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Disaster Mitigation in Health Facilities

Wind Effects

Structural Issues

Prepared by: Daniel Comarazamy
Grupo de Estabilidad Estructural (Ge²/INTEC)
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Reviewed by: Tony Gibbs

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OBJECTIVES

The main objective of this material is to assist health infrastructure planners (including hospital administrators, engineers, architects, technicians, etc.) from hurricane-prone Latin American and Caribbean countries (Slide No. 2) in learning about the impact that extreme winds can have on buildings. It also strives to convey the basic principles of mitigating hurricane damage in health facilities.

This training material focuses on reducing the vulnerability of structural elements: namely, those parts of a building—such as foundations, columns, beams, walls, and slabs—that withstand gravitational and lateral loads to ensure the stability of the structure.

Examples are drawn from the partial or total failure of hospitals in the region as a result of hurricane damage, and guidelines and recommendations suggest how to reduce the structural vulnerability of existing and planned health facilities.

This material aims to make the hospital community and the health sector in general aware of those factors that render health facilities vulnerable to hurricanes.

INTRODUCTION

Immediately following a hurricane, all health facilities must continue operating in order to provide effective treatment for the medical emergencies that commonly occur. It is imperative for hospital administrators to carry out integrated vulnerability assessments that evaluate the structural, nonstructural, and operational aspects of the services provided.

Although this material is limited to the impact of strong winds, it is important to note that in many Latin American and Caribbean countries hospitals must be designed to withstand multiple natural hazards such as earthquakes, floods, volcanic eruptions, and landslides. For this reason, it is important to locate health facilities in areas that are the least likely to be impacted by these phenomena.

STRUCTURAL VULNERABILITY

The terms *structural* or *primary systems* refer to the parts of a building that bear its gravitational and lateral loads, transferring these loads to the ground and keeping the structure stable. They include foundations, columns, load-bearing walls, beams, and diaphragms.

NONSTRUCTURAL VULNERABILITY

Nonstructural or secondary systems fall into three categories: (1) architectural elements; (2) basic (mechanical and electrical) service infrastructure; and (3) equipment. The first category includes those building components—windows, doors, roofs, suspended ceilings, partitions, and non–load-bearing walls—that are attached to the structural elements but do not play a primary role in resisting wind or other loads. The second category comprises those elements that are essential to the operation of the building, such as piping or electrical wiring and heating, ventilation, and air conditioning (HVAC) systems. The third category includes the physical contents of the building such as medical equipment and supplies, furniture, machinery, etc.

In health facilities, nonstructural components, particularly medical equipment, are in many cases more expensive than the structure itself. They account, on average, for more than 80% of the total cost of building and equipping a hospital.

ADMINISTRATIVE AND FUNCTIONAL VULNERABILITY

Functional and administrative vulnerability depends on several factors:

(1) The distribution of architectural spaces and their relationship to the medical and support services provided inside the hospital;

(2) The impact of this distribution on administrative processes such as contracting, procurement, maintenance, case-management, and internal and external communications; and

(3) The physical and functional interdependence that link the different areas of a hospital.

The appropriate distribution and articulation of the spaces that make up a health facility can guarantee the continuity of the hospital's operations not only in normal times but also during emergencies and disasters, when demand for health care services is likely to peak.

THE PROBLEM

The diverse natural disasters that have afflicted Latin America and the Caribbean bear proof that health facilities are particularly vulnerable to such events—particularly hurricanes, earthquakes, and floods.

Several factors aggravate this situation:

- A marked increase in the population density of hurricane-prone areas;
- The quality of construction materials, particularly away from major cities, is often defective and often they are not used appropriately to withstand strong wind pressures;
- Modern wind-resistant construction methods are seldom applied.

Hospitals are critical facilities that must continue to serve the community both during and immediately after a severe hurricane. It is essential to assess their vulnerability and implement mitigation measures in order to ensure operational continuity in emergency situations.

