is due east and west. This enables a building to collect sunlight on the elongated south side throughout the year. This orientation also minimizes the solar exposure on the east and west sides.

Ventilation has a greater effect on internal conditions than the sun in single-family homes in Hawaii. Therefore, orientation with respect to the prevailing winds should take precedence over solar considerations. Prevailing winds are from the northeast i most areas, but can be altered by topography and landscaping. Site surveys must be conducted to determine the exact direction of the wind. Buildings should be oriented to encourage cross ventilation and good air movement in all usable spaces.

The orientation of a buildings for earthquakes or hurricanes are not a concern. Hurricane winds and seismic motions can strike a building from any direction or orientation. Strength in any one particular direction is of little use, A building must be strong and able to resist lateral forces from several directions.





Top: East-west orientation is optimal for solar protection from extreme morning and afternoon sun conditions. It is also optimal for solar collection on South. (Modified from State of Hawaii, Department of Education 17) Bottom: Optimum orientation for ventilation for rooms (State of Hawaii, Department of Business, Economic Development, and Tourism 15)

6.3 BUILDING DESIGN

Building Height

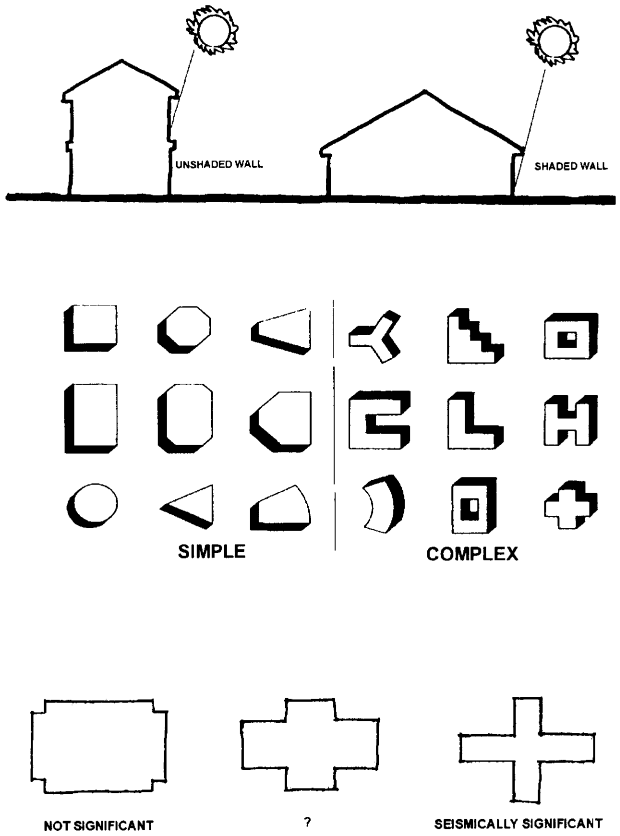
The ideal building form in Hawaii should be low to the ground. Low buildings are more aerodynamic and are forms that are more stable in high winds and earthquakes (lower center of gravity). Low roof with overhangs also provide better sun and rain protection.

Taller two-story buildings result in the need for more shading and less stable conditions during earthquakes and hurricanes.Two-story forms can be used in areas where the maximization of usable floor area on a site is desired. These building forms can also be beneficial when adverse surrounding conditions make it difficult to attain sunlight on low roofs.

Building Shape

Building shapes should be kept as simple as possible. Although complex forms can promote daylighting and natural ventilation, these shapes (in both plan and elevation) produce concentrated wind and seismic forces. Reentrant corners, numerous complex connections, and large surface area exposure create points of weakness where failure is likely to occur. Complex forms also increase the amount and complexity of connections. Slight variations of simple forms have little effect upon a building's seismic and wind response.

When complex shaped building forms are used, special attention

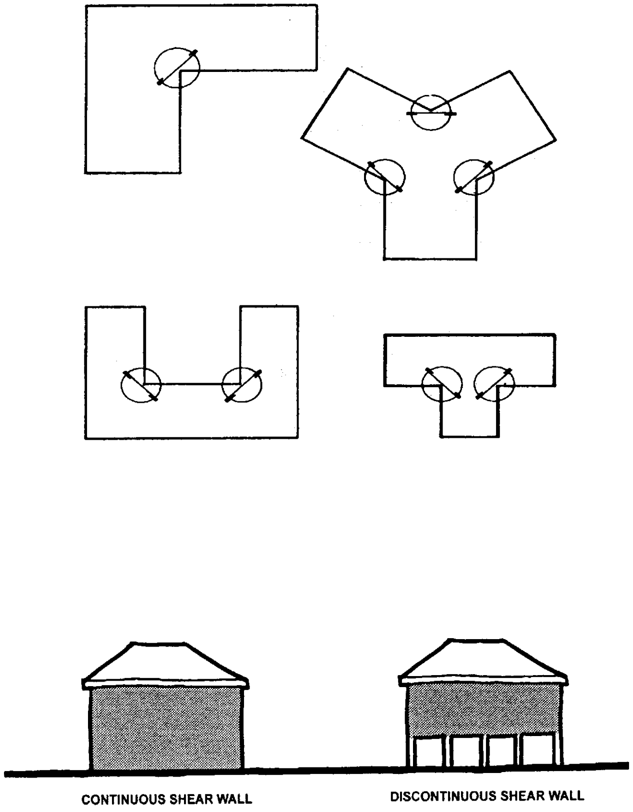


Top: Tall building forms are less aerodynamic and can not be adequately shaded from the sun and rain. Middle: Simple versus complex building plans (Christopher Arnold 232) Bottom: Examples of complex forms with various degrees of significance (Crawley 109) must be given to connections. Foundations should be diagonally reinforced as shown. In addition, strong connections at all corners should exist to resist concentrated forces.

Raised Floors

Raised floors are ideal in areas prone to flood and coastal wave action. They also allow a building to be cooled from below. However, raised floors create soft stories that are vulnerable in earthquakes and hurricanes. Lateral forces from earthquake motions and high hurricane winds subject lower columns and posts to immense forces.

Buildings with column supported floors must use shear walls or diagonal bracing. Diagonal bracing or shear walls that are continuous to the foundation provide lateral resistance from hurricanes or earthquakes. In coastal areas they provide lateral resistance while remaining open and allowing water and wind to circulate below. Shear walls and diagonal bracing should be placed in at least two directions (orthogonal). In coastal areas shear walls or bracing should be placed normal to the beach line. Shear walls must be continuous through the foundation.



Top: Diagonal foundation reinforcing at re-entrant corners (United Nations, Department of Economic and Social Affairs 85) Bottom: Continuous shear wall versus discontinuous shear wall. The discontinuous shear wall will produce high stresses at the column/ floor connection and is where failure is likely to occur.

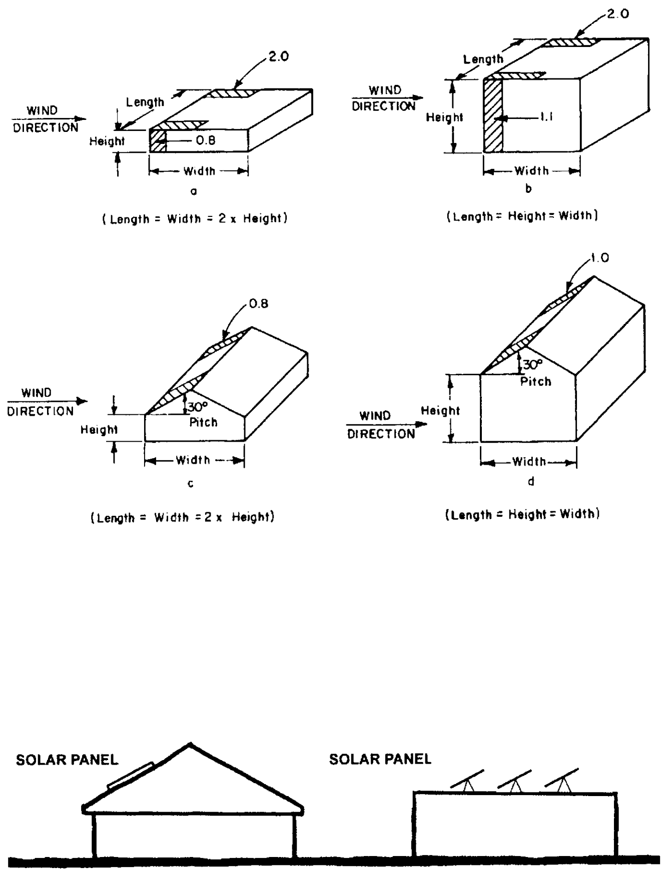
6.4 ROOF DESIGN

The roof proportionally dominates most homes and other low-rise buildings. The roof's large surface area and its function of providing shelter from adverse weather conditions makes it the most important building component. The design of a roof is critical in determining a home's climate response, energy efficiency, and hurricane resistance.

Sloped versus Flat

Hawaii has a variety of microclimates that dictate the appropriateness of a roof type. In drier microclimates, a flat roof can be used with minimal problems. Ponding of water and roof leakage are common problems in flat roofed buildings, so special attention should be given to its design and construction. Adequate slopes to drains, waterproof roof membranes, and properly detailed internal gutters and downspouts reduce the chance of leaky roofs, algae growth, and clogged gutters and downspouts. In addition to having more leakage problems than sloped roofs, flat roofs also experience larger uplift forces during high winds.

