EXPERIMENTAL EVALUATION OF A DAMAGE PREDICTION MODEL USING DATA GENERATED BY HURRICANE GILBERT AND ITS IMPLICATIONS TO OTHER HAZARDS

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Abstract

A theory is developed to simulate damage to cladding in a hurricane environment and the theory is tested using perishable data provided by a natural hazard, namely, Hurricane Gilbert which traversed the Caribbean and Gulf of Mexico between Sept. 8 and Sept. 14, 1988. The observed and predicted variable in the theory is the number of failed cladding units. The observed number of cladding units that failed is obtained via field surveys of buildings in the path of the hurricane. The predicted number of failed cladding units is estimated by the expectation of a random number. That number is expressed in terms of the number of cladding units present in a predicted region and the probability of failure of a cladding unit in that region. The probability of failure of the cladding unit is obtained using results from Structural Reliability Theory. The resistance statistics of the cladding elements are estimated from engineering judgment or from a calibration of the observed damage. The loading on the structure is expressed as a function of the pressure coefficients, the air density, and the wind speed. The meteorological literature provides analytical models for the hurricane gradient wind and the boundary layer models.

Data are collected for damaged engineered buildings. With the objective of minimizing the uncertainty in the predictions, the buildings and the surrounding sites are further analyzed to identify the sites that (by virtue of their location, the surrounding terrian, geometry, and confidence in the data collected) minimize the uncertainty in the assignment of pressure coefficients, surface wind velocity, and the statistics of the resistance variables. One such site is selected and the model tested for several combinations of values for the gradient windspeed, the pressure coefficients, and the resistance of the cladding.

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Introduction

In many hurricane landfall scenarios, some people, who for whatever reason find themselves in the path of a major hurricane, might have to seek shelter in designated buildings (Salmon, 1984). Thus, a method of evaluating the relative safety of potential hurricane shelters is needed so that emergency management officials may rationally select shelters that offer inhabitants the best chances of survival, or as a corollary, subject them to the least risk. Over the past several years, as part of an interdisciplinary research program supported by NSF*, we have developed a risk-based methodology to evaluate the safety of occupants in buildings subjected to hurricane winds (Stubbs, 1990). In the methodology, occupant safety is expressed in terms of the risk of death or injury to an occupant. The risk depends upon the location of the occupant in the structure and the reliability of all the protection systems between the occupant and the external hazard. Established techniques from Structural Reliability Theory are used to evaluate the reliability of the structural frame, the roof, the exterior walls (including doors and windows), the interior partitions, and the foundation (Thoft-Christensen and Baker, 1982). Techniques from risk analysis are then used to integrate the component reliabilities with empirical death-damage statistics for structures (derived from earthquake records) to estimate the risk of death or injury to the occupants (Stubbs and Sikorsky, 1985). The entire analysis procedure has been automated as part of the referenced grant.

The methodology has been used to evaluate the feasibility of vertical evacuation along the Gulf and Atlantic Coasts. The methodology has also been utilized by the Tampa Bay Regional Planning Council to evaluate, during minor hurricanes (Category 1 or 2), the relative risks of relocating the elderly to

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inland medical facilities versus keeping them in the hospital (Stubbs et al., 1987). The methodology has also been used to provide emergency management officials on the Gulf Coast with unambiguous descriptions of the relative safety of various portions of selected shelters in hurricanes of various magnitudes (Stubbs, et al., 1989).

Although a concerted effort has been made to relate the elements of the model to the observed behavior of buildings (e.g., the model has been calibrated on the basis of the assumed behavior of buildings at their design load), because of the lack of systematically collected data, the model predictions for hurricanes have never been validated experimentally using as-built structures. Therefore, all predictions made to date should really be regarded as tentative or ball park. On the one hand, if the damage predictions for the model were corroborated with real data, the confidence in the model would be significantly enhanced. On the other hand, if the damage predicted were not corroborated with real data, the model could be adjusted or upgraded.

At the time of the writing of the proposal that engendered this research, we thought that Hurricane Gilbert in traversing Jamaica, the Cayman Islands, the Yucatan Peninsula, and the Gulf Coast (Sept 10 - Sept 17, 1988) had impacted engineered buildings (many designed by U.S.-based companies) with winds ranging reportedly from 80 to 200 mph. In other words, we thought that Hurricane Gilbert had created a real-world experimental condition, otherwise impossible to recreate in a structural laboratory, that might permit us to evaluate, under real-world conditions, the validity of certain parts of the model.

This paper documents our attempt to utilize a natural disaster, namely Hurricane Gilbert, to create the conditions of a large-scale, scientific experiment which may be used to evaluate, among other things, the accuracy of certain assumptions in the proposed risk model of occupant safety. The first objective of the research, is to carry out an experiment to test parts of an existing model of damage prediction to buildings. The second objective of the research is to extrapolate what has been learned in developing this experiment which occurred in a wind hazard to other large scale hazards.

The Experimental Design

In order to test any model (or theory), we need to compare predictions that are logically derived from the model with observations occurring in nature. If the predictions and observations agree within "acceptable" limits, the model is tenable. What constitutes "acceptability" depends, among other things, upon the nature of discipline as well as the problem under consideration.

The range of damage-related observations that can be made after a hurricane has impacted a building is limited to the extent of damage sustained by various parts of the building system. Table 1 summarizes the general trend of damage sustained by engineered structures when subjected to the wind component of hurricanes. Since, under such conditions, most of the damage is concentrated in the roof and cladding subsystems, this study will be limited to testing the model predictions for roof and cladding damage. In this study the term cladding will include structural elements that are either directly loaded by the wind or receive wind loads originating at relatively close locations and that transfer those loads to the main wind-force resisting system. Examples include curtain walls, exterior glass windows and panels, roof sheating, purlins, girts, studs and roof trusses (ANSI, A58; 1982). So in effect the term "cladding" subsumes that of roofing.

The question of how to quantify cladding damage remains unanswered. In the damage prediction model under study here, we are interested ultimately in occupant safety, which is measured in terms of the risk of death to the occupant. That risk is related to the collapse (i.e., the physical removal of) part or all of the cladding between the occupant and the hurricane. Thus the experimental variable to be observed in this study is the collapse of all, or part, of the cladding subsystem. That is, the failure condition selected in this study is the state of collapse. Other levels of damage (e.g., minor, moderate) are ignored at this time. The extent of the collapse may be measured in terms of the area (or number of typical units) of cladding that ceases to protect the potential occupant.

Because of the uncertain environment created by the hurricane-structure interaction, the predicted number of cladding units to collapse in a given hurricane environment must be treated, in the least, as a random variable. This random number will be defined on the positive real axis. The best we may hope to achieve at this stage in the analysis is to estimate the first two moments of the random number. Accordingly, if D(v) is the random number representing the number of cladding units to fail in a hurricane of wind speed v, we wish to generate estimates of the expectation of D, E[D(v)], and the variance of D, Var [D(v)].

A value for the predicted number of roofing and or cladding elements may be obtained as follows. Assume that the cladding can be divided into areas a_i(i=1,2, ...B). Assume also that the probability of failure, P_i, for each cladding panel in the area is the same. Then if N_i is the number of panels in area i, the expected number of panels to fail, $D_{P_i}(v)$, is given by

$$D_{P_i}(v) = P_i(v)N_i \quad (1)$$

The expected number of panels to fail in a building (or a face of the building) is then given by, respectively,

$$D_{P(building)} = \sum^{\text{all faces}} N_i P_i \quad (2)$$

$$D_{P(face)} = \sum^{\text{sections}} N_i P_i \quad (3)$$

Similarly, estimates of the variance of the random number D may be obtained from the following expressions:

$$Var[D_{p(region)}] = P_i N_i^2 - D_{Pi}^2 \quad (4)$$

$$Var[D_{p(building)}] = \sum^{\text{all faces}} N_i^2 P_i - D_{p(building)}^2 \quad (5)$$

$$Var[D_{p(face)}] = \sum^{\text{sections}} N_i^2 P_i - D_{p(face)}^2 \quad (6)$$

Upper and lower bounds on these estimates may be generated from a knowledge of the variance in the estimate P_i. However, such a study, though feasible, is beyond the resources available in this study.

