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

3.1 Field Sites

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

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

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

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

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

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

3.2 Observations Of Building Performance Under Wind Loading

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

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

3.3 Diagnostic Modes Of Structural Failure

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

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

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

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

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

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

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

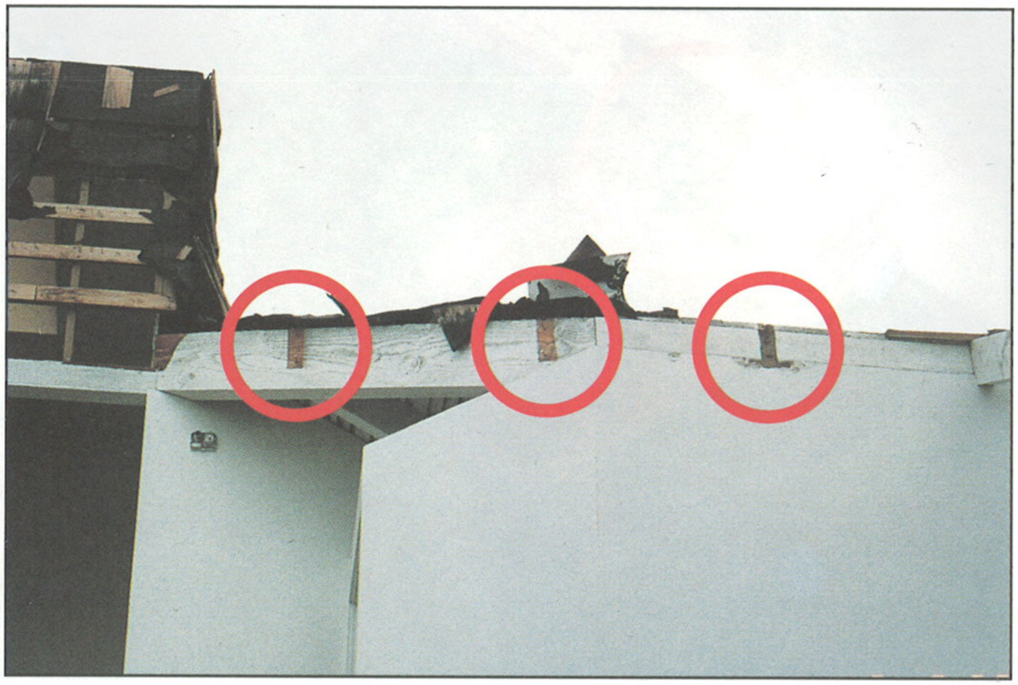

FIGURE 22. *Roof rafter construction with simple nailing or toenailing failed under uplift forces. Note two nails used to connect each rafter to hip beam.*