In Hawaii where tropical rains are a common occurrence, waterproofing and drainage of a roof are important. Solar collection, wind resistance, and rain protection encourage the use of sloped forms over flat roof forms. Sloped roofs have the advantage of being more aerodynamic and allow for quick rainwater runoff. Sloped roofs allow solar panels high solar exposure, angled supported and easy attachment. Thus, the sloped roof is more appro-



Wind effects on a flat roof versus a sloped roof (National Bureau of Standard, Design, Siting, and Construction 30) Bottom: Sloped versus flat roof. Sloped roofs are better for shedding rainwater, collecting solar energy and are more aerodynamic than flat roofs.

priate to the Hawaiian climate than the flat roof.

Sloped Roofs

Sloped roof forms come in a variety of forms including the gabled, offset, semi-gabled, hipped, and “Hawaiian” style roof.

The gabled roof with end wall vents provides adequate roof ventilation, but insufficient protection from the sun and high winds. The gabled roof form benefits from its ability to incorporate both soffit and end wall vents that allow cross and stack ventilation of an attic space. The high end wall overhangs of a gabled roof are unable to provide adequate shading or rain protection to the windows at occupant level. End walls and overhangs are also vulnerable to high winds.

Offset roofs with operable clerestory windows also encourage stack ventilation. Offset roofs with clerestory windows allow indirect daylighting deep within a space. Because its form and construction is similar to the gabled roof, end walls overhangs are also unable to provide adequate shading or rain protection to the windows and are susceptible to failure in high winds.

Hipped roofs are the most structurally stable and aerodynamic of the previously discussed roof forms. They too are subjected to uplift forces at overhangs, but do not experience end wall problems. Hipped roofs do not allow for the incorporation of vents into the roof form. Venting requires “add-on” vents such as ridge vents or operable skylights. The low overhangs of hipped roofs provide rain and solar protections.

Semi-gabled roofs and double pitched "Hawaiian" style roofs are modified hipped roofs that combine the structural advantages of the hipped roof with the ventilating advantages of the gabled roof. These roof forms have the low overhangs of hipped roofs for rain and solar protection. They also incorporate the vents of gabled roofs for stack and cross ventilation. Because semi-gabled and "Hawaiian" style roofs address all of these climatic factor, they most appropriate roof for the Hawaiian climate.

Optimal Roof Slope

There are inconsistencies in the "appropriate" roof slope in Hawaii. High roofs, framed with exposed beams, encourage natural stack ventilation and are aesthetically preferred over low flat ceilings. High roofs also allow better distribution of natural light from clerestory windows or skylights above. However, high roofs are less aerodynamic than low sloping roofs.

Simple-formed low-sloped hipped roofs are the more appropriate for hurricane resistance. This roof form is more aerodynamic and experiences less wind induced forces. The ideal slope for hurricane resistance is 30 degrees, as there is minimal uplift pressure upon the windward face of this roof slope. On the other hand, the ideal roof orientation and slope for solar collection is facing due south at a 22 degrees inclination. However, the slope of the collection panel can vary to 30 degrees and have little effect on the yearly efficiency of the system (system is 98% efficiency at 30 degree slope). Studies have also proved that roofs slopes between 25 to 35 degrees are optimal for economy and insulation values[2]. Thus, a roof slope of 30 degrees is recommended for roofs in Hawaii.

Roof Overhangs

Overhangs serve both an aesthetic and a practical function by shading building walls from the sun and rain. Different sized overhangs are required on each building side due to differences in sun exposure. In Hawaii the north side requires small overhangs to block the direct summer sun and provide rain protection. The east and west sides need moderately sized overhangs to provide protection from the rain and high angled late morning and early afternoon sun. The south side needs large overhangs to block the direct sun throughout the day and the majority of the year. In addition to providing solar protection, overhangs direct rainwater well away from the building's base and therefore lessen foundation drainage problems. They can also help to cool, collect, and direct breezes to building inlets.

Large overhangs, although desirable for shading, rain protection, and cooling, are not advisable in high wind situations. Large overhangs experience large uplift forces which are difficult to detail for and require the expertise of an engineer. Overhangs should be limited to 3.0 feet and have rafters or trusses that are tied down to

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[2] Louchak Chan. An Investigation of the Effect of Roofing Design on the Thermal Performance of Single Family Residential Houses in the Hawaiian Climate, thesis, University of Hawaii at Manoa (May 1980) 47.

the wall with hurricane straps. Overhangs should also have adequate soffit vents to prevent pressure build up and encourage natural ventilation of the roof.

Roof Insulation

Heat from the roof is the prime source of heat gain for most low-rise buildings in Hawaii. The thermal design of a roof is critical as the roof is exposed to the intense rays of the sun throughout most of the day. Roof insulation and radiant barriers can reduce the heat gain through a roof.

Insulation placed above a flat ceiling or within the sloped rafter space can greatly reduce heat gain within the space below. Because of the roof's intense solar exposure, high R-value insulation (R=20 or greater) is required. An alternative to insulation is a radiant barrier. Properly applied layers of radiant barriers can be just as effective as high R-value insulation. Fiberglass rolls or batts with aluminum foil further increase the effective thermal resistance of the roof. Whether a home has insulation or a radiant barrier, an air space needs to be provided above them to vent hot air and allow moisture within the roof to evaporate.

Roof Openings and Vents

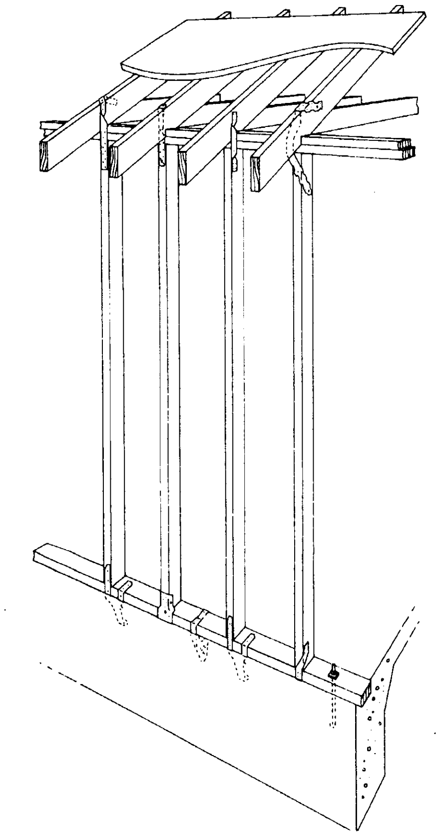
Roof openings provide excellent opportunities for daylighting and ventilation. Operable skylights allow daylighting and stack ventilation. They can be opened to let warm interior air out and be closed during high winds.

Although roof openings are beneficial for daylighting and cooling, they produce areas of discontinuities within the structure that are vulnerable in earthquakes and hurricanes. Therefore framing around these opening must be reinforced with doubled structural members and metal connectors when roof openings are used in both new and existing homes. Careful detailing of framing and connections around openings is mandatory to ensure that a skylight remains intact during high winds and earthquake vibrations and does not leak.

Roof Framing

The roof framing of a building must resist and transmit lateral and gravity loads. Rafters and trusses should be appropriately sized and connected according to building code requirements. Special attention must be given to connection points; they are susceptible to failure and should be reinforced with metal connectors and hurricane fasteners. It is crucial that rafters be tied to the top plates with appropriately sized and installed hurricane straps so the roof is able to withstand lateral and uplift forces.

Roofs framed with beams or rafters create high sloped ceiling that promote stack ventilation and indirect daylighting. These roof framing types are prone to failure during an earthquake or hurricane because they lack structural redundancy. Roofs framed with trusses are more hurricane and earthquake resistant and provide structural redundancy. Exposed trusses with sloped ceilings can offer the advantages of both roof systems. All roof framing lumber should be pressure treated to resist termite infestation and rot.



Typical roof & wall connections with stud spacing same as truss/rafter spacing (Southern Building Code Congress International 80)

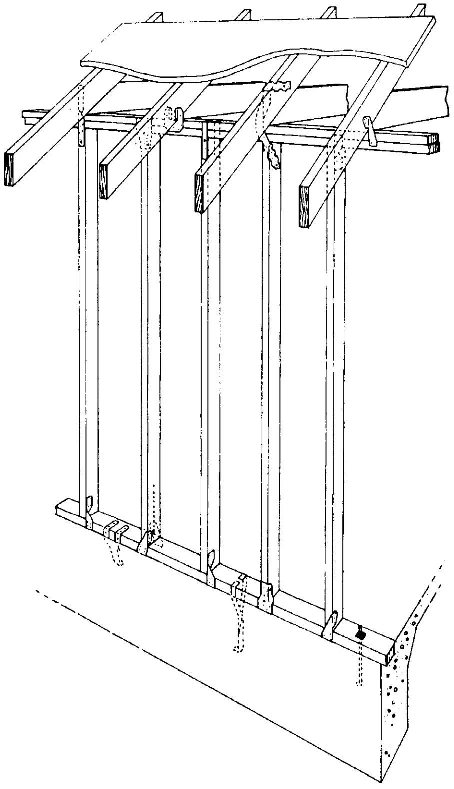
Roofing Sheathing and Materials

The selection of roofing material and sheathing plays a critical role in a building's thermal performance and hazard resistance. Roof sheathing provides enclosure and is part of a building's lateral resistance.

Plywood, tongue-and-groove decking, and metal decking are recommended roof sheathing materials. Sheathing should be attached with strict adherence to building codes.