In this study we wish to compare field observations of cladding collapse with the predicted random variable D. In order to estimate D, we must know P_i and N_i. The latter is known *a priori* from the geometry and building details. The former is a function of, among other things, the loading experienced by the structure and the resistance of the cladding elements. The loading experienced by the structure is a function of the strength of the hurricane, the duration and direction of the hurricane, the geometry of the building, the nature of the hurricane boundary layer, the height and shape of the structure, and the geometry and proximity of other structures. The resistance of the cladding or roof elements depends upon, among other things, the strength and geometry of the building materials, the quality of workmanship utilized to design and install the cladding and the age of the material. The load on the structure can be estimated by utilizing results from Meteorology and Wind Engineering. The resistance of the units can be estimated via engineering judgment and calibration. The calibration in turn has to assume certain results from Structural Reliability Theory, Meteorology and Wind Engineering. Once the load and resistance statistics have been estimated, Structural Reliability Theory can be used to compute P_i.

Thus the sequence to be followed in testing the capability of the model to predict cladding failure includes

(1) Defining the typical cladding unit
(2) Computing P_i for each unit and defining the regions of equal P_i
(3) Computing $D_{p(region)}$, $D_{p(face)}$, $D_{p(building)}$
(4) Collecting systematic observations $d_{p(region)}$, $d_{p(face)}$ and $d_{p(building)}$
(5) Comparing the pairs ($D_{p(region)}$, $d_{p(region)}$), ($D_{p(face)}$, $d_{p(face)}$), and ($D_{p(building)}$, $d_{p(building)}$)

The bulk of the theoretical effort in applying this approach is concentrated in the second step. The details of the required calculation are presented in the next section.

Computation of Failure Probabilities for Roof and Cladding Elements in a Hurricane Environment

Rationale

Let the resistance (strength) of a cladding (or roofing) unit be given by the random variable R which is a measure of the pressure needed to collapse the unit. Let the load on the unit be given by the random variable S which is the pressure exerted by the hurricane on the unit. The margin of safety provided by the panel may be given by the random variable Z, where

$$Z = R-S \tag{7}$$

The unit collapses when $Z < 0$ and the probability of collapse of the unit is given by

$$P_f = P[Z<0] \tag{8}$$

Depending upon the level of information available on R and S, P_f may be evaluated using several approaches (e.g., see Madsen, Krenk and Lind, 1986). In this instance, we expect, at most, a knowledge of only the first and second moments of R and S and will therefore estimate the probability of failure of the unit using the simple set of formulae

$$\beta = (\bar{R} - \bar{S}) / [Var[R] + Var[S]]^{1/2} \quad (9)$$

where $\bar{R}$ and $\bar{S}$ are the mean resistance and load, respectively, and

$$P_f = \Phi(-\beta) \quad (10)$$

where β is the reliability index and $\Phi(\bullet)$ is the standard normal distribution function.

Estimation of Cladding Loading

The net pressure, P_n, on the cladding element may be given by the relation (Simiu and Scanlon, 1986)

$$P_n(\underset{\sim}{r},\theta) = 0.00256\ C_{Pn}(\underset{\sim}{r},\theta)\ U^2(z,\theta) \quad (11)$$

in which, θ signifies the wind direction, $\underset{\sim}{r}$ indicates the location of the cladding on the building, z is the height above ground level, U is the wind speed, and C_{Pn} represents the net pressure coefficient. Pressure coefficients are obtained from current codes, published tables or wind tunnel tests.

The hurricane wind speed, $U(z,\theta)$, is a complicated function of, among other things, the hurricane boundary layer, the effects of the surrounding terrain, the interaction among nearby structures, and is a subject of much current research (See, e.g., Simiu et al., 1976). At least six experimentally tested models of hurricane boundary layer are known to the author (Powell, 1980). Of the six models, the model which estimates surface wind speeds by simply multiplying the low-level aircraft winds by a factor of 0.8 is most appealing, from a computational point of view. Furthermore, statistical comparison of all six models using data from several hurricanes showed that the 0.8 approximation is as least as good as the more complicated models. Therefore, in this study we will approximate the hurricane boundary in the region of the buildings of interest in this study layer with the equation

$$U(z,\theta) = 0.8\ U_g \tag{12}$$

where U_g is the gradient wind speed as measured by the aircraft. Perhaps in a future study the different estimations of the various models may be incorporated into a single uncertainty analysis utilizing, e.g., the Latin Hypercube Sampling Technique (Iman and Connover, 1980).

To have any confidence in the predicted loading on the panels, we must have some knowledge of the wind speed and wind direction at the building site as a function of time. Usually, the data provided by meteorologists regarding the characteristics of a hurricane are limited to the specification of the location of the eye, the pressure in the eye, and the maximum sustained winds. If some analytical model of a hurricane were available, and the model provided wind velocity relative to, say, the eye, given the position of a structure relative to the eye, then more reasonable estimates of the wind field in the vicinity of the structure might be made.

Meteorologist have proposed several models for the wind field in a hurricane using fundamental principles from fluid mechanics. In particular, Holland (1980) has provided an attractive analytical model of a hurricane. The model, which can be calibrated straightforwardly using pressure readings in the eye and known distances from the eye of the hurricane at sea level, uses the following expression to estimate the gradient wind:

$$U_g = [AB(P_n - P_c)\exp(-A/r^B)/\rho r^B + r^2f^2/4]^{1/2} - rf/2 \qquad (13)$$

where U_g is the gradient wind at radius r, f is the Coriolis parameter and ρ is the air density (assumed constant). Constants A and B are scaling parameters, P_c, P, and P_n are respectively, the central pressure, the pressure at radius r, and the ambient pressure. The parameters A and B may be obtained from the relation (Holland, 1980)

$$r^B \ell n[(P_n - P_c)/(P(r) - P_c)] = A \qquad (14)$$

using linear least squares regression as follows. Taking the natural log of both sides

$$B\ell nr + \ell n[\ell n[(P_n - P_c)/(P(r) - P_c)]] = \ell nA \qquad (15)$$

which may be rewritten:

$$B\ \ell n\ r - \ell nA = f(r) \qquad (16)$$

where

$$f(r) = \ell n[\ell n[(P_n - P_c)/(P(r) - P_c)]] \qquad (17)$$

only A and B are unknown since P_n, P_c, and P(r) are known from measurements. For example, P_c is the central pressure provided by the reconnaissance aircraft, P(r) is the pressure recorded simultaneously at a nearby airport (or data station) a distance r from the center of the hurricane and P_n is the barometric pressure several hundred miles away from the center of the hurricane. The distance r can be determined directly from the differences in the latitude and longitude of the eye and the airport. The model proposed by Holland has been shown to be superior (in the accuracy of predicting pressure and gradient velocity profiles) to two other well known models (e.g., see the Schloemer Model and the Modified Renkine Vortex (Holland, 1980)).

The gradient winds in Equation (13) are taken to be steady state winds and are, therefore, equated with mean hourly speeds (U_{3600}). These numbers are transformed to fastest-mile wind speeds (U_t) using the relation (Simiu and Scanlon, 1986)

$$U_t^{(z)} = U_{3600}^{(z)} \left(1 + \frac{\beta^{1/2} c(t)}{2.5 \ \ell n(z/z_o)}\right) \tag{18}$$

Coefficients (c_t) and β are related to the windspeed and the terrian roughness. The parameter z_o is related to the surface characteristics and is the height above the ground. Detailed guidance for selecting values for these parameters is provided by Simui and Scanlon (1986).

Estimation of Cladding Resistance

Cladding resistance is estimated in two ways in this study: via engineering judgment in conjunction with results from the First-Order Second Moment (FOSM) formulation and via calibration of the FOSM result. Both methods rely upon the simple expression for the reliability index given by the equation

$$\beta = \frac{\bar{R} - \bar{S}}{(\sigma_R^2 + \sigma_S^2)^{1/2}} \tag{19}$$

where σ_R^2 = Var[R] and σ_S^2 = Var[S]. If we assume that the design load is deterministic and known, Equation (19) may be rewritten

$$\bar{R} = \frac{\bar{S}}{1-\beta \ \nu_R} \tag{20}$$

in which $\nu_R = \sigma_R/\bar{R}$. If $\bar{S}$ is equated with the design load and β and ν_R are selected on the basis of engineering judgment (See, e.g., Ellingwood et al., 1980), the result is an estimate of $\bar{R}$. Using $\bar{R}$ and ν_R, σ_R can be obtained from the definition of the coefficient of variation.