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

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

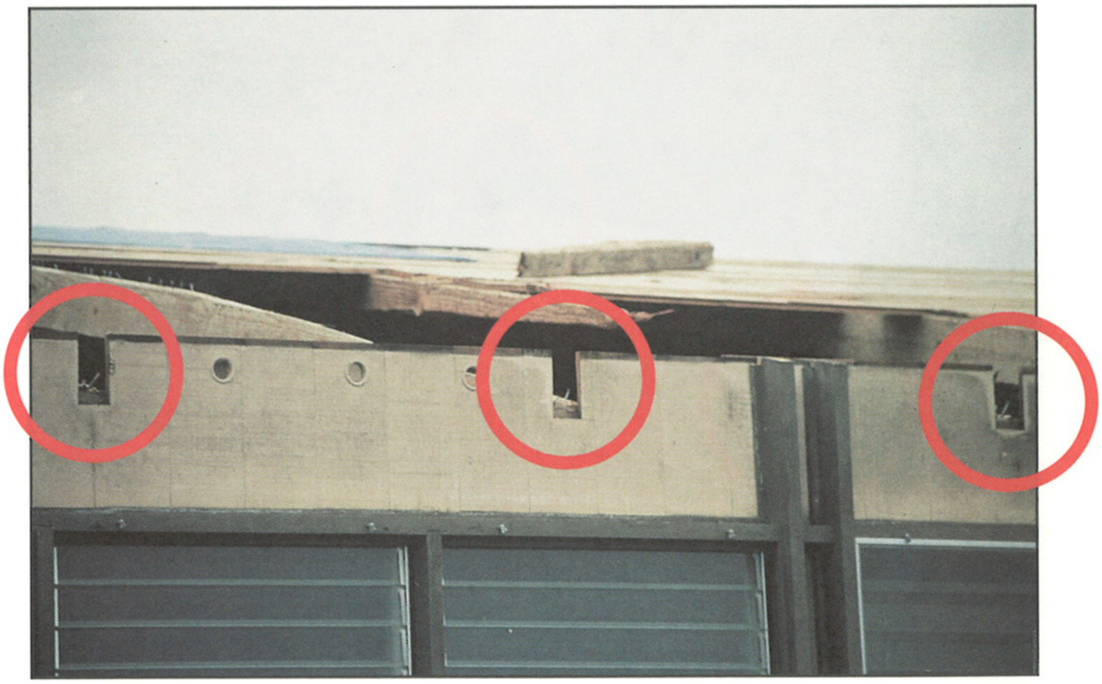

FIGURE 25. *Toenailing of roof rafters to wall system. At this critical connection, toenailing does not provide the load transfer path necessary to withstand uplift forces.*

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

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

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

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

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

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

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

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

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

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

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

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

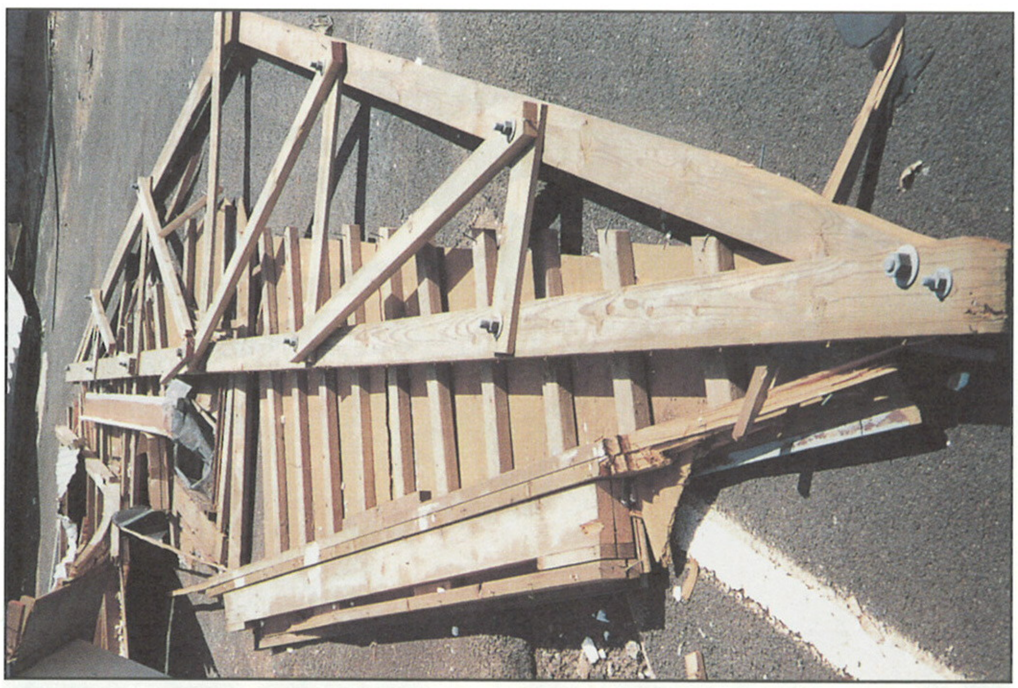

FIGURE 29. *Gable-end roof failure due to loss of roof sheathing and lack of gable bracing.*