In Hawaii a roof and wall mass should be minimized. Lightweight roofing material minimize the absorbtion and storage of heat. Light-weight roofs that are securely anchored to plywood sheathing enable a building to perform well during earthquakes and hurricanes. Appropriately applied and securely fastened roofing material can also minimize the amount of wind projectiles during high winds. Roofing materials should also be able to shed water quickly.

Properly attached corrugated metal sheets and asphalt composition shingles over plywood sheathing have performed well in high wind and driving rain conditions and are appropriate to the climate conditions of Hawaii.



Typical roof & wall connections with stud spacing different from truss/ rafter spacing (Southern Building Code Congress International 81)

Roof Color

The color and texture of a roof also influence a building's heat gain. In Hawaii it is desirable to minimize heat gain. The best method for preventing heat gain is to keep the heat out by minimizing the amount of heat absorbed by the roof. Homes in Hawaii should utilize light-colored or reflective roofing materials to reduce solar heat gain from the roof.

Solar Collection Panels

Solar hot water systems can be added to existing roofs or incorporated into new roofs. Solar collection panels do not require any additional structure and can be conveniently attached to sloped roofs. Careful attention must be given to the attachment of solar panels so they can remain intact during high hurricane winds.

6.5 WALL DESIGN

Single wall Construction

Although single-wall constructed homes are still in existence, this type of wall framing system is not recommended for new homes. Single-wall construction has little shear resistance to withstand high wind and earthquake forces. Existing single-wall homes can be reinforced to better withstand lateral forces by adding hurricane clips to tie roof framing to the walls; adding plywood to exterior and selected interior walls to increase shear resistance; and reinforcing connections to the foundations.

Single-walls also provide little protection from solar heat gain. Thin walls are unable to be insulated and thus heat from the sun is quickly radiated to the building's interior.

Double-wall Construction

Double wall construction is a common construction type utilized in Hawaii which should retain its popularity in the foreseeable future. Typically, it includes wood studs sheathed with siding and an interior wall finish such as gypsum board. Walls sheathed with plywood can perform as shear walls that will greatly improve a homes lateral resistance in an earthquake or hurricane. Wood products such as particle board and oriented strand board do not have the same structural capabilities as plywood and should not be used in lieu of plywood.

Wood construction is commonly used in Hawaii because of the availability of material, its relatively low cost, and east of construction. When these homes are well-detailed and constructed, they can adequately withstand hurricane and earthquake forces. When they are insulated and windows are thoughtfully placed, these walls can minimized heat gain. Still, wood and double wall cavities are factors that make this type of construction vulnerable to termite damage.

Alternative Wall Construction Materials

In the constant war against termites, high winds, rain, and earthquakes alternative wall materials should also be considered. Metal studs can provide good shear and bearing strength wall construction when properly detailed and engineered. They are also resistant to termite damage.

Termite problems in Hawaii have resulted in the popularity of lightweight metal framing as a residential construction material. Wood -framed houses need to be fumigated using tent-treatment every five years, but with steel frames this is not necessary. Steel studs are not only termite proof, but are non-combustible and are structurally comparable to wood. Steel frames and studs are uniform in length, straightness, and quality which aid in the ease of construction. Cost-wise, some contractors even suggest that steel framed homes should be less expensive since construction time in the field is shorter than the standard wood stud system[3]. The use of steel

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[3] Maurice H. Yamasato, "Steel Framing Offers Many Advantages." Hawaii Architect (December 1992): 24.

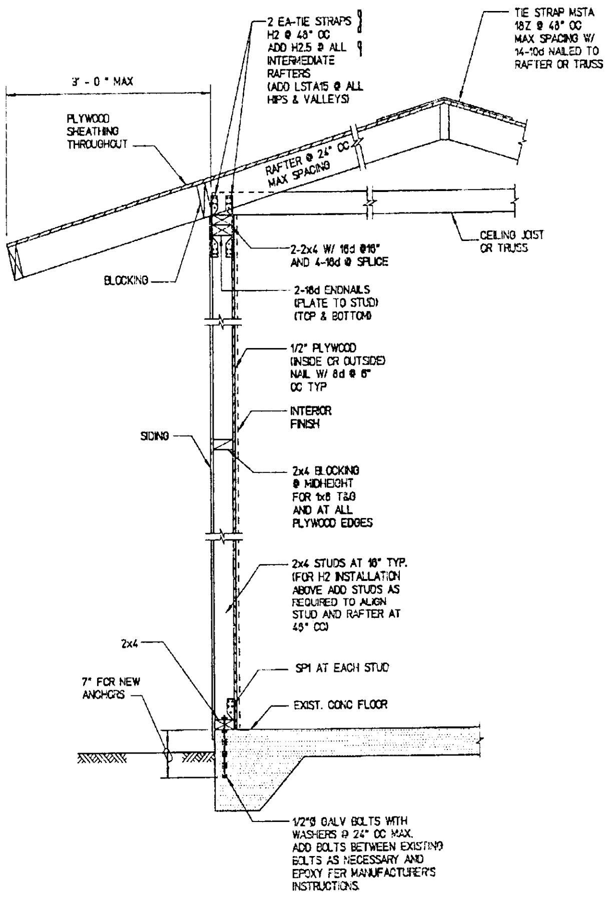
framing in lieu of wood framing would also reduce the demand for lumber, therefore having a positive effect upon forests and the environment.

Masonry and concrete walls, although more expensive, are resistant to wind and wave forces when properly reinforced and tied to its foundation. They also fare well during earthquake vibrations and are termite resistant.

Wall framing

The framing of a wall plays a large role in determining the structural stability of a home. In order to provide a continuous load path during an earthquake or hurricane, walls must be adequately tied to the roof and foundation with metal straps and connectors. Members within the walls themselves must also be fastened with metal connectors rather that traditional toenails. Metal straps help ensure strong connections and that enable the transferring of both gravity and lateral loads. All wall framing lumber should be pressure treated to resist termite infestation and rot.

Careful detailing of framing around openings increases a homes wind and water resistance. Strong metal plates that reinforce openings and adequate anchorage of window frames to rough framing are necessary. Windows at corners, although aesthetically pleasing, are vulnerable to damage during hurricanes and earthquakes. Corner windows eliminate the crucial load resisting structure at corners and should thus be avoided.



Wood framing detail recommendations for double-wall construction with slab-on-grade foundation (Structural Engineers Associationof Hawaii, Tips on Improving Wind Resistance 5)

Shear walls

Shear walls should be used in all homes to resist lateral earthquake and hurricane forces. Because wind and earth vibrations can be from any direction, lateral resisting elements oriented in several directions are recommended. In coastal residences, shear walls should be oriented normal to the beach line in order to be the most effective against wave and surge forces.

Because of Hawaii's mild climate through most of the year, large openings and the minimization of exterior walls are desirable. Walls with large openings are not ideal shear walls. Thus, interior partition walls can be designed as shear walls to resist lateral forces.

Wall Insulation

Double walls allow for the placement of insulation between the studs. Wall insulation should be used in walls where solar exposure is high and where overhangs can not provide adequate shading. Insulation is especially critical for air-conditioned homes where the indoor temperatures differ significantly from outdoor temperatures.

Window Placement

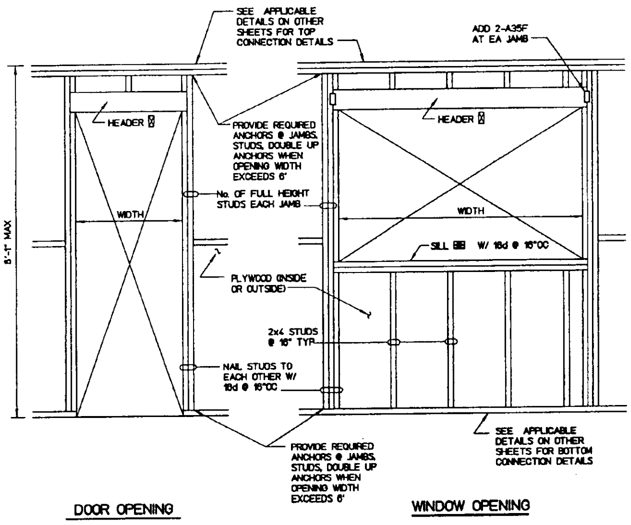
The placement of windows greatly affect daylighting, heat gain, and ventilation patterns. Windows on the north provide even lighting throughout the majority of the year. Small overhangs or shading devices need to accompany north facing windows to prevent direct sunlight and heat gain during the summer. Windows on the south are exposed to the sun throughout the majority of the day during the year and must be shaded with wide overhangs or shading devices. East and west facing windows need be minimized as they are exposed to extreme heat gain and direct sunlight in the morning and afternoon. Windows can be placed on any side if shaded properly and direct sunlight is avoided.

High windows allow daylight to penetrate deep into a space and indirectly light a space. High operable windows are potential outlets for stack ventilation. Low operable windows offer views and allow for cross ventilation.

Windows and Openings

The warm and humid day-to-day climate of Hawaii demands an open house, but the threat of violent winds and earthquakes necessitates a house that minimizes window openings and is able to be completely enclosed. Large windows are vulnerable to damage from wind projectiles and are points of discontinuity in a building framing where structural damage is likely to occur.

Dividing large openings, strengthening window framing details, and selecting laminated or safety glass types can improve a building's resistance to hurricanes or earthquakes while allowing the ability for openness and natural ventilation. Interior shear walls, and allow the openness of exterior walls, while providing lateral resistance to hurricane winds and earthquakes. All window openings should be reinforced with metal connectors and plates.



