1. Introduction

Tropical cyclone damage to low income housing has been especially severe in the Caribbean and Central America. In the Dominican Republic alone, after 1979's Hurricane David and Tropical Storm Frederic, housing losses were estimated at over 80 million pesos, with 100,000 houses affected. Such losses can be significantly reduced through the application of wind resistant building technology. The effect of high winds on common housing types and methods to increase wind resistance are considered in this section.

2. Causes of Wind Damage

Winds damage or destroy houses in two ways: roof uplift and forces on the walls. Most of the damage is due to the roof lifting off from the walls. Structural damage occurs when the connection between the roof and walls is strong, but not strong enough to keep the roof from separating. In cases when the connection between roof and walls is weak, no more structural damage occurs. Three types of forces cause roof uplift:

1) A lift force occurs when the wind strikes the house and separates to flow around and over the house. The air moving over the roof moves faster than the air moving around the structure, creating suction. This suction pulls the roof upward. At the same time, the inside of the house remains relatively airtight, resulting in a constant air pressure inside the house. This inside pressure is considered positive compared to the negative air pressure of the flowing air outside. The pull of the negative pressure and the push of the positive pressure causes roof uplift.

2) A lift force also occurs when the wind strikes a wall and is deflected upward. If there is a roof overhang, pressure is placed on the edge of the roof, prying the roof away from the wall.

3) A lift force can occur if wind enters the house through open doors or windows and pushes up from the inside. This force may add to the forces already created by positive pressure within the structure, or to the forces pushing upward on the edges of the roof.

Wall failure in a house can be caused by three types of forces:

1) Differential pressure, created by winds rushing around the structure (negative) and the pressure (positive) on the inside of the house. Eventually the pressure differential will cause the collapse of the walls.

2) Horizontal displacement, caused by winds pushing on the windward side and pulling from the leeward side, moves the building relative to its position on the foundation. Wooden houses are most likely to be damaged under these conditions.

3) Failure of the wall on the windward side due to extreme wind forces often occurs. Unreinforced block or rock structures are most vulnerable to this type of damage.

3. Effect of Wind on Structures

The ability of a structure to withstand wind stress depends more on the manner of construction than the materials used. Concrete block houses are not automatically more wind resistant than those of wood or wattle-and-daub. The factors that determine how well a house will withstand wind are as follows:

Configuration of the Roof

Gabled roofs allow the wind to pass evenly over the surface, creating undisturbed lift, which pulls the roof off the walls.

Pitch or Angle of the Roof

Houses with low pitched roofs (0°-30°) create lift on top of the roof, which lifts the roof off the house. At an angle of over 45° the windward face of the roof is exposed to excessive pressure, which cannot be borne without extensive reinforcement.

Configuration of the House

L-shaped houses are most vulnerable, because wind is channelled into the juncture between the two wings and also because winds striking the house from the other sides can create a racking effect, which causes the structure to collapse inward. When houses have open or half open porches, high winds can be deflected upward and lift the roof off.

Siting of a House

The vulnerability of a structure is determined to a large extent by its siting. Houses built on stilts on hillsides close to the coastline and those situated in long narrow valleys are especially vulnerable. Also, houses built in long straight lines close together in a grid layout (as is much government housing) are subject to the "funnel effect" during hurricanes.

Strength of Critical Connections

The strength of the following critical points of a house will also determine the extent of damage caused by high winds:

- Roof Material-Roof Frame Connection. Roof material which is not securely fastened is likely to be pried off by high winds. If the material is corrugated metal sheeting, then an additional threat is posed by the flying debris.
- Roof-Wall Connection. Two factors influence the vulnerability of this connection. An unsealed roof overhang of 46 cm. or more invites roof uplift forces. Also, if the roof frame is not attached securely to the walls, high winds can easily remove the roof.
- Wall-Wall Connection. Because of the d'ferential pressure exerted on a house during a hurricane, the walls are often pulled apart at unbraced corners.
- House-Ground Connection. When vertical columns or posts are not anchored to the ground or not set deeply enough, high winds can completely destroy a house. Untreated posts or foundations are vulnerable to insects and fungi; this deterioration decreases wind resistance.

Strength of Components

Roof - unreinforced roof frames cannot support pressure from high winds.