A hurricane can damage health facilities in one or more of the following ways:

- Strong winds exert positive (inward) and negative (outward) pressures on the envelope, or exterior, of the structure and on its connections.
- The wind's uplift force may detach objects or hurl those that are already loose at speeds of 100 km/h or more. Effectively, this turns them into windborne missiles that can rupture a building's envelope, causing injuries and severe damage.
- The rainfall that accompanies hurricanes can infiltrate the interior of a building that has lost roofing, doors, or windows, resulting in damage to costly equipment, furnishings, or other assets.
- Rainfall can be so heavy during a hurricane that it causes floods, erosion, and landslides which can lead to major damage.
- The storm surges that sometimes occur, especially when hurricanes coincide with high tides, can affect health facilities built near the coast, damaging structures while letting water infiltrate the buildings.

In short, the operations of a hospital during and after a hurricane can be interrupted due to damage to both structural and nonstructural elements.

Major hurricanes such as Georges **(Slide No. 3)** and Mitch **(Slide No. 4)**, both of which took place in 1998, have caused millions of dollars in damage and a large number of deaths and injuries, primarily due to secondary effects of the hurricanes, such as landslides or floods **(Slide No. 5)**.

HURRICANES

THE IMPACT OF HURRICANES

Over the last two decades, adverse natural phenomena have affected over 800 million people worldwide, killing many and causing economic losses worth more than US$50 billion.

According the data from the Pan American Health Organization, between 1981 and 2001 more than 100 hospitals and 650 healthcare centers were severely damaged by the effects of natural hazards **(Slide No. 6)**. The Economic Commission for Latin America and the Caribbean (ECLAC) reported direct economic losses of US$ 3,120 million.

From a financial as well as social perspective, the vulnerability of health facilities to such phenomena is more critical than for other types of structures **(Slide No. 7)**.

HOW HURRICANES FORM

Hurricanes arise when several conditions occur simultaneously **(Slide No. 8)**. They are defined as low-pressure weather systems that get their energy from the latent heat that results from the condensation of vapor over warm tropical ocean waters. For a hurricane to form, the temperature of the surface ocean waters to a depth of at least 60 meters must remain at 26°C or higher over several days. A low-pressure area, with air-mass convergence in the lower part of the atmosphere, is also required. In this low-pressure area, the winds must be hot and humid.

The hurricanes that travel through the islands of the Caribbean start out over West Africa's coastal waters as a *tropical disturbance.* If the conditions are propitious, they increase in intensity until they become *tropical depressions* (winds of up to 63 km/h), then *tropical storms* (sustained winds of between 63 and 118 km/h), and finally—and most destructively—*hurricanes*, with sustained wind speeds greater than 119 km/h **(Slide No. 9)**.

The conditions most likely to breed hurricanes in the Atlantic and Caribbean are prevalent each year from 1 June to 30 November—the *hurricane season.* Meteorologists employ anemographs along a series of hydrometric stations in order to measure and record wind velocity during hurricanes **(Slide No. 10)**.

CLASSIFICATION OF HURRICANES

Hurricanes are classified according to their intensity, which is measured in two ways: their minimum central barometric pressure, or their maximum wind velocity. A direct relationship between the two forms of measurement can be determined through mathematical models based on theoretical and empirical information.

In the early 1970s, Herbert Saffir and Robert Simpson compiled a table classifying hurricanes according to those parameters and specifying the damage caused by each category **(Slide No. 11)**. The Saffir-Simpson scale, which identifies five increasingly destructive levels of hurricanes from Category 1 to Category 5, has been adopted in the Americas to portray hurricane intensity. Based on data collected, annual comparisons have been made regarding the number and categories of hurricanes that have affected the Caribbean and North Atlantic over the past 50 years **(Slide No. 12)**.