To estimate the resistance statistics using calibration, Equation (19) is rewritten in the form

$$\bar{S}_i = \bar{R} - \sigma_R \beta_i \qquad (21)$$

If the loading, denoted by S_i, on region i of the cladding is known along with the fraction of failed panels n_i (or the fraction of collapsed area), that fraction may be taken as an estimate of the probability of collapse, P_i, of the cladding in the region. An estimate of the reliability index, β_i, for the region may be obtained from the relation

$$-\beta_i = \Phi(P_i) \qquad (22)$$

Thus for each region, i, Equation (21) is assumed to hold. With data pairs S_i and β_i, $\bar{R}$ and σ_R are treated as parameters and data pairs for the appropriate regions are used to estimate the parameters via linear regression.

Qualitative Requirements for Data to Test the Model

In Summary, the model considered here consists of the string of hypotheses which include Equations (1-6), Equations (9-10), Equations (11-13), Equation (14), Equation (18), Equation (20) or Equations (21-22). To make a prediction, we need a model and a set of initial conditions or values for the parameters. In this study the model is embodied in Equations (1-22) while the parameters needed to actualize the theory include the pressure coefficients, the hurricane gradient speed, and the resistance statistics for the cladding unit. The concomitant uncertainty in the prediction will depend directly upon the uncertainty inherent in the model itself and the uncertainty in the values assigned to the parameters in the model. Because of such factors as varying terrain conditions, proximity to adjacent structures and the geometry of the structure itself, the uncertainty associated with the values to be assigned to the model will vary with each structure surveyed. Thus in evaluating the model, it is desirable to use a set of data with the minimum uncertainty. Or, as a corollary, it does not make sense to try to validate the model with a priori uncertain data.

Accordingly, in order to minimize the uncertainty associated with the input parameters, at least the six following conditions should be satisfied by the test site and the building system. Firstly, the terrain should be such that the gradient velocity for that position can be assigned with confidence. This condition would be satisfied if, for example, the terrain surrounding the building is flat. Secondly, the geometry of the structure and its relationship to other structures or land features should be such that (a) pressure coefficients can be assigned with confidence using code guidelines or (b) pressure coefficients can be obtained numerically or via wind tunnel with modest effort. Thirdly, the assumptions used to design the structure should be obtainable. Thus buildings which are fully engineered (i.e., those buildings which received specific, individualized design attention from professional architects and engineers, are preferred over buildings which are pre-engineered (i.e., those buildings which receive engineering attention in advance of a commitment to construction and are subsequently marketed in many similar units), marginally engineered (i.e., those buildings which receive limited engineering attention), and non-engineered. If this condition is satisfied, we would be more confident in using Equation (20). Fourthly, at the time of data gathering, the data collectors should be able to confirm the locations of collapsed cladding. Thus if the damage was repaired prior to the time of the structural condition survey, the data collection should reconstruct the failure scenario with a responsible and qualified representative of the structure. Fifthly, the location and variation of the damage should be such that the calibration performed by Equations (21-22) extend over a reasonable range of β. Sixthly, and finally, the building should be such that the configuration provides the opportunities to make an independent prediction using the calibration. For example, the resistance parameters may be calibrated using the failure results from one face of the building and the calibrated resistance used to predict the observed failure on another face of the building. Or, perhaps, if two buildings of similar construction are in the same vicinity, one building may be used to calibrate the resistance of the cladding elements and the other building can be used to test the model. The six qualitative criteria are summarized in Table 2 for convenience. These criteria will be used later to further scrutinize the collected data.

If these conditions are satisfied for a given building and its surrounding terrain, then the conditions for a controlled experiment have been created by the hurricane. The known net pressure on the cladding unit is taken to be the controlled (independent) variable, while the number of collapsed cladding units become the dependent variable.

The Data Collection Procedure

On the basis of press reports and the perceived magnitude of the hurricane, we initially intended to visit Jamaica, the Cayman Islands, and the Yucatan Peninsula in Mexico. As more information regarding the nature of the destruction became available, we learned that the damage sustained by the Cayman Islands was minor and that other colleagues had surveyed the damage in the Yucatan and agreed to share their information with our team. We, therefore, revised our plans and decided to concentrate on the Island of Jamaica. The path followed by Gilbert over Jamaica is shown in Figure 1.

The principal investigator visited Jamaica from 26 December to 31 December, 1988, with the following objectives in mind: (a) to obtain an overview of the damage; (b) to select potential buildings for the study; (c) to secure permission to gather data; and finally, (d) to ensure that proper physical, immigration, and custom related arrangements were made for the survey team and the accompanying equipment.

In Jamaica, most structures classified as being fully engineered and built within the past 20 years are likely to be resort facilities. Furthermore, most of these structures were on the coast. Excellent pictures of potential structures were available from such publications as tourist brochures. Ideally, structures which appeared to fit the six qualitative guidelines were sought and the manager or a responsible representative of such buildings was contacted by telephone with the following objectives in mind:

1. To obtain an overall idea of the damage the building sustained,
2. To estimate what repairs had been done,
3. To seek permission to survey the structure, and
4. To secure the name of a contact person for future dealings.

On the basis of (a) the concentration of location of potentially engineered buildings, (b) the range of damage sustained by the structures, (c) the number of affirmative responses granted to take data and (d) the availability of a responsible contact person, we decided to concentrate our collection efforts on the north shore of the island. More specifically, we decided to limit the study to the region within about a twenty-mile radius of the City of Montago Bay.

The full team which consist of the principal investigator, a professional engineer and photographer, visited Montago Bay for the period January 8 - Jan 17, 1989. The team was responsible for documenting general data on the buildings (e.g., location, year of construction, codes used, availability of building documents), the surrounding site conditions (e.g., exposure, topography, likelihood of damage from scour and debris), and the nature of the building system (e.g. type and condition of foundation, framing, roofing, cladding, and connections). Sketches of the appropriate regions were also provided. Most importantly, the damage sustained by any portion of the building system was noted and graphically documented. In addition to the sketches, all faces of the structures were documented photographically. Interviews and walkthroughs of several buildings were also documented on videotape.

From among approximately 30 potential buildings, we decided to survey in detail fifteen buildings. At the time we thought these buildings satisfied our main criteria of being fully engineered and were built within the past 20 years. Because many of the properties are tourism related and any adverse report, from this group of investigators, regarding the safety of the structure may affect the financial future of the property, we have decided not to identify the properties by name. Instead each building will be assigned an alphanumeric designation beginning with MB101 and ending with MB115. An abbridged description of the structures studied and the damage the structures sustained are provided in Tables 3 and 4. The approximate locations of the sites are shown in Figure 2.

Analytical Hurricane Model Data

Additional data needed to calibrate the analytical hurricane model (i.e., to obtain the parameters A and B in Equation (14) were obtained from the meteorological office of the Sir Donald Sangster International Airport airport in Montago Bay. Readings of windspeed, atmospheric pressure and wind direction were taken at times to coincide with the pressure readings from the reconnaissance aircraft. From a knowledge of the latitudes and longitudes of the airport and the aircraft, the distance between the projection on the earth's surface of the eye of the hurricane and the airport was calculated. These results are summarized in Table 5.

On using linear regression, we obtain A = 74.462 and B = 1.217. Substituting into Equation 13 and using the relation $f = 2w\sin\theta$ (where w is the angular speed of the earth and θ is the latitude of the eye), we obtain an expression for the gradient wind. The velocity profile of the calibrated hurricane is shown in Figure 3. To check the accuracy of the model the wind speed and direction predicted by Holland's model is compared with the wind speed and direction taken at the Montago Bay airport. These comparisons are shown in Figure 4. The agreement for both wind speed and wind direction is excellent.

Analysis of Collected Data

The six criteria developed in a previous section of this report (See Table 2) will be used to make a comparative evaluation of the uncertainty associated with the test sites. One of the three following responses will be assigned to each criterion for each building: yes, no, or maybe. Sufficient conditions for providing a "yes" to the six criterion are listed in Table 6. If these conditions were not satisfied a response of "no" or "maybe" was assigned on the basis of engineering judgment. A summary of the responses to all 15 buildings is provided in Table 7. An explanation of the negative indicators for Building MB101 serves to illustrate how the table was filled in: (a) Criterion 1 was not satisfied because one side of the building stood next to an almost vertical drop of a very steep hill while the opposite side faced the ocean, (b) Criterion 2 was negative because we had no idea what the pressure coefficients would be for a structure so positioned, and (c) the negative response to Criterion 5 was entered because the building itself suffered no damage. In fact during the entire storm, no more than two windows (out of a possible 120) were reported broken.