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

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

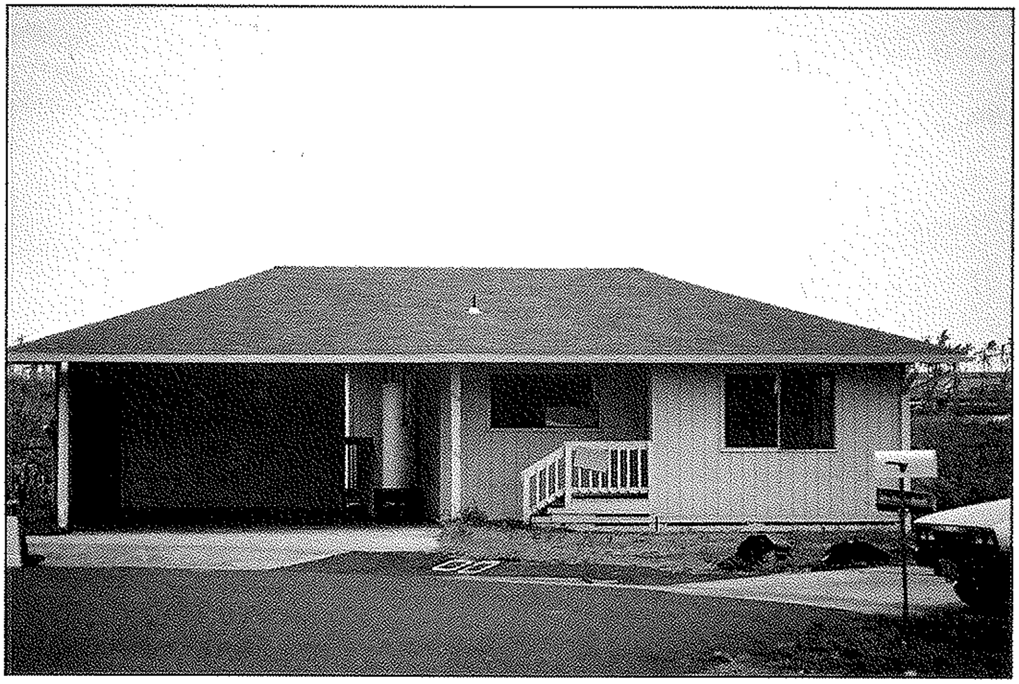

FIGURE 32. *Low-pitched hip roofs are aerodynamically superior and generally performed better than steeply pitched gable-end roofs.*

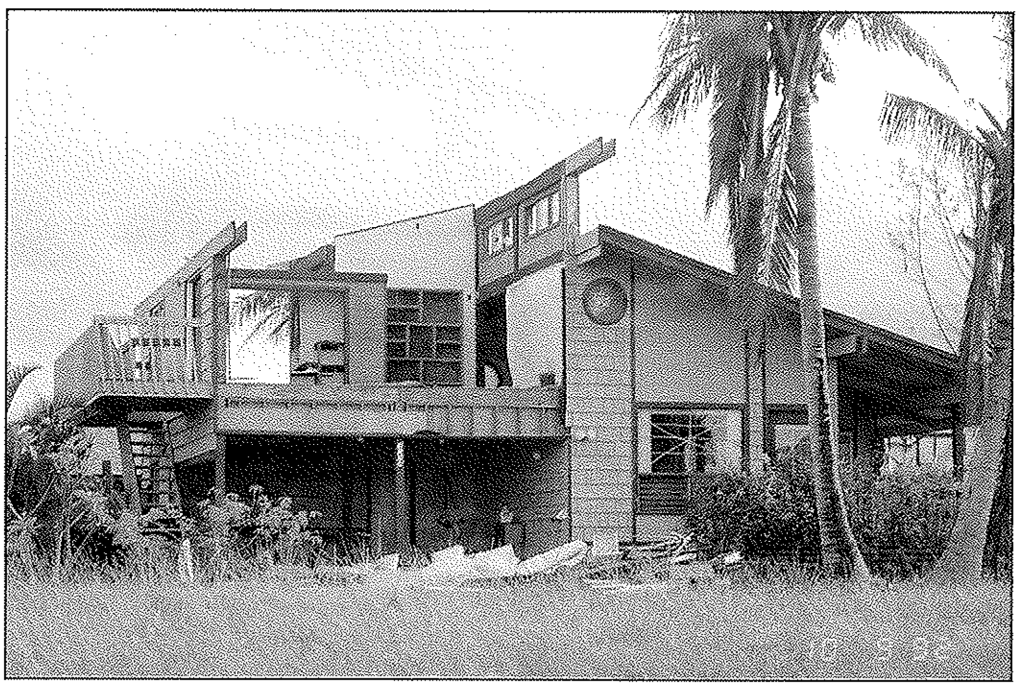

FIGURE 33. *Offset roof peak provides geometric discontinuity and results in greater localized wind-induced pressure, which can lead to roof and then wall failure.*