FACTORS AFFECTING WIND IMPACT

LOCATION AND OBSTRUCTIONS

The location of a building vis-à-vis the impact of strong winds **(Slide No. 13)**, as well as the presence of other buildings of smaller size **(Slide No. 14)**, can cause increases in wind speed and turbulence affecting both the front (windward wall) and the back (leeward wall) of the facility, significantly increasing the wind's basic pressure. Other conditions, such as openings in the lower part of buildings, cause an unusual increase in wind velocity **(Slide No. 15)** as well as turbulence behind the buildings.

The same is true for buildings with gable roofs, where the wind induces turbulence affecting the rear and side walls as well as the leeward part of the roof **(Slide No. 16)**.

The pressure exerted by strong winds on the structural system is a function of the dynamic part of Bernoulli's equation (Slide No. 17), known as *basic pressure*, which is modified by the following factors:

- Roughness of the terrain
- Height of the building
- Surrounding topography
- Importance of the structure
- Wind directionality
- Wind speed
- Turbulence
- Openings in building envelopes

Different International Standards (Slide No. 18) show several ways to measure the basic and design pressure (Slide No. 19) and also the different types of buildings and structures under study (Slide No. 20).

Noting that the trend is to follow ASCE-7 and International Building Code (IBC) philosophy, we introduce, as an example, the formulas, tables, and notations of both standards (Slide No. 21).

The factors or coefficients affecting the basic pressure are shown in the following table (Slide No. 22 and Slide No. 23):

DEFINITION	FACTOR	MEANING
Directionality	K_d	Takes into account the probability of the maximum wind coming from the same direction that produces the maximum pressure
Importance	I	Converts from a 50-year return period wind speed to a 100-year return period recommended for hospitals
Exposure	K_z	Represents the wind velocity at any 'z' height above the ground
Topography	K_{zt}	Takes into account the fact that the structure might be located on an isolated hill or escarpment with higher wind speeds than on level ground
3-sec gust	G	Represents the turbulence-structure interaction and the dynamic amplification of the wind
External pressure coefficient	C_p	Estimates the wind pressure on the exterior of the building
Internal pressure coefficient	C_{pi}	Reflects the internal pressure of the building dependent on the number and size of wall openings
Design pressure	p	Represents the design pressure that is no greater than the modified basic pressure
Design force	F	Net force on special structures and open buildings

TERRAIN ROUGHNESS

Terrain roughness exerts its own effects on wind velocity and turbulence: the rougher the surface, the lower the speed but the greater the turbulence.

The size and density of surface objects such as buildings and trees affect roughness. *Roughness length* indicates the extent of influence of terrain roughness on wind speed and longitudinal turbulence: the more uneven the terrain, the longer the extent of roughness, increasing the effect of friction on wind speed retardation **(Slide No. 24)**.

BUILDING HEIGHT

When a fluid in motion interacts with a solid surface, the resultant viscosity generates shearing forces in the opposite direction to that of the fluid's motion.

A similar effect occurs in the interface between the surface of the earth and the wind running over it: close to the surface of the soil, viscosity reduces the speed of the air almost down to zero.

As altitude increases, wind speed increases too, until it reaches a constant speed called gradient speed, which is independent of the roughness of the terrain. This variation in wind speed as a function of altitude can be predicted mathematically with a logarithmic equation. In practice, however, a much simpler model is used: the power-law method for extrapolating wind speed from one altitude to another **(Slide No. 25)**.

Some building codes in the Caribbean include tables specifying the roughness coefficients that affect basic pressure **(Slide No. 26)** in terms of both exponential windward variability and the basic uniform pressure on leeward walls.

SURROUNDING TOPOGRAPHY

The topography of a region can significantly affect wind behavior. Broadly speaking, hills and escarpments generate sudden accelerations in wind velocity that can sometimes increase wind loads by up to 80%. These increments depend on several factors, such as the location of the structure or horizontal and vertical attenuation effects **(Slide No. 27)**.

Studies must also be carried out to assess potential curbs on wind velocity due to the protection of leeward valleys and ravines **(Slide No. 28)**.