Wall -improperly bonded and reinforced walls often collapse in high winds.

Air Vents, Doors and Windows

Air vents - transoms (air vents at the tops of doors or windows, used in tropical climates to increase interior circulation) allow the entry of wind during a hurricane. The wind adds to the interior pressure, causing the house to collapse.

Doors and windows - louvered or unprotected glass doors and windows allow wind to enter the house during a hurricane, increasing the outward pressure on the walls and roof.

Although the material used in construction of a house is not the main determinant of wind resistance, certain failures during hurricanes can be attributed to material characteristics. The performance of wattle and daub, wood frame with palm board siding, wood frame with sawn board siding, slip form concrete and concrete block houses with corrugated metal roofs under extreme wind conditions is summarized in the following section.

Wattle and daub

A wood frame is erected, and bamboo or cane is woven between the vertical columns to use as a base for the application of a mud plaster to both sides of the walls. Occasionally, the wall is finished with an exterior application of a cement-sand plaster or lime wash. Roofs are prepared from grass, or, more recently, corrugated iron sheeting.

Hurricane damage results from the collapse of walls due to lack of reinforcement and deterioration of wood at the ground level. The primary damage sustained is separation of roof from walls, caused by uplift on the roof's surface as well as uplift under the eaves.

Wood Frame with Palm Board Siding

Side framing made from the outer surfaces of palm trees is nailed to a wood frame. Gable roofs predominate, although a truss system is sometimes used. Transoms are common.

These buildings tend to be weakest at the connections between:

- the roof sheeting and the roof truss,
- the roof system and the walls,
- the siding material and the walls, and
- the vertical posts and the ground.

Wood Frame with Sawn Board Siding

Board siding is nailed onto a wooden frame. A gabled roof is generally used. There are many variations in the configuration of these houses.

Roof separation, roof sheeting separation and displacements caused by lack of wall reinforcement are common hurricane-induced failures. Louvered windows, associated with this type of construction, increase the differential pressure pushing out on the walls until portions of the walls separate at the corners. Insufficient anchorage may result in the building's being lifted off the ground and toppled over. (Many wood frame houses rest on concrete slabs and are anchored only by the extension of the corner posts into the soil.)

Slip-Form Concrete

Slip-form concrete houses are constructed on a wooden frame with columns placed approximately 1 1/2 meters apart. Wide boards are attached to each side of two parallel columns and concrete is poured between the two boards. As soon as the concrete begins to set, the boards are moved upwards and another layer of concrete is poured. This continues until the entire wall is completed.

The lateral resistance and strength of the walls is often increased by barbed wire cross brace reinforcement. Gabled corrugated iron roofs are usual, although grass or palm leaf roofs are occasionally used.