Wall framing detail recommendations for openings (Structural Engineers Association of Hawaii, Tips on Improving Wind Resistance 13)

Window Frame Materials

In recent years vinyl windows have been introduced to Hawaii to in response to environmental problems. In the past rusting, rotting, corroding, and insect infesting have been problems encountered with the use of wood or metal windows. Rain, salt air and water, solar exposure, and termite problems have plagued and tested the integrity of the building materials in Hawaii. Solid vinyl windows, with stainless steel fasteners are resistant to salt water and impervious to rotting and termite destruction. Proponents of poly vinyl chloride (PVC) windows claim that they have lifetime of 50 years or more[4].

Glazing or Protective Elements

Large areas of glass are potentially considerable areas of heat gain and envelope failure. Shattered glass can cause serious human injury. By using laminated glass or tempered glass (safety glass), hazards from the shattering of glass are minimized. Laminated glass with a UV protecting clear vinyl layer reduces the chance of personal injury and heat gain. The thin layer of vinyl holds shattered glass pieces together and reduces building penetration. The majority of glass types including tinted, low emissivity, and mirrored glass can be tempered. Thus safety and the minimization of heat gain are addressed.

Although reducing personal injury and building penetration, glass

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[4] Joni Ketter, "Vinyl Windows Designed for Hawaii." Hawaii Architect (October 1991): 22.

cannot resist all projectiles carried by high winds. Storm shutters or plywood protective panels installed over openings further reduce damage from projectiles and envelope failure. Storm shutters or plywood need to be solidly mounted to the building and when installed, they offer the best protection for glazed openings during a storm.

Shading Devices

Shading devices located near openings provide solar protection, and daylight control. Shading devices can block out direct sunlight which reduce heat gains and glare. Shading devices are advantageous where high walls, inadequate overhangs, or extreme and various sun conditions occur. Shading devices types include affixed (louvers or boards) or removable exterior devices (canvas awnings) and interior devices (blinds, shades, and curtains).

Shutters or doors used for window protection can be also be used to provide shading. Shutters can also act as wing walls that can channel breezes into a building or induce air flow by causing pressure differences

6.6 FOUNDATION DESIGN

The appropriateness of a foundation type and material is largely determined by its site. Foundations vary in their ability to resist uplift, flooding, and wave action.

Perimeter Strip Foundations Continuous strip foundations provide excellent resistance to uplift and seismic forces when the superstructure is adequately tied to it. Continuous footings enable a building to move as a consolidated unit during earthquake or ground settlement.

Concrete Slab-on-Grade Foundations Concrete slab-on-grade foundations are commonly used in Hawaii. Slabs typically have thickened edge footings and provide good resistance to wind and earthquake forces. Slab-on-grade foundations are not recommended for areas that are exposed to flood waters or wave action. Because these foundations lie on the ground surface, these slabs can be easily and seriously undermined to the point of failure in flood or coastal zones.

Pier Foundations Pier foundations, consisting of concrete or wood columns or piers, allow for open plans on the ground level and elevated floors. This creates a soft story that requires reinforcing to resist wind, earthquake, and wave forces. Diagonal bracing of posts or shear walls need to be oriented in two (orthogonal) directions or normal to the beach line in coastal areas. Footings for shear walls and columns must placed on stable undisturbed or compacted soil. In coastal areas anchoring building footings the underlying bedrock reduces the chance of foundation undermining by water and waves.

Post-and-Footing Block Foundations Post-and-footing block foundations are commonly found on single-wall homes. They typically consist of 4x4 posts with 2x4 diagonal bracing that rest on small concrete footing blocks. These foundations have performed poorly during earthquakes and hurricanes and are not recommended for new buildings.

Existing post-and-footing block foundations can be reinforced at the foundation by adding diagonal bracing and tying the structure with hurricane straps and clips. Footing blocks should be replaced with those that adequately tie to posts. Partial or full replacement of the foundation with continuous footing walls can also improve a building's resistance to uplift and lateral movement, but is relatively expensive.

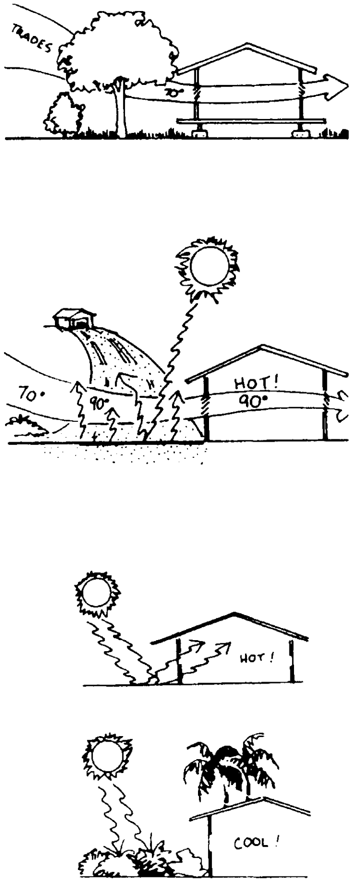
6.7 LANDSCAPING AND SURFACING

Trees and vegetation can greatly alter wind and sun exposure on a site. The types of plants, trees, and shrubs should be selectively chosen and planted to improve site conditions rather than worsen them. Trees provide pleasing and useful shade to areas surrounding a house. They can provide natural cooling through evaporation and direct breezes toward a house. Grass or water place on windward sides will slightly cool and moisten air and make it desirable for cooling interior spaces.

The placement of surrounding landscape or a building within the existing landscape can allow for desirable trade winds for natural ventilation, but can also leave a building exposed and intensify the effects high winds. Trees placed too close to buildings provides unwanted access paths for rodents or subterranean termites.

During hurricanes landscaping is a source for windborne debris. Debris from landscaping should be cleared from the site at the onset of hurricane season (June) and maintained throughout November. Coconuts and weakened tree branches are especially threatening to homes and in the past have caused immense damage.

The placement of man-made surfacing also affects human comfort within a building. The inappropriate placement of surfacing results in warm interior conditions and glare. Concrete, stone or asphalt surfacing have a high thermal capacity; they store and re-radiate



Various landscaping strategically placed can evaporatively cool the natural breezes (Jim Pearson 108) heat to the surrounding air. When these surfaces are on the windward side of buildings, the heated air is carried into the building and warm rather than cool the building occupants. Therefore ground surfacing should be placed on the leeward side of buildings. In cases where existing surfacing is located windward side of a building, vegetation placed between the warm surface and the home can cool the warmed air.

In addition to heating the air, highly reflective (light-colored) surfaces create glare. Bright surfaces can cause eye fatigue, especially when seen from the comparatively dim areas of a room. Reflective ground surfacing should be kept to a minimum on the south of the house to reduce glare and heat catchment[5].

6.8 BUILDING MAINTENANCE

Poor maintenance or lack thereof has often weakened connections through corrosion, weathering, or insect infestation. Deterioration of roof and wall materials caused by these events can contribute to structural weakness. As evidenced by Hurricane Iniki, these weakened connection or components were points where failure often occurred.

To prevent the weakening of structural components from weathering, corrosion, or infestation, the appropriate material and the proper maintenance of these materials should be employed. The

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[5] Oakley, David. Tropical Houses: A Guide to their Design. (London: B.T. Batsford Ltd., 1961) 188.

use of pre-painted wood and metal and periodic maintenance reduce deterioration by limiting areas exposed to the surrounding climatic elements. The use of proper building material such as pressure treated lumber to prevent the infestation of termites or corrosion resistant fasteners (stainless steel or galvanized metal) to prevent the compromise of material strength and integrity.

Sensible construction practices can also reduce the probability of deterioration. Wood should not remain in constant contact with the soil and should not be directly exposed to moisture. In the case where building components are damaged, periodic inspection and replacement should occur.

6.9 RETROFITTING EXISTING HOMES

Although only limited measures can be applied to retrofitting an existing home, changes made can improve a homes ability to save energy and provide hazard protection. Retrofitting steps to help existing homes to save energy include: installing roof and wall insulation, installing and using solar hot water systems and encouraging natural ventilation. The re-roofing of an existing building presents an excellent opportunity to retrofit a home. Light, reflective roofing materials, radiant barriers and insulation can reduce thermal heat gain in a home. The installation of roof vents and soffit vents, along with appropriate air venting spaces, can further reduce heat gain by venting hot air. Heat gain can be reduced by painting surface with light colors. Awnings or other types of external or internal shading devices can reduce heat gain through the windows.

Retrofitting for the purpose of hurricanes and earthquakes include: tying down or upgrading roofs, fastening trusses and rafters to underlying supports, and adding bracing to gable-end buildings. These are all feasible but labor intensive endeavors. This reports suggests some basic steps for strengthening homes, but other manuals offer more detailed and extensive suggestions (see additional reading list).

6.10 ACTIONS TO MINIMIZE HAZARDS

Although the building codes have been developed to reduce the risk of life loss and building damage, the building occupants can further minimize risks by taking additional actions. Warning systems for hurricanes can alert residents to oncoming hurricanes giving them time to secure items or protect openings, yet there are no warnings for earthquakes.

In any natural hazard, residents can reduce the risk to themselves and their homes by becoming aware of the protective measures to prepare for these situations. Assessing, inspecting, reinforcing, and strengthening potentially dangerous conditions (structural and non-structural) before an earthquake or hurricane is strongly encouraged.

In earthquake prone areas large equipment (water heaters and appliances) should be anchored, shelves and cabinets should be braced, and latching cabinets should be utilized[6]. During an earthquake personal injury can be minimize by taking shelter under the tables and desks, in hallways and corridors, and in doorways.