The suitability of the building as an experimental test site was assessed by the percentage of positive responses. The yes, maybe, and no responses were assigned weights of 1, ½, and 0 respectively. The relative percentages for each building or building system is provided in the least column of Table 7. From a comparison of the scores, the arrangement that promises to introduce the least uncertainty in the values of the assigned parameters is building system MB103. This system was therefore selected to provide initial data to evaluate the model.

Evaluation of the Damage Model Using Building System MB103 as the Experimental Location

Description of MB103 and Experimental Objectives

The location, plan, and elevation of Building MB103 are shown in Figures 5-7. The global objective of the experiment is to test the capability of the damage model, represented by Equations (1)-(22), to predict the observed damage in the building system, assuming that the input parameters are valid. This objective will be achieved by addressing the following problems.

(1) Assuming wind speeds determined by Holland's Model, pressure coefficients from a knowledge of the geometry, and the resistance of the panels from engineering judgment, predict the number of collapsed panels for the building, each face of the building, and each region of constant panel loading.

(2) Repeat problem (1) but with the change that the resistance of the cladding is calibrated using Equation (22).

(3) Repeat problem (2) but with the change that the pressure coefficients are estimated from a wind tunnel experiment.

Each of the three results will yield a testable prediction when compared with the observed damage. The difference between the results of problem (1) and problem (2) could address the accuracy of the engineering judgment approach used here. The difference between the results of problem (2) and problem (3) could address the accuracy associated with using pressure coefficients based on no interaction effects when indeed some interaction between buildings exists.

Experimental Details

The three problems were solved sequentially. The boundary layer for the hurricane was assumed to be flat with the constant velocity profile given by the magnitude, $0.8U_g$. The magnitude of the velocity used in this, and subsequent, calculations corresponded to the time at which the distance between the site and the eye of the hurricane was a minimum. This event occurred at 2200GMT on 9/13/88. At that time the wind direction was 15° North. These facts were easily deduced from the published trek of the storm and the existence of the analytical hurricane model.

Pressure coefficients were obtained from Simui and Scanlon (1986) for the direction of maximum winds. From these pressure coefficients and resulting net pressure coefficients, which were determined by assuming certain failure sequences in the building system, regions of the cladding that might be subjected to uniform average net pressure were determined. Figure 8 depicts for Tower A the regions of uniform net pressures selected in this study. Since the two structures were identical the same distribution applies to Tower B. Having identified the regions of uniform net pressure, the total number of panels in each region was noted.

The resistances of all panels were assumed to be equal. Equation (20) was used to estimate the resistance using the engineering judgment approach. The design pressure was based on the assumption of a wind speed of 110 mph and a net pressure coefficient equal to 1.3. These assumptions correspond to a design load of 40 psf. If we assume that P_f for the cladding is 0.008, or 0.01, to be conservative, and a coefficient of variation $\nu = 0.1$, we obtain $\bar{R} = 52.17$ psf and $\sigma_R = 5.22$ psf. From the observed damage pattern on the two towers, the number of damaged panels in each region of uniform net pressure was noted. Finally, using the loading and the resistance statistics, the probability of failure of a panel in each region was computed using Equation (8). Then, using the total number of panels in each region, the expected number of panels computed.

In the second problem, all steps and computations remained the same except for the estimation of the resistance of the cladding elements. This estimation was carried in accordance with Equations (22)-(23). Pairs of (S_i, β_i) are obtained from the net pressure on each region i and the inverse normal of the fraction of panels that failed. Resistance statistics for the linear regression was $\bar{R}$ = 21.53 psf and σ_R = 1.35 psf.

In the third problem all steps and computations remained the same, relative to the second problem, except for the estimation of the pressure coefficients. In this instance the pressure coefficients were obtained from wind tunnel tests on models of building system MB103. Wind tunnel tests were performed in a 2x3 ft. low speed wind tunnel. The buildings were modelled as being infinitely tall with the consequence of reducing the aerodynamics to two dimensions. Static pressure coefficients were determined for each side of the building system for wind approaching from any direction at 10° intervals. The layout of the testing arrangement and the directions along which data were taken is shown in Figure 9.

Using the pressure coefficients from the wind tunnel tests, new loads on building A were computed and, along with the same pairs of (S_i, β_i) used in the second problem, new estimates of $\bar{R}$ and σ_R were generated. Resistance statistics for the cladding using the wind-tunnel pressure coefficients were, respectively, $\bar{R}$ = 26.6 psf and σ_R = 3.6 psf.

Results

The results of the three experiments (i.e. the three problems) are summarized in Tables 8 and 9. From the tables, one can readily determine the number of panels which failed (a) on a given face of the building, (b) in a given section of the face, and (c) for the entire building. For Tower A, for example, six panels in Section 1 of the north side failed, ten (10) panels out of a total of 66 on the Northside failed, and thirty two (32) panels failed in the entire building. Face and section designations are correlated with those provided in Figure 8.

The predicted locations and number of panels for the first problem (i.e., using engineering judgment to estimate cladding resistance and pressure coefficients based on an isolated building) are summarized in Table 10. The predicted results developed on the basis of code supplied pressure coefficients and estimates of the resistance statistics derived from a regression analysis are presented in Tables 11 and 12. Finally, the predicted results based on wind tunnel derived pressure coefficients and calibration are presented in Tables 13 and 14.

Discussion of Results

The difference (i.e., error) between the number of panels observed to have collapsed and the number of panels predicted to collapse will serve as a measure of the accuracy of the model. The reliability of the model will depend on the analysis of many similar results to be obtained in the future. The accuracy of the predictions, with regards to Tower A, for the first problem may be obtained by comparing the corresponding elements of Table 8 and Table 10. The error at the building level (i.e., $D_{p(building)} - d_{p(building)}$) is +32 panels. The error at the face level ranges from 0 to 12 panels while the error at the section level ranges from 0 to 10 panels. Similar results hold for the predictions for Tower B. In other words, the calibration using pressure coefficients based on an isolated building and resistance statistics based on the design load, underestimates the damage. In fact the model with these initial conditions predict that no failure should have occurred.

In the second problem, the resistance statistics were calibrated using the observed damage on Tower A. As a result, the comparison of the results of Table 8 and Table 11 represent not a prediction, proper, but a measure of the consistency of the model. In this case the error at the building level is 32-46 = -14 panels. Similarly, the error at the face level ranges from -20 at the south face to +4 at the North face. The error at the section level ranges from 0 to -8.

The comparison of the results from Table 9 and Table 12 now represent a true prediction test of the model for the second problem. The error at the building level is -12 panels. The error at the face level ranges from -19 to zero panels. The error at the section level ranges from -8 panels to zero panels. Thus it seems that when parameters are selected in this manner, the model tends to overestimate the damage.

In the third problem, the resistance statistics were calibrated using the damage data from Tower A and the pressure coefficients were determined from a wind tunnel experiment. Comparison of Table 8 and Table 13 provide a measure of the consistency of the model. At the building level, the error is +2 panels. At the face level, the error ranges from 0 to +2 panels. At the section level, the error ranges from -1 to +1.

The comparison of Table 9 with Table 14 provides a rigorous test for the accuracy of the model. The error at the building level is zero. The error at the face level is bounded by -4 for the north face and +5 for the east face. The error at the section level is bounded by -1 in several sections and +3 in section 5 of the east face.

The maximum errors for the three problems are summarized in Table 15.

From these numbers we can make several observations. Firstly, ignoring the affects of adjacent structures and estimating the resistance on engineering judgment may lead to a gross underestimation of damage to the cladding. Secondly, if the resistance is calibrated, as discussed in this paper, and the interaction with surrounding objects is ignored, the tendency is to overpredict the damage. Thirdly, if better estimates of the true pressure coefficients are used (e.g., obtained from wind tunnel experiments) and the resistance is calibrated, there results a dramatic increase in the accuracy of the predictions. Fourthly, the magnitude of the calibrated resistance, which we may take as an estimate of the true resistance, is approximately one half the value of the resistance obtained on the basis of engineering judgment. This reduction in resistance lead to an increase in the probability of failure by at least an order of magnitude. These results are presented graphically in Figure 10.