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

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

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

3.4 Diagnostic Modes Of Successful Structural Performance

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

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

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

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

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

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

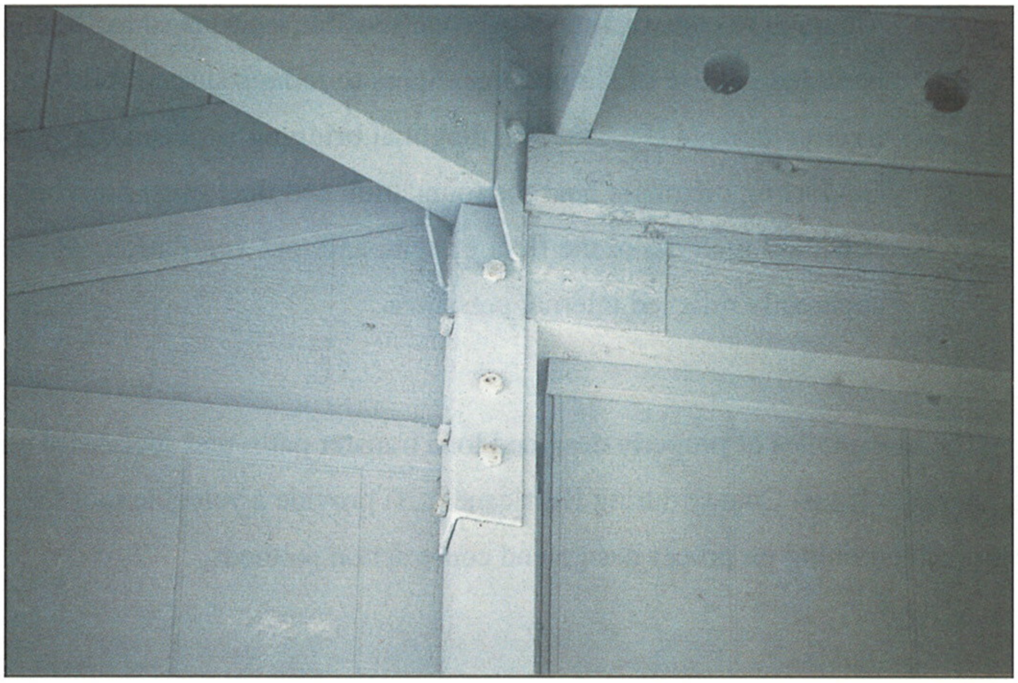

FIGURE 35. *Example of very successful heavy-gauge metal fastener connecting roof and wall systems. Note the over the top application and the number and size of lag bolts used for attachment.*

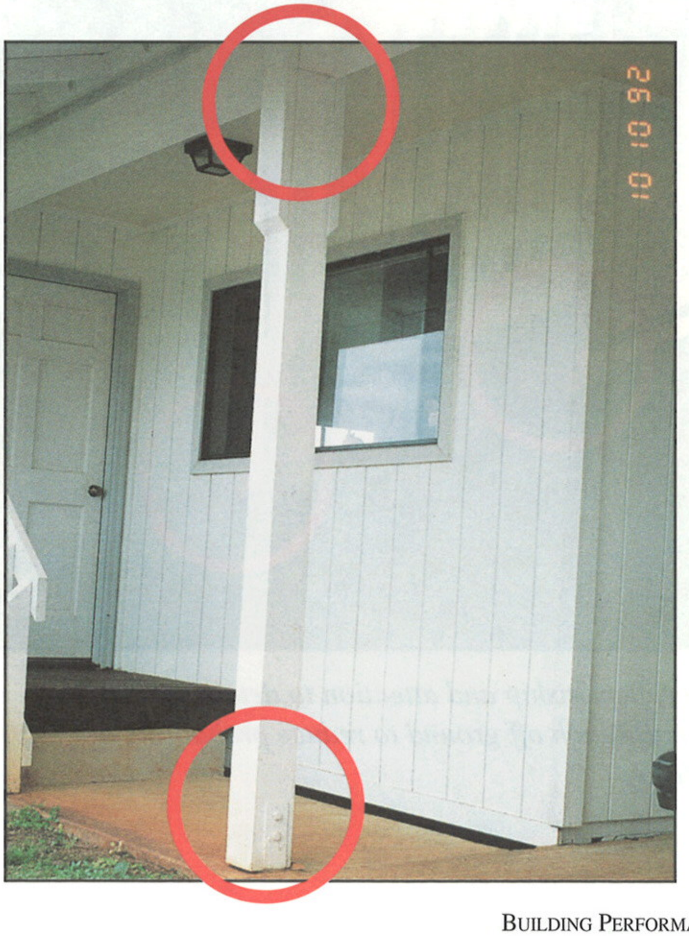

FIGURE 36. *Wood splice or strap provides a secure connection between wall and roof systems. Bolted metal anchor provides secure connection between vertical member and foundation. This is a fine example of a continuous load path.*