IMPORTANCE OF THE STRUCTURE

A differential factor affecting basic wind pressure is the importance of the structure's use, which is a function of a quadratic relation between the basic wind speed associated with an average recurrence interval and that of a 50-year recurrence interval. An importance factor is established depending on the structural system used. In the case of hospitals it is recommended to assume a 100-year return period.

WIND DIRECTIONALITY

Basic pressure is affected by the uncertainty effect caused by the likelihood of the wind hitting the structure from any given direction. This parameter, known as the directionality effect, must be taken into account when assessing design pressure.

WIND SPEED

Wind speed is the single most important factor when trying to determine basic pressure. The various wind-resistant building standards in the Caribbean and Central America express this parameter in dissimilar ways **(Slide No. 29)**, but the most common is to measure three-second gusts.

More sophisticated studies **(Slide No. 30)** and recent computer simulations make it possible to determine the various local levels of risk and even to establish risk-zoning criteria.

TURBULENCE

Wind motion is turbulent, and it is difficult to give a concise mathematical definition of turbulence. However, it is known that wind turbulence exists due to the lower viscosity of air in comparison with water. Any air motion faster than 4 km/h is turbulent; i.e., air particles move erratically in all directions.

For structural engineering purposes, it can be said that wind speed has two components: average velocity (which increases as a function of altitude) and fluctuations due to turbulence.

MODIFIED BASIC PRESSURE

Basic pressure, as modified by the parameters mentioned above, is known as Modified Basic Pressure, as per ASCE-7, which will vary depending on the conditions of each region **(Slide No. 31)**.

ρ Density of the air mass given regional conditions of pressure and temperature

K_z Factor that varies with height and terrain roughness

K_{zt} Factor that depends on the topography of the terrain and several attenuation factors

K_d Wind directionality component

I Importance of the structure for a 50-year return period

V Design wind speed measured according to the standards in use in the region. The trend is toward three-second gust measurements

WALL OPENINGS

Openings in walls exposed to the action of the wind are highly significant when defining pressure coefficients. They are the holes in the structure's façade and, in the case of hospitals, can be critical **(Slide No. 32)**.

All windows, doors, and other apertures will be considered openings unless they and their connectors have been detailed and designed to withstand wind loads and wind-borne missiles. Based on this criterion, structures fall into three categories:

- Open structures: Systems through which the wind flows freely or that have wall openings making up over 80% of the total envelope area;
- Closed structures: Those that are not defined as open or partially closed structures;
- Partially closed structures: Those that meet the following conditions:
  - The total area of openings in the wall exposed to positive or inward pressure is greater than 1.1 times the sum of the openings in the rest of the outer structure, including the leeward and lateral walls, the roofing, etc.
  - The total open area of the wall exposed to positive pressure exceeds $0.4m^2$ or 1% of the entire wall—whichever figure is smaller—while the ratio of the total area of openings to the total area does not exceed 20% in the rest of the outer structure—i.e., excluding the windward wall.

THE STRENGTH OF STRUCTURAL ELEMENTS

INTERNAL FORCES AFFECTING STRUCTURAL ELEMENTS

Structural elements are affected by internal forces; among them axial load, shear force, bending or flexural moment, and torsional moment **(Slide No. 33)**.

- The *axial load* is defined as a compression or traction force that can shorten or expand the length of an element. In the case of reinforced concrete elements, their capacity is linked to the concrete's resistance to compression, their confinement using transversal reinforcement and their longitudinal reinforcement. Failures are caused by deficiencies in one or more of these characteristics.
- *Shear force* involves the action of two parallel forces in opposite directions on an element, tending to cause a displacement or slippage of one part of the element with regard to another. The failure caused by this type of force is sudden and unexpected. When it affects vertical elements, it can compromise the stability of the entire structure.
- *Flexural moment* is defined as the tendency of a force to induce rotation around a given axis. A sufficiently severe rotation can cause an element to

fail. Within limits, however, it helps to dissipate energy. This type of force, like the axial load, makes elements expand or contract.