Concluding Remarks

In this research, we have attempted to construct a consistent theory of damage prediction for cladding and have attempted to test the theory using perishable data provided by a natural hazard, namely, Hurricane Gilbert which traversed the Caribbean and Gulf of Mexico between Sept. 8 and Sept. 14, 1988. The observed and predicted variable in the theory was the number of failed cladding units. The observed number of cladding units that failed was obtained via field survey of many structures in the path of the hurricane. The predicted number of failed cladding units was estimated by the expectation of a random number. That number was expressed in terms of the number of cladding units present in a region and the probability of failure of a cladding unit in that region. The probability of failure of the cladding unit was obtained using first-order second-moment results from Structural

Reliability Theory. Resistance statistics for the cladding elements were estimated from engineering judgment or from a calibration of the observed damage. The pressure loading on the structure was expressed as a function of the pressure coefficients, the air density, and the wind speed. The wind speed was obtained as a function of the hurricane gradient wind speed and an assumed boundary layer profile for the hurricane. The meteorological literature provided analytical models for the hurricane gradient wind and the boundary layer models.

Data were collected for fifteen engineered buildings that were struck by the hurricane. With the objective of minimizing the uncertainty in the predictions, the buildings and the surrounding sites were further analyzed to identify the sites that, by virtue of their location, the surrounding terrian, geometry, and confidence in the data collected, minimized the uncertainty in the assignment of pressure coefficients, surface wind velocity, and the statistics of the resistance variables. One such site was selected and the model was tested for several combinations of values for the gradient windspeed, the pressure coefficients, and the resistance of the cladding. In all instances the surface winds were based on Holland's model which was calibrated using data from reconnaissance aircraft and from Montago Bay airport. The hurricane boundary layer was assumed to be flat with a value equal to eighty percent of the gradient wind speed.

Findings

The principal findings of the experiment were as follows:

(1) If the pressure coefficients assigned to the structure ignored interaction of adjacent structures or landmarks, and the resistance of cladding units were estimated using engineering judgment, then the model greatly underestimated the cladding damage sustained by the building.

(2) If the pressure coefficients assigned to the structure ignored interactions of adjacent structures or landmarks, but the resistance statistics of the cladding were calibrated using the

observed failure behavior on a control structure, then the model overestimated the observed cladding damage.

(3) If the pressure coefficients assigned to the structure accounted for complications in geometry and the existence of surrounding structures or landmark (e.g., by running wind tunnel tests), and the resistance statistics of the cladding were calibrated using the observed failure behavior on a control structure, the model appears to accurately predict the observed cladding damage.

(4) The magnitude of the resistance statistics obtained via engineering judgment is approximately double the magnitude of the resistance statistics obtained via calibration.

These findings lead to the tentative conclusion that the proposed damage model is accurate, provided that the following conditions are satisfied: (a) the pressure coefficients reflect possible interaction effects, and (b) the resistance statistics are obtained on the basis of the as-built condition.

In a previous study in which this damage model was used, cladding damage was estimated on the basis of pressure coefficients, which ignored interaction affects, and resistance statistics, which were derived on the basis of engineering judgment. The predictions in those studies therefore, may have underestimated the damage to the cladding. Consequently, the resulting number of fatalities also may be underestimated. However, the truth of the latter statement cannot be determined until we test the portion of the model that relates failure of the cladding system to the magnitude of the fatalities sustained.

The fact that we have logically and consistently developed these findings supports the claim that we have shown how the destructive forces of the hurricane hazard can be used to create scenarios/conditions in which structural damage theories can be scientifically tested on a megascale. The abstracted process used here consists of the following steps:

(1) Define the variable to be observed and predicted.

(2) Develop the theory to predict the desired variable using measurable quantities related to the hurricane, the boundary layer, the site, the geometry of the building, and the resistance

of the building elements.

(3) Develop data gathering criteria which will minimize the uncertainty associated with input parameters to define the model.

(4) Collect data which satisfy the criteria developed in Step (3).

(5) Collect data defining the observed variable.

(6) Use steps (2) and (4) to predict the desired variable.

(7) Compare the results of steps (5) and (6).

Given the random distribution of damage created by a hazard, this methodology has the effect of localizing regions in which controlled experimental conditions can be established.

Implications for future work in Wind Engineering

The success and limitations of this project suggests at least six areas of future study in wind engineering:

(1) We are of the opinion that the bulk of post disaster work in wind engineering is of a purely descriptive nature. Such studies are often limited to the presentation of a series of slides describing the damage along with a catagorization of the damage. This work shows that wind engineering studies can indeed be predictive. Future damage prediction theories should be extended to other parts of the building or structural system.

(2) In too many instances, wind speed is illogically inferred from the observed damage. Such inferences may obscure the real cause of the damage, namely, low strength of materials relative to the applied loads. In this study we have attempted to independently establish estimates of wind speeds using analytical models of hurricanes developed by meteorologist and calibrating the models using data independent of the buildings. Although such models appear to provide reasonable estimates of surface wind speeds and directions, more work is needed to establish the reliability of such models.

(3) Hurricane force winds act on a structure over a period of several hours. Likewise, the damage sustained by the structure is a function of time. The damage that we observed is the cumulative damage. This study ignored time in estimating damage. Future work should examine the cumulative damage growth in building systems subjected to hurricane loading.

(4) This study showed that a dramatic improvement of the accuracy of predictions occurred when improved estimates of pressure coefficients and resistance of cladding elements were

simultaneously used in the model. Many values for pressure coefficients used in design ignore interaction effects. Other than time-consuming and expensive wind tunnel tests, is it possible to use computer models which account for turbulence to predict more reliable estimates for pressure coefficients for complicated geometries?

(5) In addition, it is obvious that engineering judgment is not an accurate method of estimating the strength of cladding. Here we showed that the as-built resistance was substantially lower than the as-designed resistance. The difference has been explained in terms of poor quality of workmanship, poor quality of materials, poor quality of design and human error. Can we develop rules to relate the as-designed to the as-built? This study suggests that a tentative rule is to half the design resistance to get the as-built resistance.

(6) This study has provided us with an indication of the accuracy of the damage prediction model for cladding failure. While many of the independent hypothesis which make up the model can be further refined to, perhaps, even increase the accuracy, we have no idea of the reliability (i.e., the repeatability) of the model. To estimate the reliability of the damage model we must repeat the experiment conducted in this study many times. Future post disaster studies should focus on this effort. If we have an accurate and reliable model for cladding damage, then we have a rational basis for reliable cladding design and design improvement.

Implications to Other Hazards

The abstracted procedure, listed earlier in this section, of the approach taken in this study suggests how the approach may be specialized to the other hazards. In such cases, the hazard in question, is analogous to the hurricane and the hurricane boundary layer, the item to be observed or predicted is analogous to the cladding unit, and the smallest class of units to be observed is analogous to the number of cladding units in a section. We will conclude this paper by discussing the implication of this research to the earthquake hazard. A review of a recent paper serves to establish the state of the art in earthquake engineering on this same topic. In that paper, Hwang and Jaw (1990) discussed the problem of evaluating the vulnerability of structures subjected to earthquakes. In that paper, without saying how it might be accomplished, the authors cited the need to calibrate/verify fragility curves (i.e., failure probabilities as a function of earthquake intensity) using actual data. They went on to point out the dangers involved in relying on engineering judgment and cited two recent examples of attempts to calibrate fragility curves. Both efforts, however, were limited by engineering judgment. Admitting that earthquake-induced damage data were too scarce to provide sufficient information and that the fragility data estimated from engineering judgment might not be reliable, Hwang and Jaw (1990) proceeded to generate a set of fragility curves that they claimed were more reliable than engineering judgment. The curves attempted to quantify the uncertainties associated with the randomness and modeling error in both the earthquake and the structure by addressing the uncertainties in key parameters that define the analytical model for the earthquake-structure system.

While the referenced model for calculating fragility curves is consistent and useful, in view of the approach developed in this research, the refinements of the theory alone will never lead to the calibration of fragility curves for at least two reasons. First, a fragility curve , per se, for a single structure is not testable in the scientific sense. That is, if a fragility curve is taken to be a prediction, against which observations in the real-world do we compare it? Secondly, in a scientific experiment, the control variable should correspond to a specific set of conditions represented by one point on the abscissa.

We believe that the approach of Hwang and Yaw (1990) can be extended into a scientifically testable format if the following additions are made.

(1) Assuming that an earthquake of known magnitude has hit a region, define the observed variable as the number of structures (N_O) that have collapsed as a result of induced lateral forces exceeding the lateral resistance.