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

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

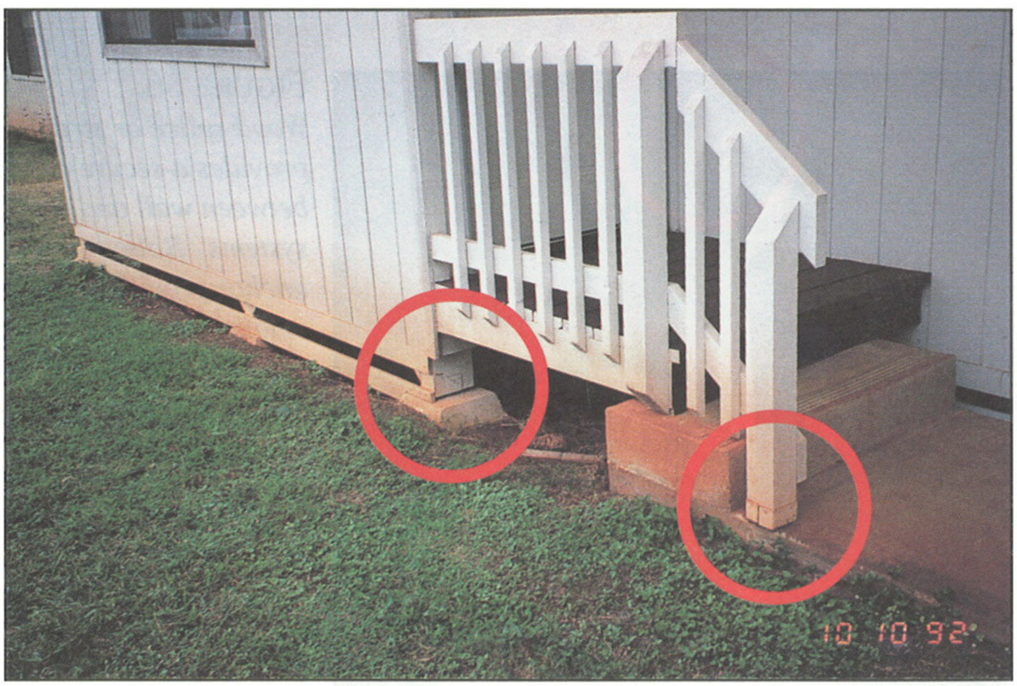

FIGURE 37. *Sensitive craftsmanship and attention to detail: Vertical preservative-treated posts 1/4 inch off ground to reduce probability of termite infestation and decay.*

3.5 Roof Sheathing

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

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

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

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

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

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

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

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

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

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

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

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

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

3.6 ROOF CLADDING

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

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

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

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

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

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

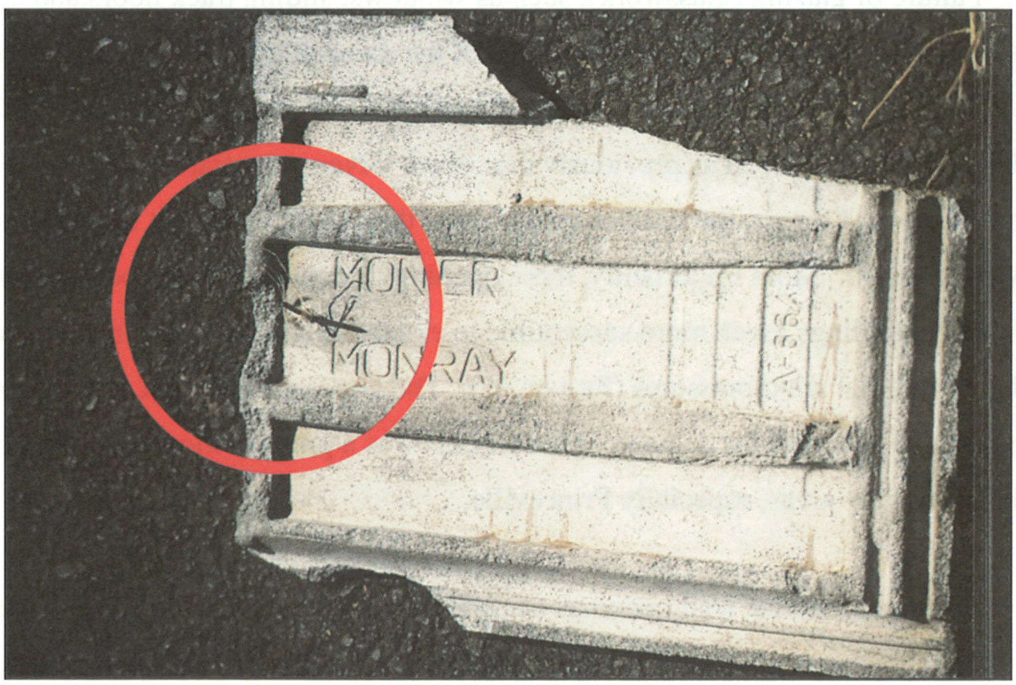

FIGURE 45. *Heavy concrete tile attached at one point with undersized nail. It was also observed that neighboring tiles had not been nailed.*