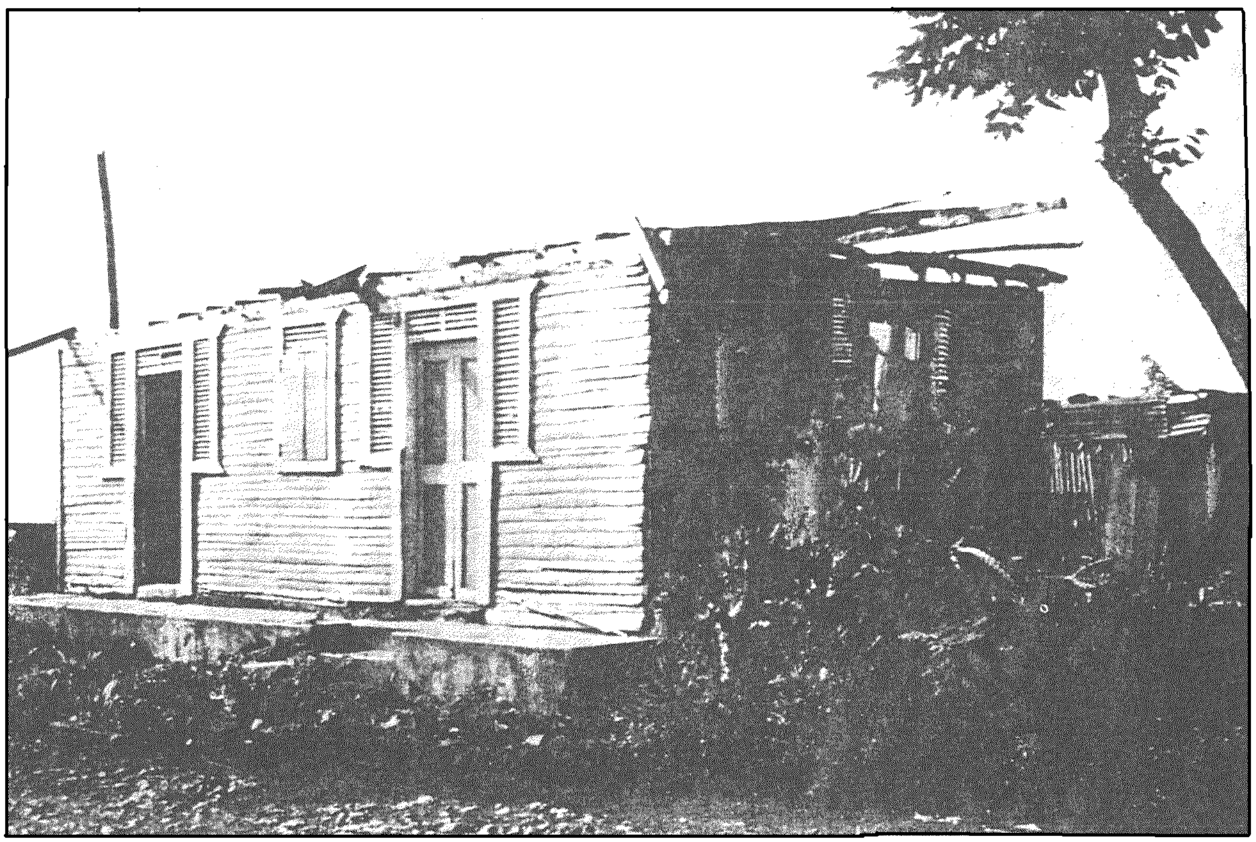
Hurricane damage includes: separation of the roof from the walls (because of weak roof frame-wall connection); failure of the gables and failure of the walls (due to separation of the concrete from the wooden columns). Post-hurricane studies show a high percentage of explosive damage (due partially to the presence of louvered windows and transoms).

Concrete Block with Corrugated Metal Roofs

When properly reinforced, concrete block is one of the most resistant materials.

Roofing is generally made of corrugated iron sheeting placed on a wood frame, attached to a wood frame system and tied to the walls by bending a portion of the iron used in reinforcing the concrete column or ring beam around the base of the truss. Roofs are almost always gabled.

Separation of the roof from the wall (due to poor connection of the roof truss to the wall) and collapse of walls (due to unreinforced or poorly reinforced walls) are the principal types of hurricane damage to concrete block houses. The porches characteristic of this housing style permit excessive amounts of wind to create uplift under the gable end of the house, lifting the roof off the structure. False facades, also typical of concrete block housing, are susceptible to high wind damage. In extreme cases, end walls can be pulled away, precipitating the collapse of the entire structure.



Roof Damage Sustained by Rural House in the Dominican Republic. (Photo by Aaron Benjamin, USAID Urban Development Officer, Santo Domingo.)

4. Building to Resist Wind Forces: Siting

Good site location or orientation in terms of local topography and natural cover can be determined to some degree from historical wind data that give the frequency, velocity, and direction of the prevailing or predominant wind. This information can be utilized to locate building sites and position individual dwelling units to minimize the hazard from wind. Wind damage may be minimized by staggering houses (to avoid the "funnel effect" created by grid layouts) and taking advantage of natural windbreaks (such as landforms or stands of trees). Houses should not be sited on hillsides near the coast (especially if they are on stilts), as high winds can be deflected up the side of the hill.

5. Building to Resist Wind Forces: Design

Configuration of the Roof

A hip roof configuration reduces the uplift force caused by extreme winds. Gabled roof designs should be avoided. (See photo at end of "Building to Resist Wind Forces" for illustration of a hip roof.)

Pitch or Angle of the Roof

Roofs should be built with a pitch of 30°-45° to most effectively resist wind.