In preparation for a hurricane, potential projectiles should be eliminated. Window and openings should be protected with shutters or panels of plywood.

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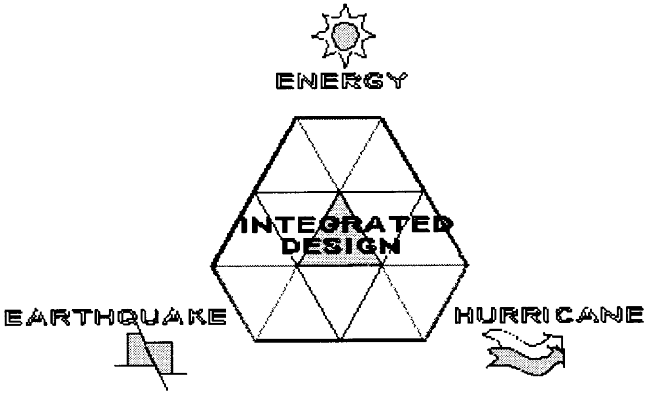
[6] Nowak, Andrzej S. & Ted V. Galambos, ed. Making Buildings Safer for People During Hurricanes, Earthquakes, and Fires. (New York: Van Nostrand Reinhold, 1990) 169.

6.11 CONCLUSION

As mentioned earlier, there is no single solution to the “ideal home” for Hawaii. The appropriate design of a home is site specific. This thesis has outlined a comprehensive approach to designing residential architecture appropriate for Hawaii. It has explored three existing design approaches; energy-efficient and climate responsive design, earthquake resistant design, and hurricane resistant design. The incorporation of all these design approaches are essential to home appropriate for the unique environment of Hawaii. Still, each building site is different so the guideline presented must be applied to each specific site. This thesis has been written in hope of influencing architectural decisions made during the schematic design and design development stages of a project that can greatly improve the energy efficiency and structural stability of a home.



The responsibility of understanding design and construction strategies for an energy and structurally efficient home lies in the hands of the owner, designer, and builder. Overall it remains evident that large numbers of personnel involved with the construction industry do not understand how housing structures should be tied together in order to reduce lateral forces cause by hurricanes and earthquakes. Even when there is an understanding, inadequate attention is given to good construction practice. This is especially the case in areas where housing developments are rapidly constructed.

Education of proper and safe construction methods are therefore essential. Technical educational programs in building need to be set up and targeted at all who are responsible for dealing with residential construction in hurricane an earthquake prone areas.

Owners, builders and developers must also be educated about the critical role the various components of the building plays so that compromises in the integrity of the building are not made and homes appropriate to Hawaii are built.

7.0 BUILDING ANALYSIS

7.1 HOUSE DESIGN #1

Roof Design:

- Gabled/ shed roof
- Low slope
- Dark colored roof
- Small overhangs
- Truss framed roof with flat ceilings
- Foil-lined batt insulation in roof

Wall Design:

- Double-wall construction
- Openings on the south side

Foundation Design:

- Concrete slab-on-grade

Energy Efficiency:

The dark color of the roof causes large heat gains, however the insulation below reduces heat flow to the usable space. The gabled roof does not have ridge vents or a high slope to encourage natural stack ventilation. Still, the hot air beneath the roof is cross vented with soffit vents. Heat that is radiated through the ceiling and heat from occupants will concentrate below the low ceiling and at occupant level and cause user discomfort.

The roof has low, but shallow, overhangs on the east and west which provides shade during the late morning and early afternoon.

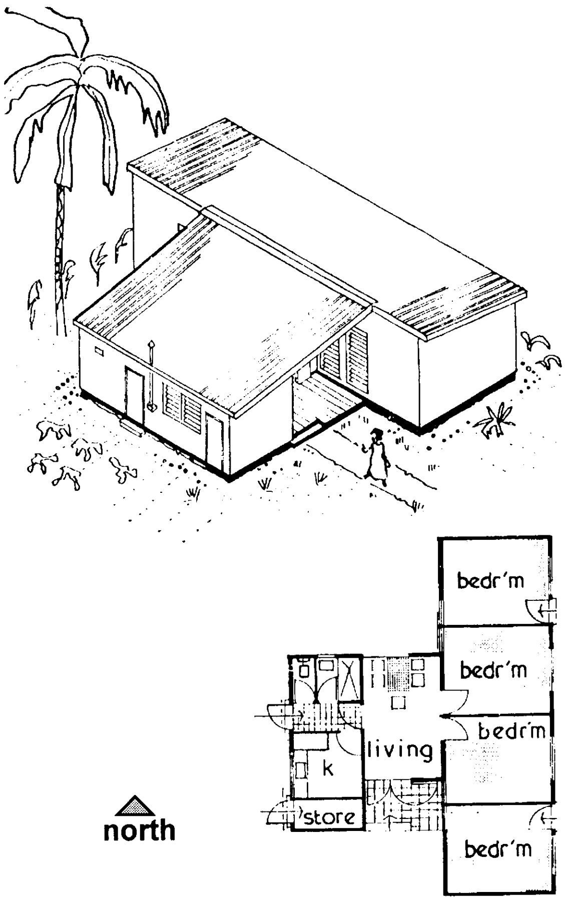


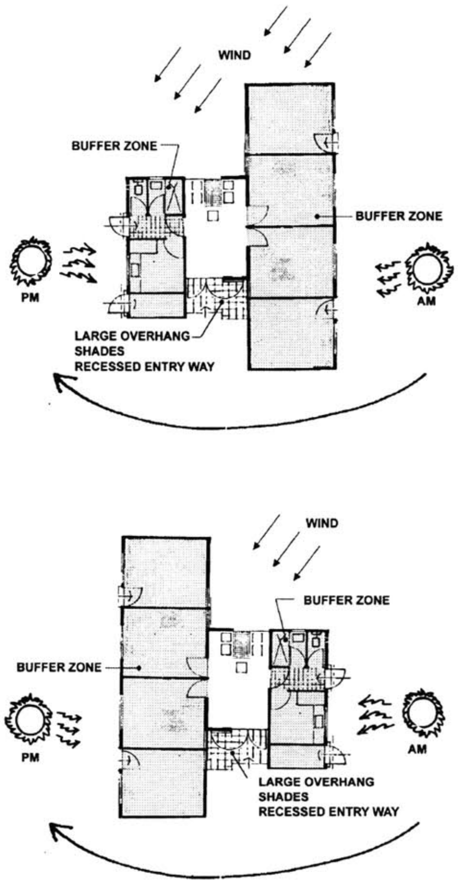
Figure modified from Tropical Houses (David Oakley 238).

The north side has a high overhang that is sufficient to provide shading from the high summer sun. The south entrance is recessed and has a large overhang which keeps the direct sun from entering the living space.

Wall openings are minimized on the north and south sides, and placed mainly on the east and west sides. This make the east and west side of the building extremely warm during the morning and afternoon. The arrangement of the bedrooms, kitchens, and storage on the east and west sides act as buffer zones to mitigate the extreme effects of the sun and delay heat gain to the living area cool. If prevailing winds are from the northeast, the relatively narrow width of the bedroom wing allows for effective cross ventilation. Jalousie windows allow for the entry and directing of cross ventilating breezes. Little ventilation will occur in the living area because the northeast bedroom blocks the wind. Ventilation of the living room can be increased by opening the bedroom doors.

Ventilation of the living area could be greatly improve if the building was mirrored along the north-south axis. The "T"-shape would then "catch" breezes and funnel them into the living area.

Low-lying vegetation on the site provides evaporative cooling, but is insufficient to provide shading.



Top: Diagram showing buffer zones and poor circulation in living area
Bottom: Mirror plan is better for ventilation
modified from Tropical Houses (David Oakley 238).

Earthquake Resistance;

The complex "T"-shaped plan of the building will cause the building

parts to experience differing seismic motions. This will cause concentrated forces at reentrant corners. The location of doors and windows adjacent to reentrant (inverted) corners make these areas vulnerable to lateral earthquake forces. The reentrant corner at the southern recessed entry way is extremely vulnerable to seismic motion. The beam above this entry way must be securely connected to the ridge beam; this framing connection must be able to resist twisting of the structure. Connections at the corners and around openings must be reinforced with metal connectors and ties so the differing movements of the wings can be resisted.
The slab-on-grade foundation is likely to perform well during lateral ground motions. The slab should be reinforced adequately to ensure that it moves as a unified whole.

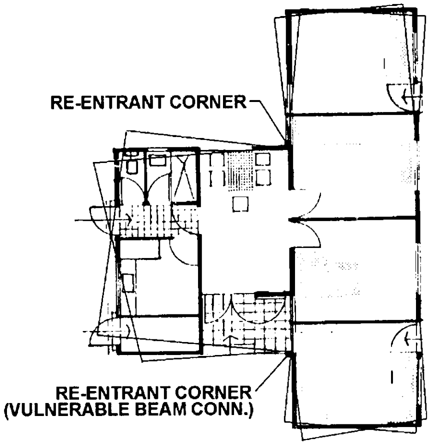


Diagram showing re-entrant corners, weak points, an twisting action modified from Tropical Houses (David Oakley 238).

Hurricane Resistance:
The low-lying building elevation and sloped roof are aerodynamic and appropriate for high wind resistance. However, the complex shaped plan and gable roof are not ideal for high winds. The complex plan causes wind vortices (whirlwinds) that are able to produce extreme forces upon the building walls and overhangs. If wind were to approach from the northwest of the southwest, the "T"-shape of the building would cause wind to collect and higher pressures will result. Because overhangs are small, uplift forces are not large but walls and windows are exposed to driving rains.