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

3.7 GLAZING AND TRANSPARENT OPENINGS

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

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

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

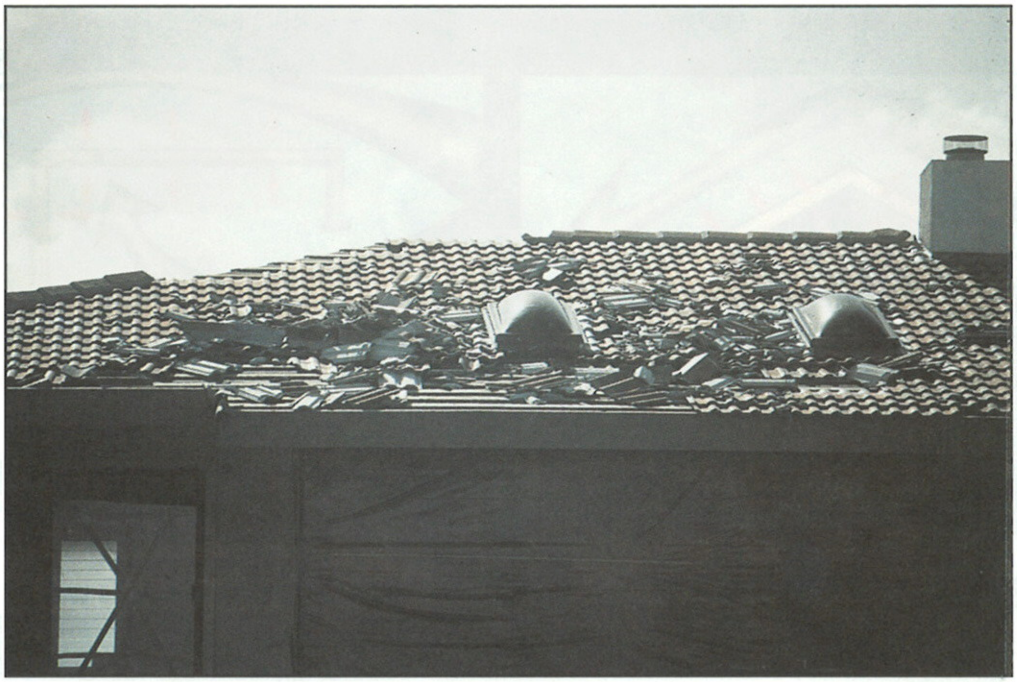

FIGURE 46. *Roof cladding system composed of interdependent elements. Failure of one tile led to failure of adjacent tiles in a "chain reaction" effect.*