- *Torsional moment* is a force that tends to cause non-coplanar rotation in the element with regard to its longitudinal axis. Failure due to this cause tends to be as dangerous as failure due to shear force, since both forces cause distortion or tangential stresses on the structural system. It can cause the partial or total collapse of the structure **(Slide No. 34)**.

DESIGN PRESSURE

The action of the wind exerts a basic pressure that, modified by all the factors mentioned above, is known as *design pressure.* Design pressure is a function of various pressure coefficients that are determined experimentally, gust coefficients, and the internal pressures that occur during a hurricane.

When designing the architectural configuration of a multistory hospital, it must be taken into account that, buildings dynamically sensitive to the action of the wind, i.e., flexible buildings, are generally subjected to higher wind forces than those buildings that are not dynamically sensitive, i.e., those that are rigid.

This condition depends mainly on the natural frequency of the structure: a building is considered flexible when its natural frequency is lower than 1 Hz. Hence, when determining design pressure, the gust coefficient will be different depending on whether the structure is rigid or flexible **(Slide No. 35)**.

As noted earlier, design pressure increases exponentially with altitude on the windward side and is uniform on side walls, leeward walls and roofs, both in the case of tall buildings **(Slide No. 36)** and systems with gabled roofs **(Slide No. 37)**.

TYPES OF HURRICANE DAMAGE

The correct location of health facilities is vitally important in hurricane-prone areas, as was brutally demonstrated when Hurricane Gilbert tore the roof off Princess Margaret Hospital in a matter of minutes as it tore through Jamaica in 1988 **(Slide No. 38)**.

Extreme winds can sometimes uproot the very foundations of a structure **(Slide No. 39)**. The designers of a health facility must factor in that hurricanes can overturn inadequately anchored buildings, particularly if their structure is light.

When not designed correctly, steel frames can also fail under strong wind pressure, as when Hurricane David tore through Dominica in 1979, leaving much of the population homeless **(Slide No. 40)**. Generally, this type of failure takes place at the connections.

Masonry structures are not immune to the action of the wind. Although they are considered comparatively safe, the loss of the roof makes masonry walls perform as if they were structurally unattached, causing their partial or complete failure.

The design of concrete structures is generally guided by seismic load considerations. When this is not the case, the designer must make sure that the hospital can withstand the wind load in order to prevent a catastrophe in the event of a hurricane.

Timber structures are inherently the least safe **(Slide No. 41)**. Moreover, due to its growing scarcity and cost, wood is not necessarily more affordable than concrete and steel.

It is worth noting, however, that wooden health facilities can be designed and built to withstand hurricanes, so long as the timber chosen has the right mechanical characteristics for structural use, the correct connections are employed, and effective maintenance routines protect the wood from humidity and insects.

The proper attachment of roofing support systems is of crucial importance for health facilities **(Slide No. 42)**.

THE IMPACT OF HURRICANES ON STRUCTURES

WIND-RESISTANT DESIGN STANDARDS

The philosophy of most wind-resistant design standards is simple—ensuring that the design and construction of structures allow them to withstand likely wind loads without damage, and exceptional wind loads with the least damage possible. The most important of these standards include ASCE-7, which is used in the United States, Australia's AS1170.2, the Caribbean's CUBiC, Europe's ENV 1991-2-4, and Japan's AIJ. Although there are some differences among these standards, they all follow a similar procedure for calculating wind loads.

The theory behind such standards starts out from the fact that basic pressure is proportional to wind speed squared. Wind speed varies from place to place depending on the climatic characteristics of the area in standard conditions (speed measured at an elevation of 10 m above ground level over open terrain without obstructions, with a recurrence period of 50 years).

Once the basic design wind-speed of the region has been determined, modifications are introduced based on the local topography, terrain roughness, and altitude. Inappropriate location and design can wreck even expensive structures, particularly when they are close to the coast **(Slide No. 43)**.