The large jalousie windows will have relatively high infiltration rates. This additional positive pressure from the interior augments the suction effects caused by wind flowing over the roof and increases the chance of roof uplift. Therefore, jalousie windows should be protected with plywood panels or removable shutters to reduce infiltration and glass breakage.

The low-lying vegetation and flat site creates high exposure wind conditions. The lone palm tree is a source of windborne debris. The flat site, full-height jalousie windows and the low floor elevations make this home prone to flooding when heavy rainfall occurs.

Other Considerations:

The slab-on grade foundation provides little separation between the ground and wooden double walls above. Any crack or opening in the slab present a possible entry point for subterranean termites. Open areas in concrete slabs located at drains, pipes and cables should be filled with epoxy grout and basaltic termite barriers to protect against termite penetration.

Soil under the slab should be treated with insecticides and a basaltic termite barrier provided. Proper drainage of water away from the foundation would also discourage nesting within the building. “Termite treated” wood, should be used to prevent termite nesting and the growth of fungi, worm and other organisms that weaken timber. A continuous welded sheet metal guard should be placed under the bottom plate so in case termites do access the wood, they are forced to expose themselves.

7.2 HOUSE DESIGN #2

Roof Design:

- Gabled roof
- Low slope
- Medium sized overhangs
- Light colored roof
- Radiant barrier

Wall Design:

- Double-wall construction
- Several small windows on south and north sides
- Large windows on east and west sides
- Windows with shutters
- Jalousie windows

Foundation Design:

- Concrete continuous perimeter strip footing

Energy Efficiency:

The light color of the roof and radiant barrier reflect heat and reduce heat gain. The gabled roof does not have a high slope, but end wall and soffit vents cross and stack ventilate the roof space. This significantly reduces the heat radiated through the ceiling.

The east and west sides have high overhangs that are insufficient to provide shade from the morning and afternoon sun. The small overhang on the north side provides adequate shading from the high angled summer sun. The roof has low, moderate overhangs

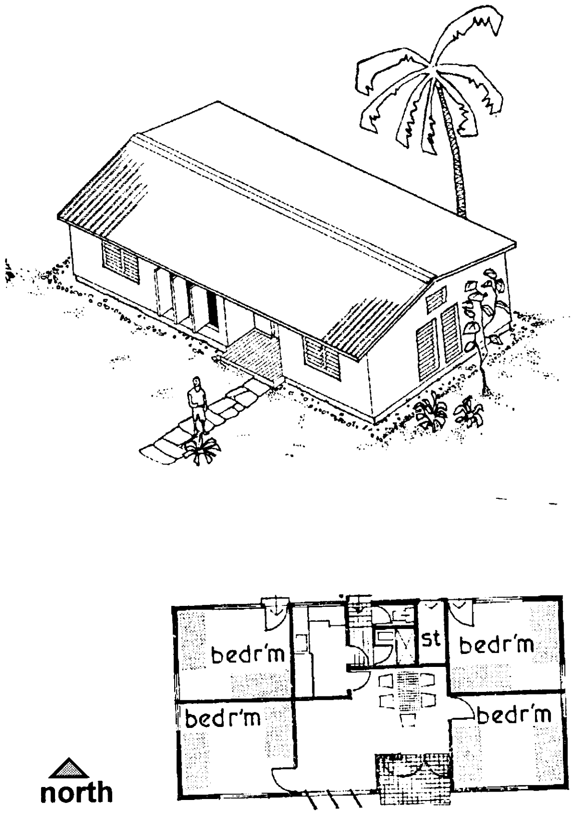


Figure modified from Tropical Houses (David Oakley 256).

on the south which provides shade throughout most of the year, yet is inadequate for blocking the low winter sun. The south entrance is recessed and has a large overhang which keeps the direct sun from entering the living space. Shutters on the south windows provide further protection from the low winter sun.

The building is oriented along an east-west axis which minimizes wall area and heat gains from east and west. However, large openings occur on the east and west sides and insufficient overhangs allow direct sunlight to enter. This increases heat gain during the morning and afternoon.

If prevailing winds are from the northeast, little air circulation will occur in the main living spaces. Bedrooms on the north and east sides would receive all the useful breezes. Jalousie windows allow for the entry and directing of cross ventilating breezes.

Ventilation of the living area could greatly improve if the building had a open plan. High jalousie windows or fixed louvers on interior walls could also aid in distributing breezes.

Low-lying vegetation on the site provides evaporative cooling, but is insufficient to provide shading.

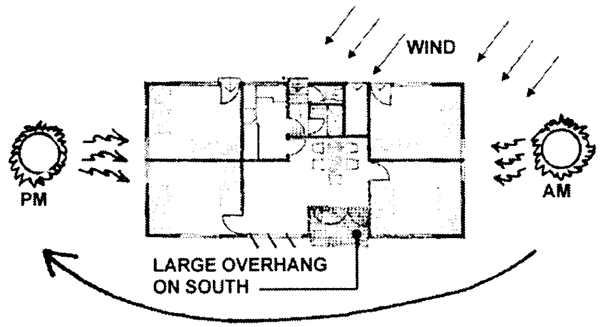


Diagram showing poor circulation in living area because wind is blocked by service spaces. Large overhang on south and building orientation minimizes heat gain.
modified from Tropical Houses (David Oakley 256).

Earthquake Resistance;

The building plan, although appearing simple and symmetrical from the outside, has a stiff core where many walls and storage, bath, and toilets are located. During an earthquake the structure will rotate and twist around this stiff area.

Windows and doors are placed away from corners and are inset. This promotes good reinforcing and allows substantial corner wall area to be used to resist lateral forces.

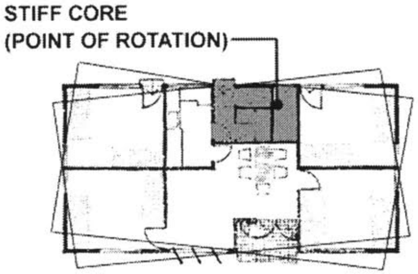
The continuous concrete perimeter wall footings are ideal for resisting lateral forces induced by earthquakes and hurricanes. They provide good uplift resistance and enable a building to move as a whole.

Hurricane Resistance:

The low sloped roof and regular shape promotes good wind resistance during a hurricane. The moderate overhangs also contribute to the appropriateness of the design. However, the gabled roof has vulnerable end walls and overhangs. Gable end walls should be constructed with balloon framing or upper cripple walls should be adequately braced (see Gable end treatment diagrams on page 134).

The shutters on the south wall will protect windows from flying projectiles. The large jalousie windows should be protected with plywood panels or removable shutters to reduce infiltration and glass breakage.

The low-lying vegetation and flat site creates high exposure wind conditions. The lone palm tree is a source of windborne debris.



During an earthquake the building will tend to rotate around the stiff cental core where walls and other stiffening elements are concentrated modified from Tropical Houses (David Oakley 256).

The flat site, full-height jalousie windows and the low floor elevations make this home prone to flooding when heavy rainfall occurs.

Other Considerations:

The low-lying foundation provides little separation between the ground and wooden double walls above. Any crack or opening in the slab present a possible entry point for subterranean termites. Open areas in concrete slabs located at drains, pipes and cables should be filled with epoxy grout and basaltic termite barriers to protect against termite penetration.

Soil under the foundation and slab should be treated with insecticides and a basaltic termite barrier provided. Proper drainage of water away from the foundation would also discourage nesting within the building. “Termite treated” wood, should be used to prevent termite nesting and the growth of fungi, worm and other organisms that weaken timber. A continuous welded sheet metal guard should be placed under the bottom plate so in case termites do access the wood, they are forced to expose themselves.

7.3 HOUSE DESIGN #3

Roof Design:

- Semi-gabled roof with roof vents
- Light colored roof color
- Wide overhangs over lanais

Wall Design:

- Setback walls
- Low fixed louvered vents
- Adjustable jalousie windows
- Lightweight single-wall construction

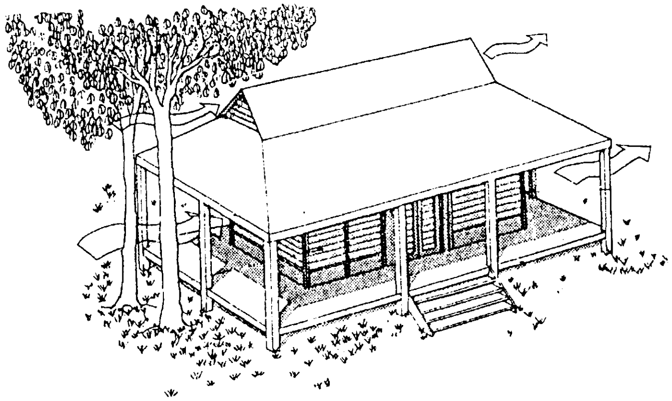
Foundation Design:

- Elevated wood framed floors
- Wood columns
- Buried concrete footings

Energy Efficiency:

The semi gabled roof provides solar protection and indirect day-lighting with the large low overhangs over the lanai. These overhangs also help to cool and channel breezes to the building interior. The light color of the roof is highly reflective and reduces the amount of heat absorbed by the roof. Roof vents on top aid in the ventilation of warm air from the roof.

Adjustable jalousie and fixed louvered windows allow for ample cross ventilation. Adjustable jalousies allow for breezes to be directed within the interior space.