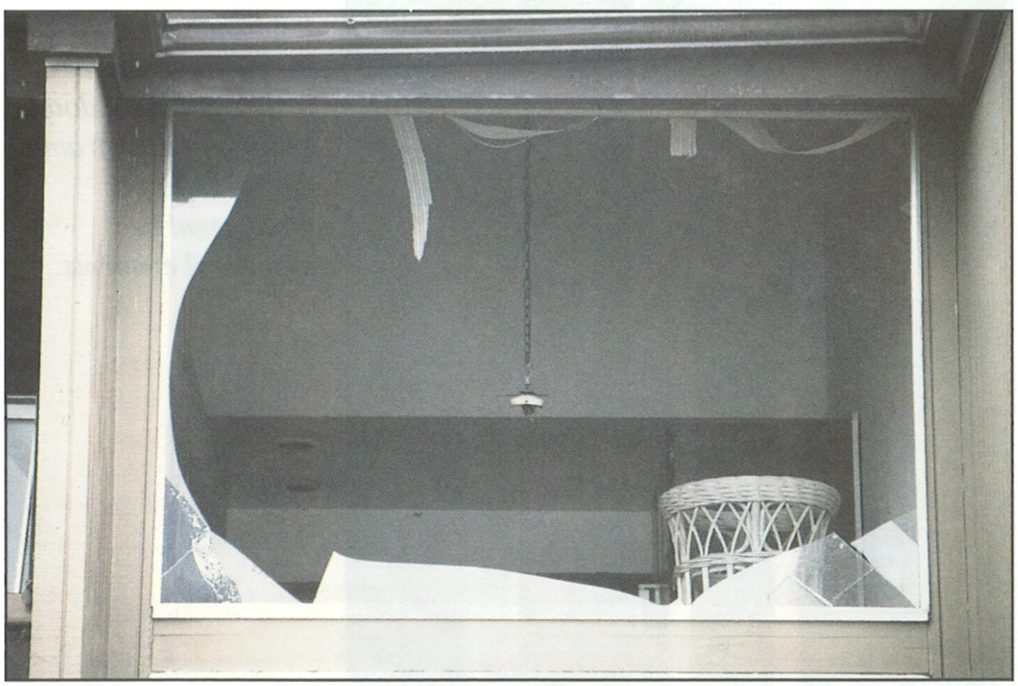

FIGURE 47. *Glazing broken by windborne debris or direct wind pressure.*

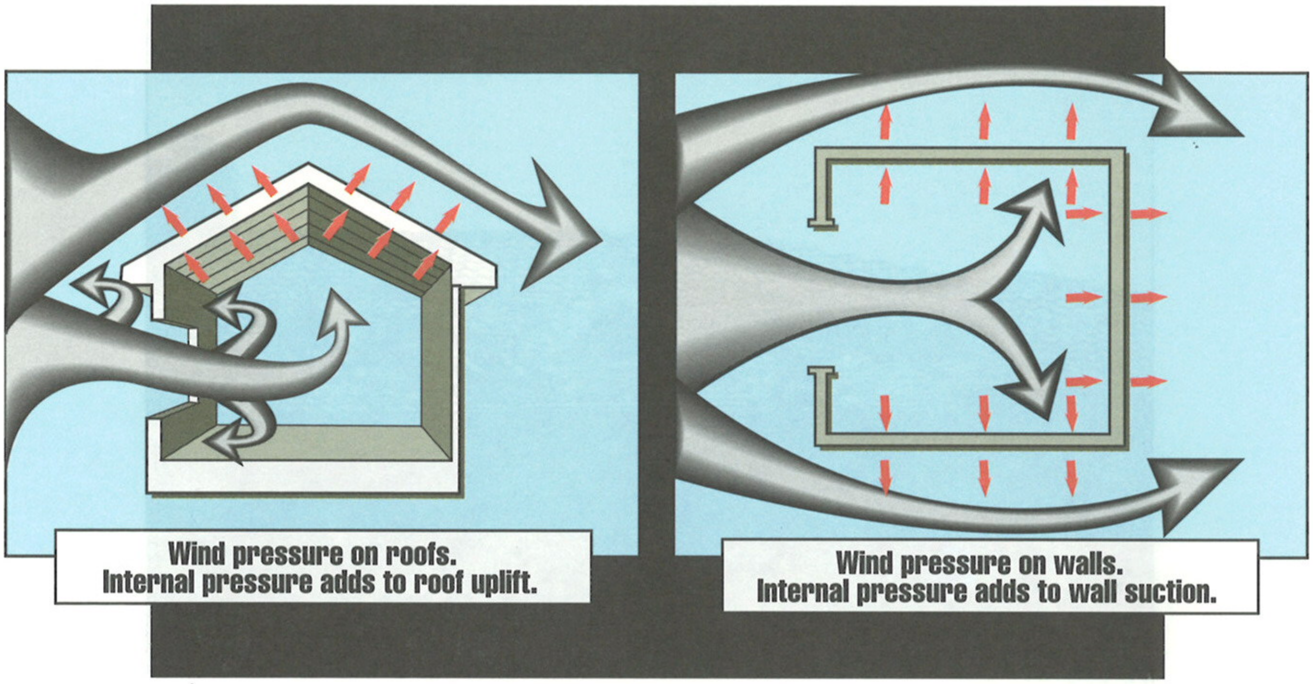

FIGURE 48. *Loss of opening protection allows wind entry and increases internal exposure.*