STRUCTURAL VULNERABILITY DUE TO ERRONEOUS DESIGN

Floor plan

A structure's floor plan determines largely how the building will respond to wind loads. It is advisable that the configuration be symmetric, in order to ensure a balanced distribution of the wind loads; if a non-symmetrical configuration has been chosen, the designer of the health facility must be sure that the structure will not be affected by torsion **(Slide No. 44)**. In addition to a carefully thought-out structural design, strict attention must be paid to controlling the quality of the building materials, their use, and the construction methods employed.

Elevation plan

All other things being equal, the height of a building affects its response to wind loads. If the design introduces sudden changes in configuration or size from one story to another, high pressures will be generated, particularly at the corners and on protruding elements, with negative effects on the structure.

Roofing

The type of roof shape that best interacts with wind loads is a hipped roof (the kind that slopes in all four directions from a rectangular plan), particularly if the angle of the slope is between 20 and 30 degrees. The next best type of roof—at least in comparison with mono-sloped or flat roofs—is the gable roof (one with two slopes), so long as it slopes at a similar 20-30 degree angle **(Slide No. 45)**. It is also advisable that eaves or overhangs be eliminated or kept short in order to prevent extreme wind loads from causing roof structural failure, since long eaves tend to generate high uplift pressures, particularly in the case of low-slope or flat roofs **(Slide No. 46)**. Experience shows that the local pressures caused by strong winds are greatest at the corners and on the ridges of a roof.

Reinforced concrete roofs generally perform satisfactorily when confronted with lateral wind loads. However, attention must be paid to the strength and suitability of the connections between the concrete roof and masonry walls or tie beams, given the negative, outward pressures that can be generated when the breaching of an entry door or window due to collision with windborne debris creates an opening in the building envelope.

The influence of nearby buildings

The concentration of buildings in a particular area may have positive or negative effects on the wind resistance of a health facility. If the buildings were designed and built following up-to-date wind-resistant standards, windward buildings will protect the other structures and the action of the wind will have few negative effects **(Slide No. 47)**.

By contrast, if the windward buildings have not been designed and sited properly, they may contribute to the turbulence that affects nearby structures **(Slide No. 48)**.

Other effects

Hurricanes have other devastating effects that can affect a health facility indirectly. For instance, the heavy rains associated with hurricanes can increase the volume of water flowing through rivers and brooks, eroding the base of a bridge's pier **(Slide No. 49)** or causing a landslide that cuts off a stretch of road or breaks off lifelines **(Slide No. 50)**, isolating the facility or disrupting key utilities.

HURRICANE-RESISTANT DESIGN PROCESS

The process of designing health facilities to withstand extreme wind loads involves a series of steps that must be guided by the existing risk demand where the structure is to be sited.

BASIC STUDIES

It is necessary to know the basic design wind speed of the region where the health facility is to be located. The basic design speed has to do with the likelihood of maximum annual wind speeds. Depending on where the structure is located, these speeds will be classified as hurricane- or non-hurricane wind speeds.

In the case of non–hurricane-force winds, the design wind speeds will be based on the records for the region. In the case of hurricane-force winds, records may be too scarce or inaccurate to reflect the actual design wind speed. If the latter is the case, simulations must be carried out in order to assign the correct design wind speed to the hurricane-susceptible area.

In addition, those sites that are prone to flooding, landslides, or storm surges must be identified, since such phenomena—common byproducts of hurricanes—can significantly compromise the structural integrity of a hospital.

DEMAND

Most of the problems that affect the vulnerability of health facilities to hurricanes and other disasters are caused by lack of communication and coordination among the various stakeholders entrusted with the design of the facilities. A joint effort is required of all those involved—medical personnel, administrators, engineers, and architects—so that the ultimate design has near-zero tolerance for wind-induced damage. For instance, any breach of the building's envelope during a hurricane, such as parts of the roof flying off or the collapse of doors or windows, can lead to the functional failure of the entire hospital.