Configuration of House

When expected wind loads are high, the selection of a housing configuration which permits as direct a stress path as possible is recommended. The preferred length-to-width ratio is 3:1 or less. Long rectangular and L-shaped house plans should be avoided, since they are especially vulnerable to high wind damage. Porches or elaborate facades should not be constructed. If cultural preferences dictate the addition of a porch, one that can blow off without damaging the rest of the house should be designed.

6. Building to Resist Wind Forces: Components and Critical Connections

Roof

Framing for the roof involves the use of either trusses or a rafter and joist system. Trusses are fabricated with metal plate connectors or bolted joints. In some larger structures, split-ring connectors are used. Trusses generally are made from an engineered design and under controlled conditions, so they have less potential for failure than the conventional rafter-and-joist system.

Where rafters are used, some type of collar tie is important to keep the roof from dividing at the peak. Ceiling joists, well nailed or bolted to rafters, prevent the roof from spreading outward. Purlins are connected to rafters or trusses in several ways. Nailed joints are among the most vulnerable because in this application the nail is loaded in direct withdrawal. Short boards nailed to the purlin and the rafter provide a stronger joint by loading the nails laterally.

Walls

A properly bonded and reinforced wall can best resist high winds. For wooden walls, siding must be securely nailed to the frame and vertical columns must be closely spread to reinforce it. In constructing concrete block walls, vertical columns, ring beams and binding mortar should be incorporated. In order to reduce collapse of the walls, diagonal bracing (X-bracing) should be utilized at the corners, especially in houses constructed of wood, wattle and daub or slip form concrete.

Air Vents, Doors and Windows

Sheltered or battened air vents, doors and windows can prevent damage caused by wind penetration.

Foundations

The damaging effects of storm surges or floods on the foundation itself may be avoided by providing adequate foundation materials whose properties do not deteriorate under the prolonged action of water. If the foundation is constructed of soil, mortar, and stone, a stabilizing ingredient can be added which will improve its resistance to water damage.

inexpensive protective banks or pole-type foundations may serve to protect the building from severe storm surges.

Roof Material - Roof Frame Connection

Metal sheet roofing should be of appropriate thicknesses. The quality of fasteners should be adequate. For example, by simply doubling the number of nails used to hold roofing in place, the probability of sheets blowing off in high winds can be reduced substantially. In general, nails resist or transmit smaller loads than screws, and screws resist or transmit smaller loads than bolts or lug screws. One method of tying roofing to purlins is the use of sheet metal straps. One end of a strap is bent at a 90° angle, and the bent portion is riveted to the roofing. The strap is nailed to the side of the purlin and bent under the purlin. The attachment of the strap to only one side of the purlin results in an unsymmetrical load so the strap can be twisted off by wind forces. Two straps riveted to the roofing on both sides of the purlin and lapped under the purlin would resist forces due to movement in the connector.

If roofing has not been anchored, and a storm is predicted, wind storm anchorage kits (consisting of fiber nets thrown over the building and anchored to the ground or anchorage cables) can be utilized.

Roof - Wall Connection

Since, in present tropical construction, the most frequent failure caused by high winds is the loss of roofs, this juncture is particularly important. A roof overhang of less than 46 cm. (18") with a barrier that prevents air from being trapped under the eave of the roof substantially reduces the uplift forces on the edge of the roof. Anchors for the ring beam and metal straps should be used to reinforce the connection. It should be recognized that improved design which holds the roof securely will ultimately result in the concentration of greater loads in other parts of the building. Details of wall construction and anchorage to the foundation which were adequate when roof failure relieved the total load on the building, may not be adequate when the roof remains intact. The building will be subjected to a large overturning movement as well as to uplift load on walls.

Wall - Wall Connection

A diagonal brace at the tops of corners can counter the effect of the differential pressure.

House - Ground Connection

For wooden houses or structures that use wooden vertical columns, the posts should be set deeply into the ground and should have some form of anchoring device at the base. The wood should be pre-treated to resist insects and moisture. Concrete block houses should have a strong moisture proof foundation. The vertical column iron rods should be securely anchored in the foundation.

7. Building to Resist Wind Forces: Materials

The guidelines set forth in this section are derived from the INTERTECT publication, Introduction to Wind Resistant Housing.