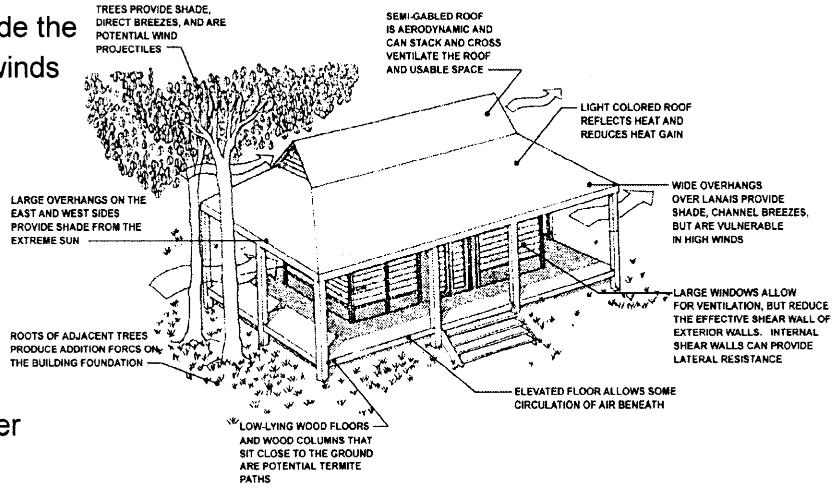
north

Figure modified from Hawaii Home Energy Book (Jim Pearson 115).

BUILDING ANALYSIS: HOUSE DESIGN #3

The floor is elevated from the ground to allow air circulation under the structure and possible floor vents through which cooled air can enter the interior.

Grass cools the incoming air through evaporation and reduces the surrounding glare. The high canopies of the trees shade the rooftop and lower heat gains. Trees also help to channel winds to the lanai areas and to building inlets.



Advantages and disadvantages of buidling form
modified from <u>Hawaii Home Energy Book</u> (Jim Pearson 115).

Earthquake Resistance:

The building form is compact and symmetrical which is ideal during an earthquake. However, discontinuities including the large lanais and large windows make the building susceptible to damage. Connections at these elements must be designed to withstand lateral forces. Columns of the same length and size will react the same under vibrations are also good for seismic resistance.

Interior shear walls or diagonal bracing within the structure would greatly improve the building's seismic performance since the large opening in the exterior walls make them ineffective as shear walls

Trees planted close to the building foundation can disrupt and weaken the foundation. Tree roots can create extreme forces upon a building's foundation during an earthquake.

Hurricane Resistance:

The low angled semi-gabled roofs is aerodynamic and able to perform well during high hurricane winds. Still, the large overhangs are prone to excessively high uplift forces. Beam, column, and rafter connections should be engineered and reinforced with appropriately sized metal connectors.

Trees adjacent to the building, although providing shade, are potential threats to the home in high winds. Dislodged branches are sources of wind projectiles that can cause damage to the building of those surrounding it. High winds can cause the trees to uproot and fall on top the building.

Other Considerations:
Although the building is elevated from the ground, design for termite resistance is minimal. Wood columns practically sit on the ground allowing termites easy access the wood structure above. Low elevated floors are adjacent to moist soil and unable to be vented adequately. The moist dark area under the floor and the close proximity of the floor structure to the ground is an optimal nesting ground for subterranean termites.The wood stairs sitting on the moist ground is also another ideal nesting area for termites.

Soil under the foundation and slab should be treated with insecticides and a basaltic termite barrier provided. Proper drainage of water away from the foundation would also discourage nesting within the building. "Termite treated" wood, should be used to prevent termite nesting and the growth of fungi, worm and other organisms that weaken timber.

7.4 HOUSE DESIGN #4

Roof Design:

- Offset roof with roof vents
- Light colored roof color
- Lower roofs
- Downspouts

Wall Design:

- Large fixed glass windows
- Adjustable low jalousie windows
- Double wall construction

Foundation Design:

- Elevated wood framed floors
- Concrete columns
- Deep concrete footings
- Reinforced concrete walls on ground level

Energy Efficiency:

The offset roof provides operable clerestory windows that aid in the stack ventilation of warm air. The light color of the roof is highly reflective and reduces the amount of heat absorbed by the roof. Offset roof overhangs are too high above windows to provide shading so additional awnings provide localized shading. These overhangs also block direct sunlight and channel cool breezes to the building's interior. Adjustable jalousie and fixed louvered windows allow for ample cross ventilation. Adjustable jalousies allow for breezes to be directed within the interior space.

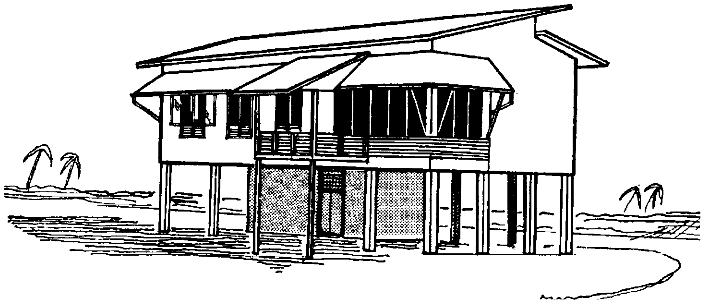


Figure modified from Tropical Houses (David Oakley 31).

BUILDING ANALYSIS: HOUSE DESIGN #4

The floor is elevated from the ground to allow air circulation under the structure and possible floor vents through which cooled air can enter the interior. Floors are also elevated to take advantage of higher velocity trade winds.

Earthquake Resistance;

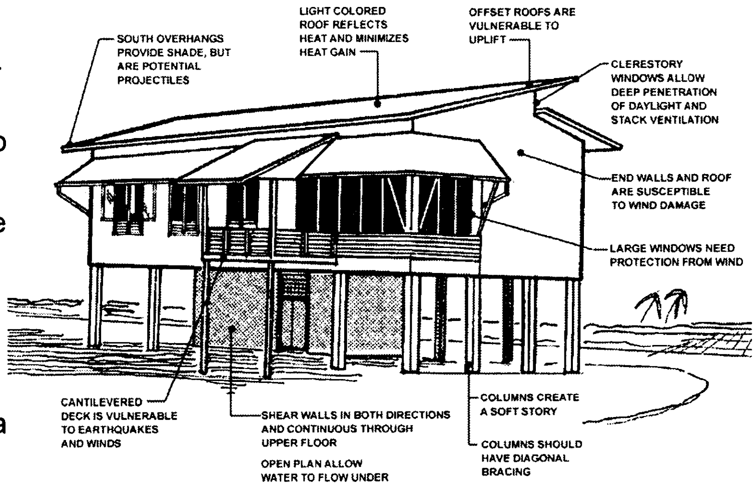
The building form is compact and symmetrical which is ideal during an earthquake. However, discontinuities including the lower soft story and large windows make the building susceptible to damage. The protruding lanai is vulnerable to earthquake vibrations. The differential movement of the lanai and the main structure is likely to cause concentrated forces at the reentrant corners. The thinner columns that support it are prone to buckling. Connections at these elements must be designed to withstand lateral forces.

The reinforced concrete walls of the circulation area on the ground level act as shear walls to resist lateral motion. Three walls (without openings) enable the structure to resist forces from a multitude of directions.

Hurricane Resistance:

The two story building located on the unprotected coast is highly susceptible to extreme wind and wave forces.

The offset roof, although allowing stack ventilation, is not optimal for hurricane winds. The offset roof creates areas of wind turbulence and thus areas of concentrated forces. The large overhangs at the ridge and at the end walls are extremely vulnerable to uplift.



Advantages and disadvantages of buidling form modified from Tropical Houses (David Oakley 31).

Large openings are vulnerable to windborne projectiles and should be protected with shutters or plywood sheets during a hurricane. Large panes of glass should be of laminated or tempered glass to minimize personal injury and building penetration. Awnings, although providing shade, are potential projectiles during high winds

The relatively open plan on the first level reduces the chance of flood damage and allows waves and water to pass under the building with little resistance. As aforementioned, the ground level walls act as shear walls. The two side walls are oriented normal to the beach line to resist wave and surge forces. Additional diagonal bracing would greatly improve the lateral resistance of the structure. Concrete footings should be anchored securely and keyed into the underlying lava bedrock to prevent foundation undermining.

Other Considerations:

The building is prone to termite problems because of its warm coastal location. Concrete columns that extend to the upper floor provide a good separation between the moist ground and the wood superstructure. Metal guards should be placed on top of the columns for additional termite protection.

Salt corrosion is a potential problem on this coastal site. Stainless steel and other non-corrosive materials should be used. Adequate concrete coverage over reinforcing or the use of corrosion-resistant reinforcements should be used. Metal fasteners and other hardware should be galvanized to resist corrosion. Details should also accommodate the shrinkage and swelling of wood due to the moist coastal air.