(2) Define the predicted variable as the expected number of structures E[N] that will collapse given the earthquake, where,

$$E[N] = \sum^{B} P_i N_i$$

in which N_i is the number of structures with computed probability of failure P_i, B is the number of groups of buildings studied, and N_T, the total number of buildings studied is given by $N_T = \sum^{B} N_i$

(3) Use a method like that of Hwang and Yaw (1990) to compute P_f for each structure subjected to the specific earthquake incorporating various hypotheses related to, e.g., engineering judgment, nonlinearity and calibration. Order the probability of failures into B groups.

(4) Compare E[N] with N_o. If the agreement is acceptable, assume P_f is true. Since the load variable, i.e., the earthquake, is known with some certainty, the value of the resistance used defines the particular structure.

Step (3) is not trivial and might demand some ingenuity in designing the experiment. Furthermore, to carry out such a program is equivalent to a modest research effort. However, the results of such an effort would close the gap, so to speak, in the civil engineering design/construction process. Whereas aerospace structures, like aircrafts, are designed and tested before final release upon the market, civil engineering structures are designed, constructed and released with the hope that they would perform as designed. Today an overwhelming body of evidence supports the hypothesis that as-built buildings do not perform as the intended as-designed structure. Using approaches such as the one presented in this study, natural disasters may be used beneficially to test the _in situ_ performance of buildings. Feedback from such experiments should lead to more efficient, reliable, and safer structures in the future.

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Table 1: Summary of Observed Damage Sustained by Engineered Structures in a Hurricane Environment

Building Subsystem	Typically Observed Damage
Foundation	None
Structural Frame	None
Cladding	Minor - Total
Roofing	Minor - Total

Table 2: Qualitative Criteria to be Used to Evaluate Experimental Sites

Criterion No.	Description of Criterion
1	Gradient wind speed is confidently assigned to site.
2	Pressure coefficients are confidently assigned to all faces of the building.
3	Structure received detailed design attention from engineers and architects.
4	Sustained damage is confirmable.
5	Observed damage is sufficient to provide calibration using Eq. (21).
6	Building configuration provides opportunity for independent prediction using the calibrated resistance.

Table 3: Abbriged Description of Surveyed Buildings

Building	Date of Construction	Approximate Footprint (Sq ft)	# Floors	Primary Function	Surround-ing Terrain	Foundation System	Lateral Resistance	Cladding System	Roofing System
MB101	1980	900	14	Condominum	Hilly	Cassions	Rigid Frame	10"thick concrete wall; Aluminum frame windows	Concrete deck
MB102	*	2500	1	Restaurant	Hilly	Slab on grade	Masonary Wall	Bearing Wall	Wooden Shingles
MB103	1981	10,368	11	Hotel	Flat Coastal	Piles	Concrete Shear Walls; Windows	Shear wall; Aluminum Frame Windows	Concrete deck
MB104	*	11,000	9	Hotel	Hilly	*	Concrete Shear walls; glass doors	Shear walls; sliding glass doors	Concrete deck
MB105	*	11,500	3	Hotel	Flat	*	Moment Resist-ing frame	Nonbearing Masonary wall with glass windows	Shingles over wood decking
MB106	1982	7,400	3	Hotel	Flat Coastal Belt	*	Reinforced CMU walls	CMU walls	Galvanized steel
MB107	*	5,000	3	Hotel	Flat Coastal Belt	*	Braced Rein-forced Con-crete frame	CMU walls	Galvanized metal
MB108	1979	22,100	4	Hotel	Flat	*	Moment resist-ing concrete frame	Concrete panels with aluminum frame windows	Sheet metal over con-crete slab
MB109	1969	6,900	4	Hotel	Flat	*	Moment resist-ing concrete frame	"	"

Table 3 (Cont.): Abbridged Description of Surveyed Buildings

Building	Date of Construction	Approximate Footprint Sq ft	# Floors	Function	Terrain	Foundation	Lateral	Cladding	Roofing
MB110	1969	9,300	4	Hotel	Flat	*	Moment resisting concrete frame	Concrete panels with aluminum frame windows	Sheet metal over con-crete slab
MB111	1969	6,800	4	Hotel	Flat	*	"	"	"
MB112	1969	13,650	4	Hotel	Flat	*	"	"	"
MB113	1969	6,800	4	Hotel	Flat	*	"	"	"
MB114	1969	9,300	4	Hotel	Flat	*	"	"	"
MB115	?	5,000	2	Hotel	Hilly	Load Bending walls	"	"	"

*Unknown

Table 4: Damage Sustained by Surveyed Building

Building No	Roof	Cladding
MB101	Loss of exhaust duct	two out of 120 windows broken on north side
MB102	20 out of 152 roof panels	None
MB103	None	32 out of 192 window units in Tower A 18 out of 170 window units in Tower B
MB104	Unconfirmed	Unconfirmed
MB105	Lost roof shingles and deck	None
MB106	20% loss of cladding	None
MB107	100% loss of cladding	None
MB108	10% of area lost	20 percent of North side
MB109	50% of area lost	10 percent of East side
MB110	10% of area lost	15 percent North side
MB111	None	40 percent North side
MB112	55 percent of area lost	50 percent North side 5 percent West side
MB113	None	25 percent North side
MB114	None	10 percent North side
MB115	Unconfirmed	Unconfirmed

Table 5: Data Used To Calibrate Hurricane Model

Date	Time GMT	Central p_c (MB)	Ambient p_n(MB)	Airport p_r(MB)	Distance r (km)
		Pressures			
9/12/88	0900	963	1007.7	1006.1	*
	1000	963	1005.7		*
	1100		1005.3		322.6
	1200		1005.2		293.9
	1300		1003.8		265.3
	1400		1003.8		236.8
	1500		1003.0		208.2
	1600	963	1002.7		179.8
	1700		1000.3		151.4
	1800		998.7		123.3
	1900	963	*		95.4
	2000		*		68.3
	2100		988.7		43.5
	2200	963	*		*
	2300		*		*
	2400		*		*
9/13/88	0100		*		*

*READING NOT TAKEN

Table 6: Rules for Evaluating Surveyed Buildings

Criterion No	Sufficient Condition for a "Yes"
1	Region surrounding building is flat and open.
2	Flow around building is not influenced by adjacent structures or terrain.
3	Date of design and construction and name of responsible architect or engineer on record.
4	Building representative providing the information witnessed the original damage and recalls all subsequent repairs.
5	Regions of uniform reliability range from collapse to full survival.
6	Materials and construction are identical for at least two faces of the system.

Table 7: Evaluation of Test Sites for Experimental Candidate

Building #	Satisfaction of Criterion Number						
	1	2	3	4	5	6	Indicator (100 = Max)
MB101	N	N	Y	Y	N	Y	50
MB102	N	N	N	Y	N	N	17
MB103	Y	M	Y	Y	Y	Y	91
MB104	N	N	Y	N	N	Y	34
MB105	Y	N	M	N	N	Y	42
MB106	Y	N	M	Y	N	Y	42
MB107	Y	N	M	Y	N	Y	42
MB108	Y	M	Y	Y	N	Y	74
MB109	Y	N	Y	Y	N	Y	66
MB110	Y	N	Y	Y	N	Y	66
MB111	Y	N	Y	Y	N	Y	66
MB112	Y	N	Y	Y	N	Y	66
MB113	Y	N	Y	Y	N	Y	66
MB114	Y	N	Y	Y	N	Y	66
MB115	N	N	N	N	N	Y	17

Y = Yes
N = No
M = Maybe

Table 8: Summary of Observed Damage for Tower A

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	6	0	10	10	26
2	2	0	0	1	3
3	0	0	0	0	0
4	1	0	0	1	2
5	1	0	0	0	1
Total Failed by Face	10	0	10	12	32
Total # of Panels	66	66	30	30	192

Table 9: Summary of Observed Damage for Tower B

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	0	0	10	0	10
2	0	0	1	1	2
3	0	0	0	0	0
4	0	0	1	1	2
5	0	1	3	0	4
Total Failed by Face	0	1	15	2	18
Total # of Panels	60	60	30	20	170

Table 10: Summary of Predicted Damage for Tower A&B Using Engineering Judgment and Pressure Coefficients Based on an Isolated Building

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
Total Failed by Face	0	0	0	0	0
Total # of Panels					

Table 11: Summary of Predicted Damage for Tower A Using Calibrated Resistance and Pressure Coefficients Based on an Isolated Building

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	6	0	10	10	26
2	0	1	0	0	1
3	0	8	0	0	8
4	0	3	0	0	3
5	0	8	0	0	8
Total Failed by Face	6	20	10	10	46
Total # of Panels	66	66	30	30	192