Wattle and daub

In order to improve the structural performance of this type of house, the following actions are recommended:

- All wooden parts of the house in contact with the ground should be treated.
- The primary columns (corners and columns in the middle of each wall) should be buried a minimum of 18" (46 cm) and should use some form of anchoring device.
- Diagonal or cross-braces should be added between all the primary columns of the building, especially in the corners.
- The roof-wall connection should be strengthened by using metal straps to help bind the roof to the wall, especially at the vertical columns.

The hurricane resistant potential of this type of structure, if properly built and reinforced, would be moderate. Structural performance can be improved, although, due to the type of construction, the building cannot be made airtight or sufficiently strong to withstand extremely high winds (over 100 mph), and structural damage can still be expected. If all the basic rules are followed, however, a substantial improvement in the performance in high winds will be attainable.

Wood Frame with Palm Board or Sawn Board Siding

- Use a hip roof configuration, rather than a gable roof.
- Use more nails to secure the iron sheeting to the roof frame.
- Use metal straps to help secure the roof frame or truss to the walls.
- Keep all overhangs to 18" (46 cm) or less.
- Close in the overhang with a wooden eave.
- Add diagonal or cross-braces to the wall frame, especially in the corners.
- Place additional stiffeners vertically to help reinforce the siding.
- Build shutters to close off the transom in high winds.
- Treat all wood that is placed in or on the ground with preservative to reduce deterioration.
- Anchor the vertical columns and place them in a minimum of 18" (46 cm) into the ground.

If the above recommendations are carried out, the potential for this type of structure to resist high winds will be substantially increased. If properly built, this type of structure will provide moderate safety in hurricanes.

Slip Form Concrete

The following actions are recommended to improve structural performance in high winds:

- Use a hip configuration for the roof.
- Use a truss system for the roof, rather than a frame system.

- Use more nails to secure the metal sheets to the roof trusses.
- Tie the roof trusses to the ring beam by use of metal straps, giving special attention to the corners.
- Seal the eaves of the structure to reduce uplift under the overhang.
- In structures that do not use barbed wire cross-bracing, it is recommended that, at a minimum, barbed wire be used. If possible, it is recommended that chicken wire be used for additional strength between the wooden columns.
- Use shutters to help close off louvered windows during periods of high winds.
- Treat wooden posts before placing them into the ground.
- Use anchors at the base of all posts in the ground, and bury the posts to a minimum of 18" (46 cm).

If the above recommendations are carried out, the wind resistant potential of slip-form concrete structures will be substantially increased. properly reinforced, this type of building can offer good wind resistance.

Concrete Block

In order to improve the structural performance of concrete block housing in high winds, the following actions are recommended:

- Use a hip configuration for the roof.
- Use a roof pitch between 30°-45°.
- Increase the number of nails used to attach the metal sheets to the roof frame.
- Seal off the eave of the roof and reduce the overhang to less than 18" (46 cm).
- Fasten the wooden roof truss more securely to the ring beam of the walls by using special anchors, and double the number of anchors on each connection.

- Use one horizontal ring beam in the middle of the wall.
- Use vertical reinforced concrete columns at an interval no greater than 2 1/2 meters between columns.
- Use shutters on the outside of all louvered windows.
- Design front porches on structures such as "A" and "B" above so that they are structurally independent of the roof, thereby reducing the chance of uplift under the porch removing the entire roof.
- Use porches such as those illustrated in "C" and "D" above only on concrete block houses that use concrete slab for the entire roof.

If the recommendations outlined above are incorporated into the design of concrete block houses, the wind resistant potential of the structures will be excellent and only minor damage should occur in wind storms.

8. Building to Resist Wind Forces: Building Codes

Some of the building codes in use that take into account hurricane force winds for buildings and structures are listed below. These codes range from "specification" type codes which specify and detail every operation, to "performance" type codes which give the desired end product or loading the structure should withstand, but do not tell how it is to be accomplished. None of the Latin American countries considered have adopted building codes which incorporate wind resistance standards.

The Uniform Building Code of the International Conference of Building Officials, USA

The National Building Code of the American Insurance Association, USA.

The South Florida Building Code

The Bahamas Building Code

The Japanese Building Code

Southern Standard Building Code of the Southern Building Code Congress, USA

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