DESIGN

Once the basic design wind speed has been determined, wind-engineering principles must be applied in order to determine the wind loads that the health facility will actually have to endure. Given likely wind pressures, the structural engineer can design the facility so that its primary structural system can withstand the wind loads borne by the structure with little or no significant damage.

Structural analysis must take into consideration both positive and negative internal pressure. In both cases, assessments must be made of the pressures perpendicular to the roof ridge (Slide No. 51) and parallel to it (Slide No. 52).

It is also important to pay attention to the design of the nonstructural elements, such as components and cladding, since such elements may be subjected to significant pressure because of their limited effective areas.

VERIFICATION

The displacements suffered by a structure's elements because of the pressures exerted by extreme winds can cause both structural and nonstructural damage. It is essential to verify that the maximum absolute and relative displacements that may occur fall within the parameters set by the most up-to-date local construction standards.

For example, health facilities designed as flat-slab structural systems, supported directly by columns without caps or drop panels able to absorb piercing forces **(Slide No. 53)** have been shown to be inefficient and difficult to restore after a hurricane. A simple evaluation of the plans will rule them out altogether.

It is also important to make sure that the wind loads affecting the structure will be transferred by design from the roof down to the foundations through a continuous load-transference path **(Slide No. 54)**. If the design does not take this into account, the connections must be redesigned correctly to prevent the collapse of the structure **(Slide No. 55)**.

VULNERABILITY OF EXISTING HEALTH FACILITIES

Structural vulnerability assessments are carried out in order to evaluate the safety of existing or planned health facilities in the face of extreme winds **(Slide No. 56)**. Current wind-resistant hospital design standards demand that the structure be able to withstand:

- The design hurricane event without damage; and
- Hurricanes greater then the design event with only minor nonstructural damage that can be repaired easily.

Such assessment is extremely important in the case of existing health facilities, since it identifies weak structural or nonstructural elements that require retrofitting in order to ensure functional continuity in the aftermath of a hurricane.

A hospital vulnerability assessment is aimed at evaluating the susceptibility of the structure to hurricane-caused damage, as well as to cataloguing the kinds of damage that may occur **(Slide No. 57)**.

WIND VULNERABILITY ASSESSMENT METHODOLOGY

Wind vulnerability assessment procedures fall into two categories:

a) Qualitative methods

b) Quantitative methods

Qualitative methods

Qualitative methods **(Slide No. 58)** are employed to carry out a quick and straightforward assessment of the structural safety of the health facility in question.

The structure is classified according to such factors as the age of the building, its state of conservation and maintenance, the quality and characteristics of the materials used, the number of stories, the architectural configuration, and the structural systems.

One of the key aspects to bear in mind, when applying such methods, is the likelihood of elements to buckle. It is one of the most common problems found in structures subjected to strong wind loads.

Other factors that influence qualitative vulnerability assessments are the topography of the site, its exposure, its location in an urban or rural setting, and the design wind speed for the area where the health facility is located.

If the qualitative assessment uncovers deficiencies in the building's ability to withstand strong winds, it is necessary to carry out more detailed quantitative assessments.

Quantitative methods

Quantitative methods evaluate the resilience of an existing health facility's primary structure, also known in this context as the main wind-force resisting system **(Slide No. 59)**.

Broadly speaking, the procedure is similar to that employed when assessing the design of new structures. The main difference, of course, is that variables such as the actual site, structural system, the quality of the construction materials, and use of façades and other nonstructural elements cannot be chosen from scratch, guided by the most up-to-date wind engineering standards. Instead, these variables must be accepted as a given and analyzed in order to determine their degree of vulnerability to extreme wind conditions, as well as what corrective measures may be taken.

Quantitative methods, if they are to be effective, call for large amounts of data—in fact, as much pertinent data as can practically be collected. This makes them more precise than qualitative assessments in predicting the likely types of failure that may occur, both overall and in the case of specific elements, and hence more reliable when evaluating the resistance of a building to extreme winds. On the other hand, they are costlier and more time consuming for the assessment team.