Table 12: Summary of Predicted Damage for Tower B Using Calibrated Resistance and Pressure Coefficients Based on an Isolated Building

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	0	0	10	0	10
2	0	1	0	0	1
3	0	8	0	0	8
4	0	3	0	0	3
5	0	8	0	0	8
Total Failed by Face	0	20	10	0	30
Total # of Panels	60	60	30	20	170

Table 13: Summary of Predicted Damage for Tower A

Using Calibrated Resistances and Wind Tunnel Pressure Coefficients

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	6	0	10	10	26
2	1	0	0	0	1
3	1	0	0	0	1
4	1	0	0	0	1
5	1	0	0	0	1
Total Failed by Face	10	0	10	10	30
Total # of Panels	66	66	30	30	192

Table 14: Summary of Predicted Damage for Tower B

Using Calibrated Resistance and Wind Tunnel Pressure Coefficients

Number of Failed Panels					
Section of Face	Face of Building N	S	E	W	Total Failed by Section
1	0	1	10	0	11
2	1	1	0	0	2
3	1	1	0	0	2
4	1	0	0	0	1
5	1	1	0	0	2
Total Failed by Face	4	4	10	0	18
Total # of Panels	60	60	30	20	170

Table 15: Summary of Accuracy of Predictions

Problem No	$\bar{R}$	σ_{PR}		Maximum Error of Prediction (No. of Collapsed Panels) Building	Face	Section
1[a]	52.17	5.22	Tower A	+32	+12	+10
			Tower B	+18	+15	+10
2[b]	21.53	1.35	Tower A	-14	-20	-8*
			Tower B	-12	-19	-8
3[c]	26.6	3.6	Tower A	+2	+2	±1*
			Tower B	0	+5	+3