7.5 HOUSE DESIGN #5

Roof Design:

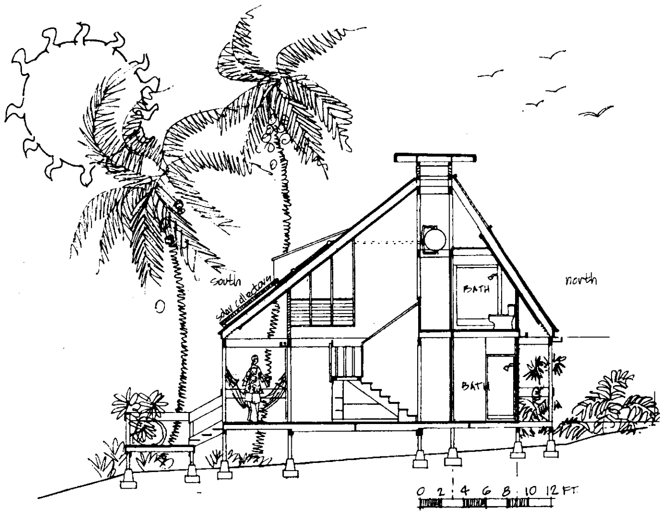
- High sloped roof
- Open beam ceiling
- Light colored corrugated aluminum roofing
- 3-layer radiant barrier
- Solar collectors

Wall Design:

- Large fixed glass windows
- Adjustable low jalousie windows
- Double wall construction

Foundation Design:

- Elevated wood framed floors
- Concrete columns
- Deep concrete footings
- Reinforced concrete walls on ground level



Section
Figure modified from Hawaii Home Energy Book (Jim Pearson 140).

Energy Efficiency:

The light colored corrugated aluminum roofing and the triple layer radiant barrier reflect solar heat and reduce building heat gains. The two stories reduces the roof area needed per usable area and lessens heat gain. The high slope of the roof and the clerestory windows promote stack ventilation.

There is a large overhang on the south to block out the low angled winter sun and solar panels to collect solar energy throughout the year. The small north overhangs provide adequate shading from the high summer sun.

The clerestory window lets indirect sunlight deep into the space. Because the windows are placed on every side, wind blowing from any direction can aid in ventilating rising warm air. Translucent skylight also allow for indirect daylighting.

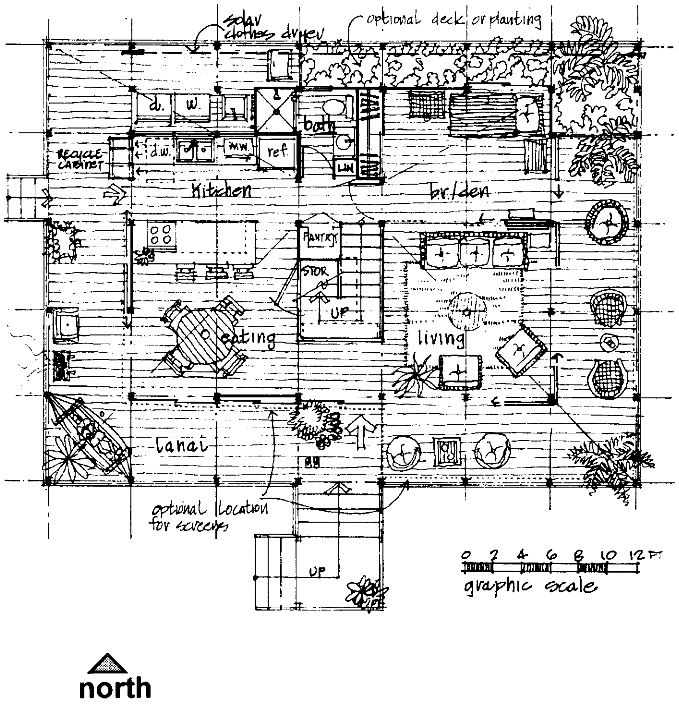
The lanais on the east, west and south sides allow for large overhangs for solar protection and a pleasant outdoor space. Sliding shoji doors allow for daylighting and cross ventilation. The open plan also encourages natural ventilation of spaces. Elevated floor allows for the venting and cooling of the floor and the space beneath it.

Vegetation around the building provides shading and evaporative cooling to the lanai and interior areas.

In addition to the passive design strategies mentioned, the building also utilizes wind power and energy and water saving appliances. Rain and gray water is also collected and reused. Recycle cabinets are built -in to encourage recycling.

Earthquake Resistance;

The simple compact plan and tapering pyramidal section are favorable during an earthquake. However, openings in the floor for stairs and two story living space make these areas vulnerable to earthquakes. Large opening in the interior and exterior walls also make the building susceptible to damage.



First level floor plan
Figure modified from Hawaii Home Energy Book (Jim Pearson 138).

The elevated floor creates a soft story which is supported by posts of differing lengths. The shorter, stiffer posts will experience more stress and are liable to fail first during an earthquake. The wood post sit upon concrete foundation block which make the foundation susceptible to lateral displacement and differing settlement. The massive water heater in the attic space will tend to amplify earthquake motion.

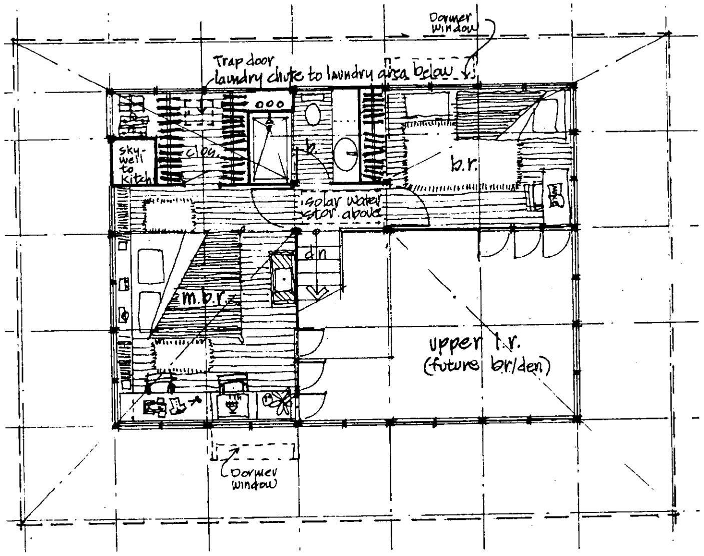
Hurricane Resistance:

The highly sloped, beam supported roof is very susceptible to strong wind forces. High wind pressures on steeply sloped roofs, make the roof especially vulnerable to high winds. High sloped roofs are not aerodynamic, but are able to shed rainwater quickly. The large overhangs over the lanais are extremely susceptible to uplifting wind forces. Large sliding door openings and glass jalousie windows are prone to wind projectile damage.

Vegetation on the site may block some wind, but coconut trees with coconuts are sources of wind debris. Coconuts should be picked and dead branches removed at the onset of hurricane season.

Other considerations:

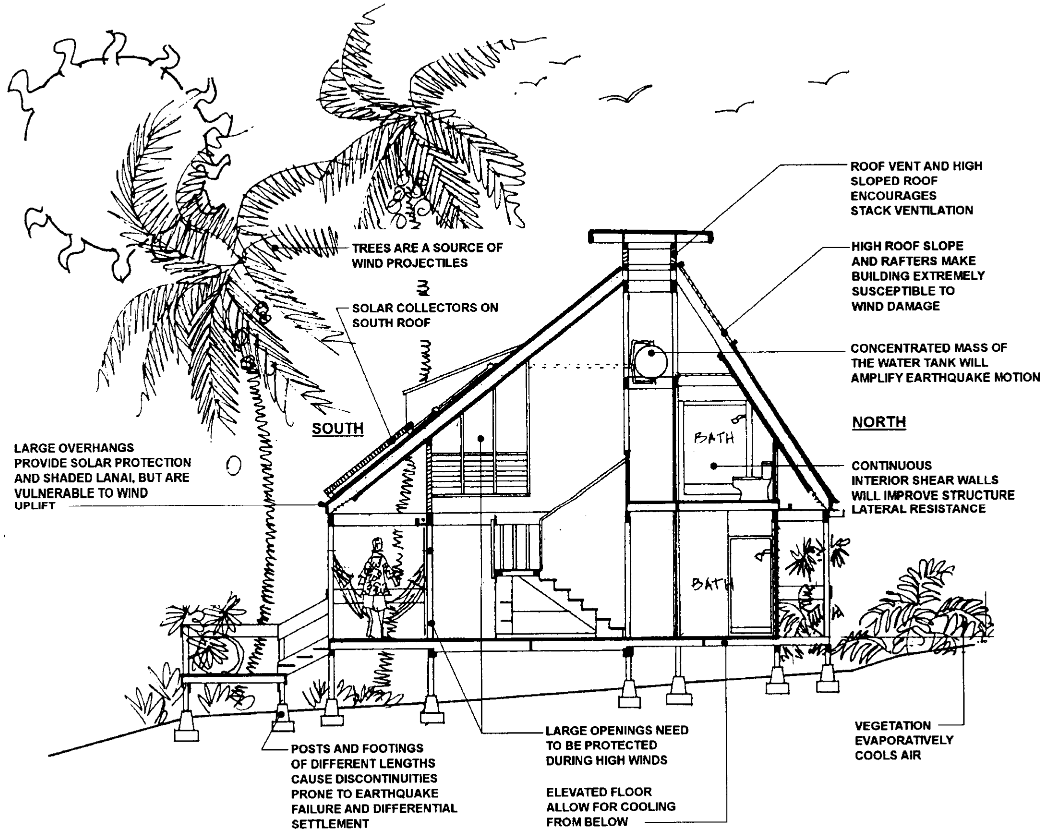
Wooden floor posts are elevated above the ground to defend again termite penetration. Metal guards should be placed on top of the columns for additional termite protection. Soil under the foundation and slab should be treated with insecticides and a basaltic termite barrier provided. Proper drainage of water away from the founda-



north

Second level floor plan
Figure modified from Hawaii Home Energy Book (Jim Pearson 139).

tion would also discourage nesting within the building. “Termite treated” wood, should be used to prevent termite nesting and the growth of fungi, worm and other organisms that weaken timber.



Building section shows advantages and disadvantages of building form
Figure modified from Hawaii Home Energy Book (Jim Pearson 140).

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