Regardless of the method of analysis, if the structure does not meet the performance objectives required, retrofitting is required to reduce its vulnerability to strong winds.

RETROFITTING EXISTING STRUCTURES

When vulnerability assessments uncover structural deficiencies, existing structures must be retrofitted. Retrofitting, however, should not affect the functionality of the health facility or the quality of the health care provided, nor should it imply temporarily vacating a critical facility that by definition should operate year-round.

In determining which elements to reinforce, attention should be paid to the specific hazards associated with extreme wind conditions. Some elements might need to be added; others should perhaps be discarded or replaced. Nonstructural elements must also be taken into account. Do they augment the structural response of the facility to hurricanes **(Slide No. 60)**, or degrade it?

The design of new elements must be as rigorous, in terms of wind-resistance, as that produced when a new health facility is being planned. Special attention must be paid to the detailing of the connections between the new elements and the existing structure. Broadly speaking, by transferring wind and other loads to the new structural elements, the retrofitting should relieve the existing structure of those deformations and stresses that formerly increased its vulnerability.

It is worth noting that the structural retrofitting of a hospital to improve wind performance is significantly simpler and less expensive than structural retrofitting aimed at reducing seismic vulnerability.

COMMONLY EMPLOYED RETROFITTING TECHNIQUES

Structural retrofitting strives to improve a building's capacity to withstand the high pressures associated with hurricane-force winds. It also seeks to reinforce those nonstructural elements that, should they fail, would allow the force of the wind to breach the building's envelope, generating internal pressures that could threaten the structural integrity of the facility as a whole. The penetration of wind and water would doubtless affect the functionality of the hospital during and after a hurricane as well as putting at risk the medical and support equipment.

When retrofitting a hospital, the following measures will improve hurricane performance:

- Ensure that wooden or steel columns are properly anchored to the foundation system **(Slide No. 61)**.
- Use galvanized connectors to guarantee a good connection between wooden beams and columns **(Slide No. 62)**.
- Make sure that the roof is waterproof—for instance by heeding appropriate building standards when attaching asphalt membranes or corrugated iron sheets to the roof bracing system.
- Provide additional lateral reinforcement by introducing shear walls or bracing elements.
- Strengthen the rigidity of external masonry walls by incorporating additional concrete columns.
- Use galvanized straps to ensure a good connection between the primary and secondary beams, particularly in sloped roofs **(Slide No. 63)**.
- Ensure a good connection between wooden beams and preformed concrete beams by using special clamp irons **(Slide No. 64)**.
- Carry ouy an effective maintenance routine, such as the protection of metal structures from corrosion.

- Provide adequate anchorage of metal sheet roofing and steel joists to the main masonry structure (Slide No. 65).
- Connections between structural and nonstructural elements, such as masonry partitions, must be made in such a way to ensure that lateral loads be carried out by the primary system (Slide No. 66) and that deformations should not induce failure of the wall (Slide No. 67).
- Retrofitting of interior or exterior walls of a hospital should comply with local regulations in accordance with the recommendations of vulnerability assessments (Slide No. 68).
- Additional structural retrofitting details are shown in the following slides: (Slide No. 69), (Slide No. 70), (Slide No. 71), (Slide No. 72), and (Slide No. 73).

TEXT, SLIDE, AND IMAGE CREDITS

- D. Comarazamy—Text and Slides
- T. Gibbs—Photos and text review
- C. Compañy—Photos
- J. Vermeiren, OAS—Images and Graphs
- A. Comarazamy—CAD drawings
- F. Sanchez—Graphic design and editing
- NOAA—Images of hurricanes
- PAHO, *Disaster Mitigation in Health Facilities*

Prepared by:

Grupo de Estabilidad Estructural (Ge^2) / INTEC
Ave Los Próceres, Galá
Apdo 349-2
Santo Domingo, Dominican Republic
www.intec.edu.do