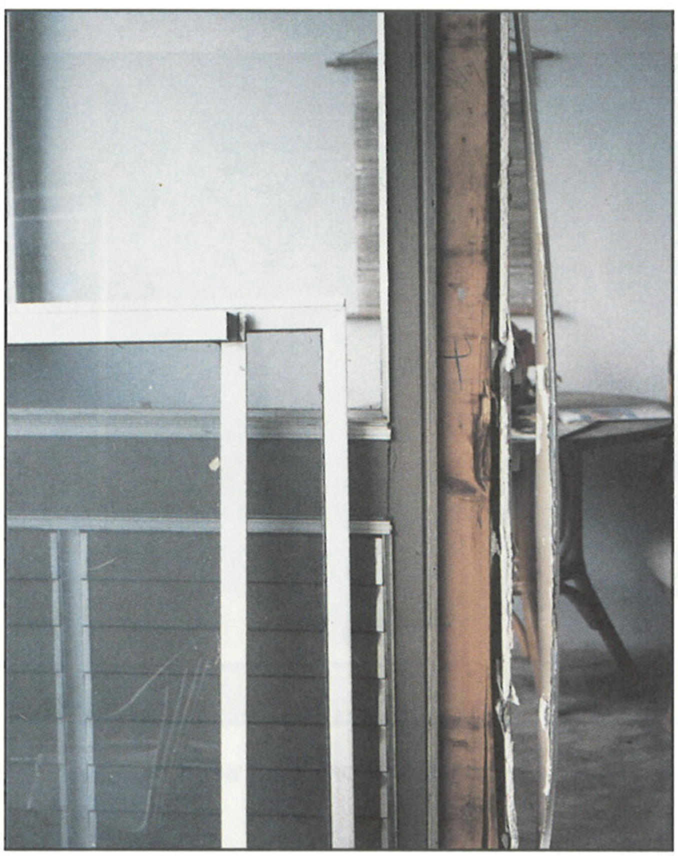

FIGURE 49. *Implosion of transparent shatter-resistant sliding door. Failure of door frame due to improper attachment to structural elements.*

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

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

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

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

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

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

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

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

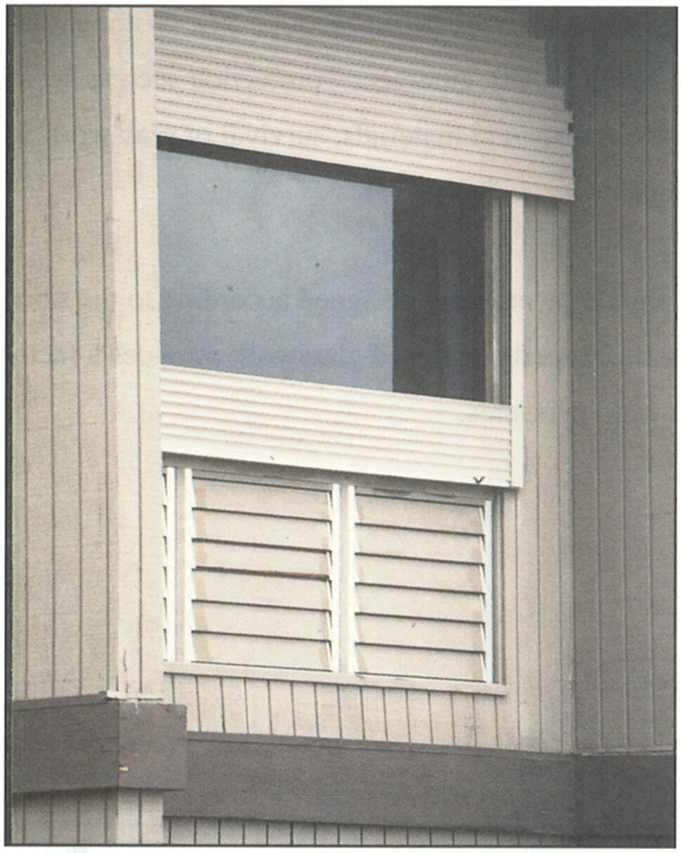

FIGURE 54.
In-place protective devices for glazing reduced the occurrence of building envelope failures.

3.8 WINDBORNE DEBRIS

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

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

3.9 Deterioration

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

- Use of proper building material, such as chemical-pressure-treated lumber, to reduce insect infestation, or corrosion-resistant fasteners to reduce attachment failures due to weakened fasteners.

- Use of pre-painted wood and metal and periodic maintenance to reduce open-weather deterioration.

- Application of sensible construction practices that reduce the probability of deterioration. For example, taking care that no part of a wood foundation system comes into contact with the soil (Figure 37).

- Inspection and replacement of damaged elements.

3.10 Pre-Engineered Steel Warehouses

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

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

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

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

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

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

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

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

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