* results in this row represent a calibration of the model

a Pressure coefficients from codes, resistance from engineering judged

b Pressure coefficients from code resistance from calibration

c Pressure coefficients from wind tunnel, resistance from calibration

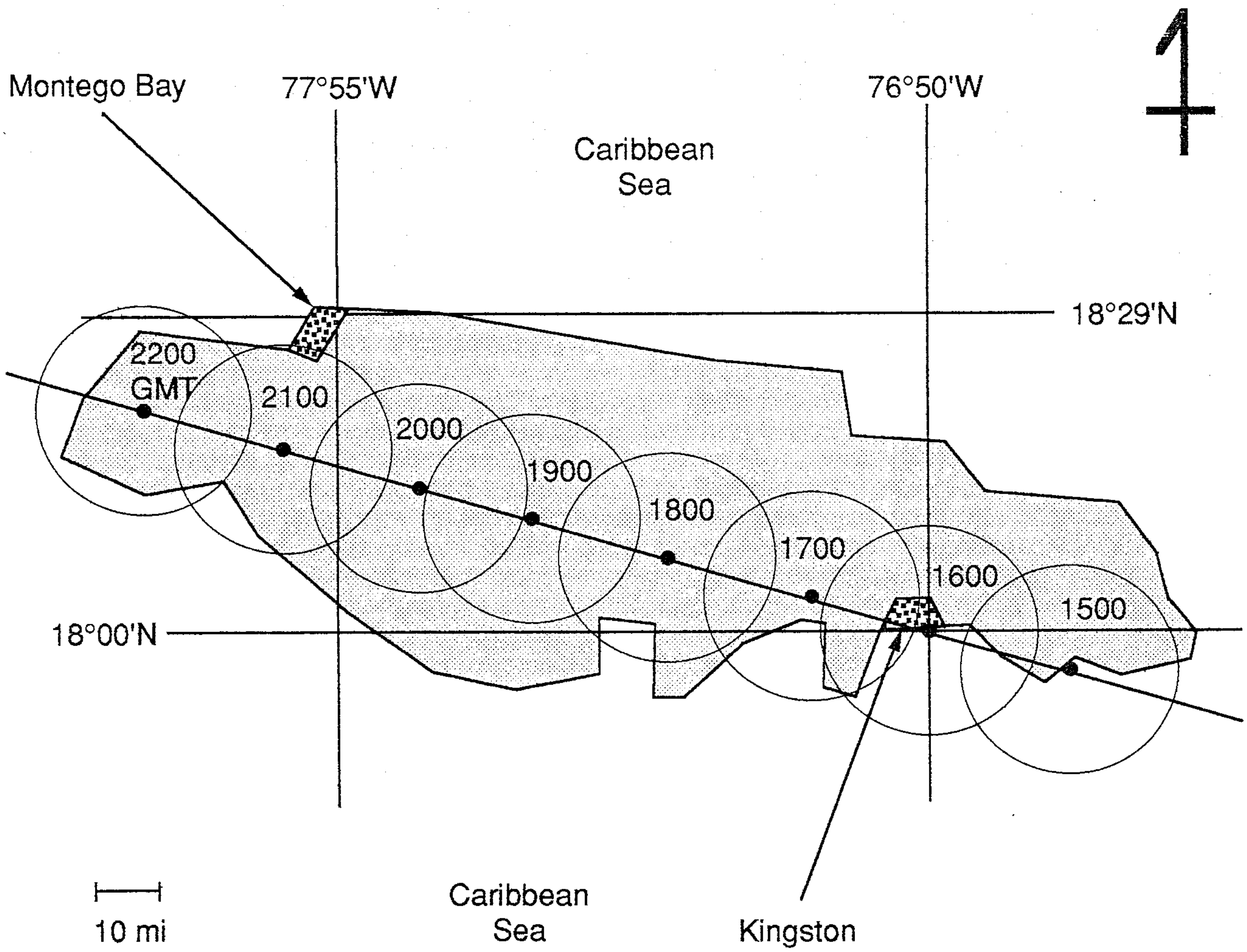


Figure 1. Path of Hurricane Gilbert Over Jamaica, Sept. 12, 1988

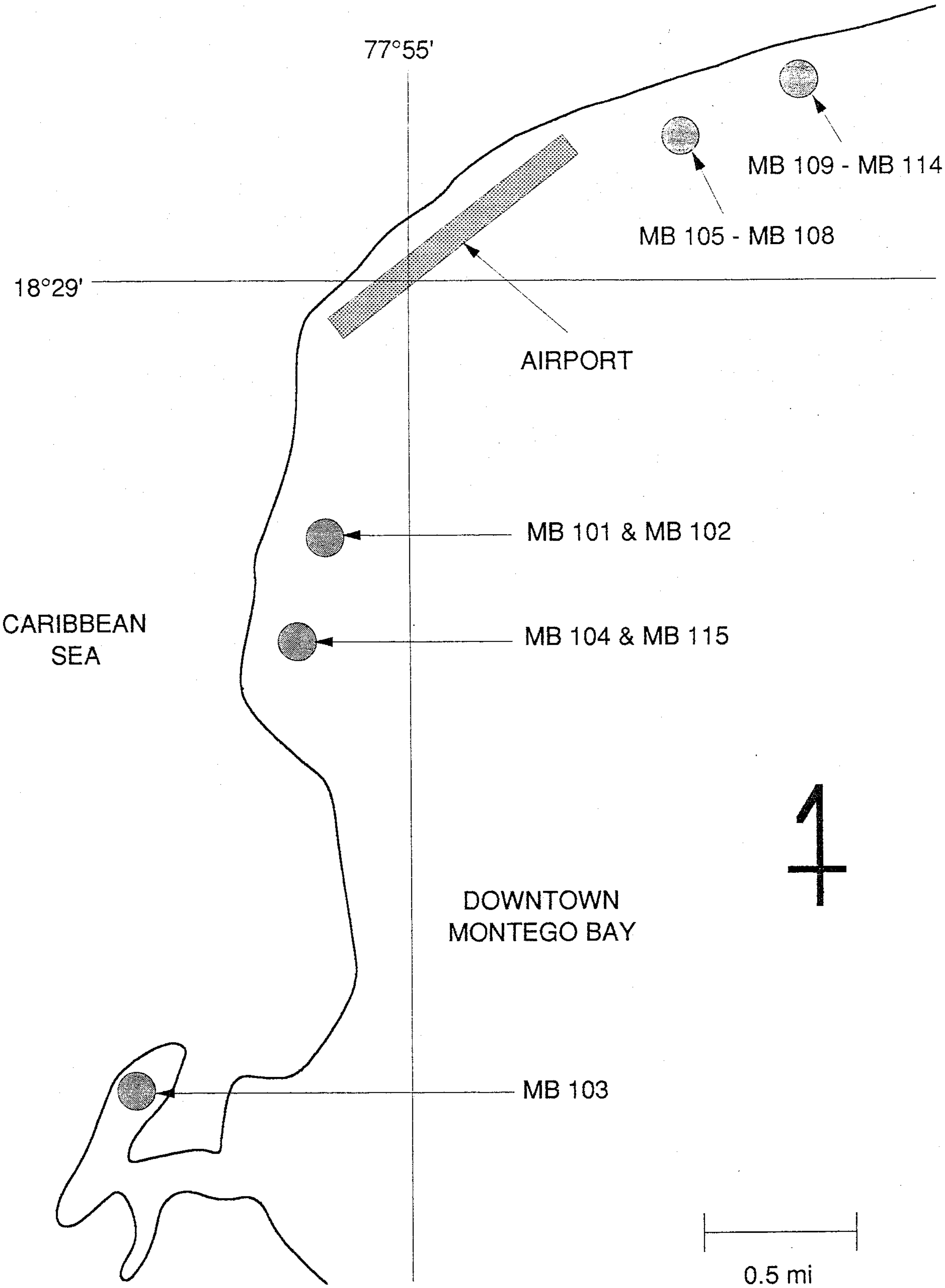


Figure 2. Approximate Locations of Building Sites

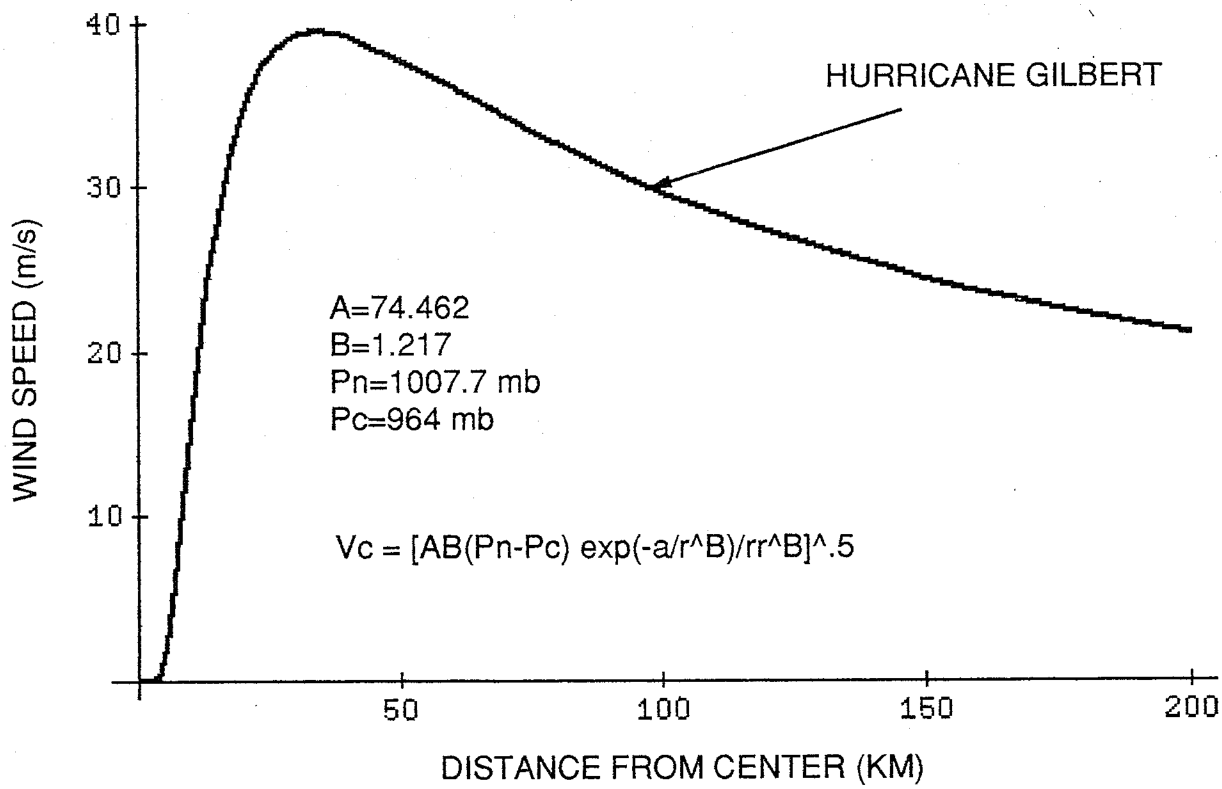


Figure 3. Windspeed Profile of the Calibrated Hurricane Model

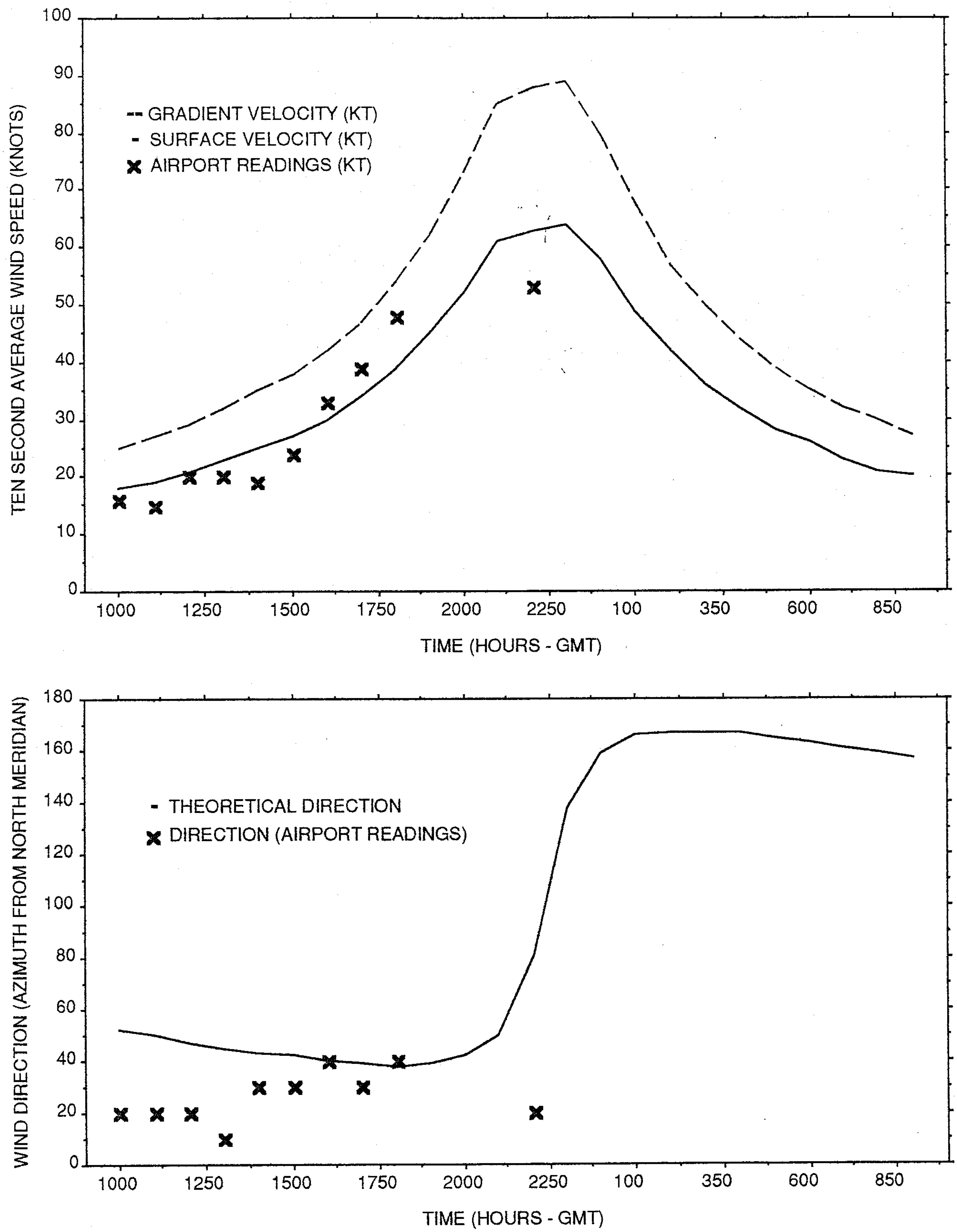


Figure 4. Comparison Between Predicted Wind Velocity Measured
Wind Velocity at Montago Bay Airport

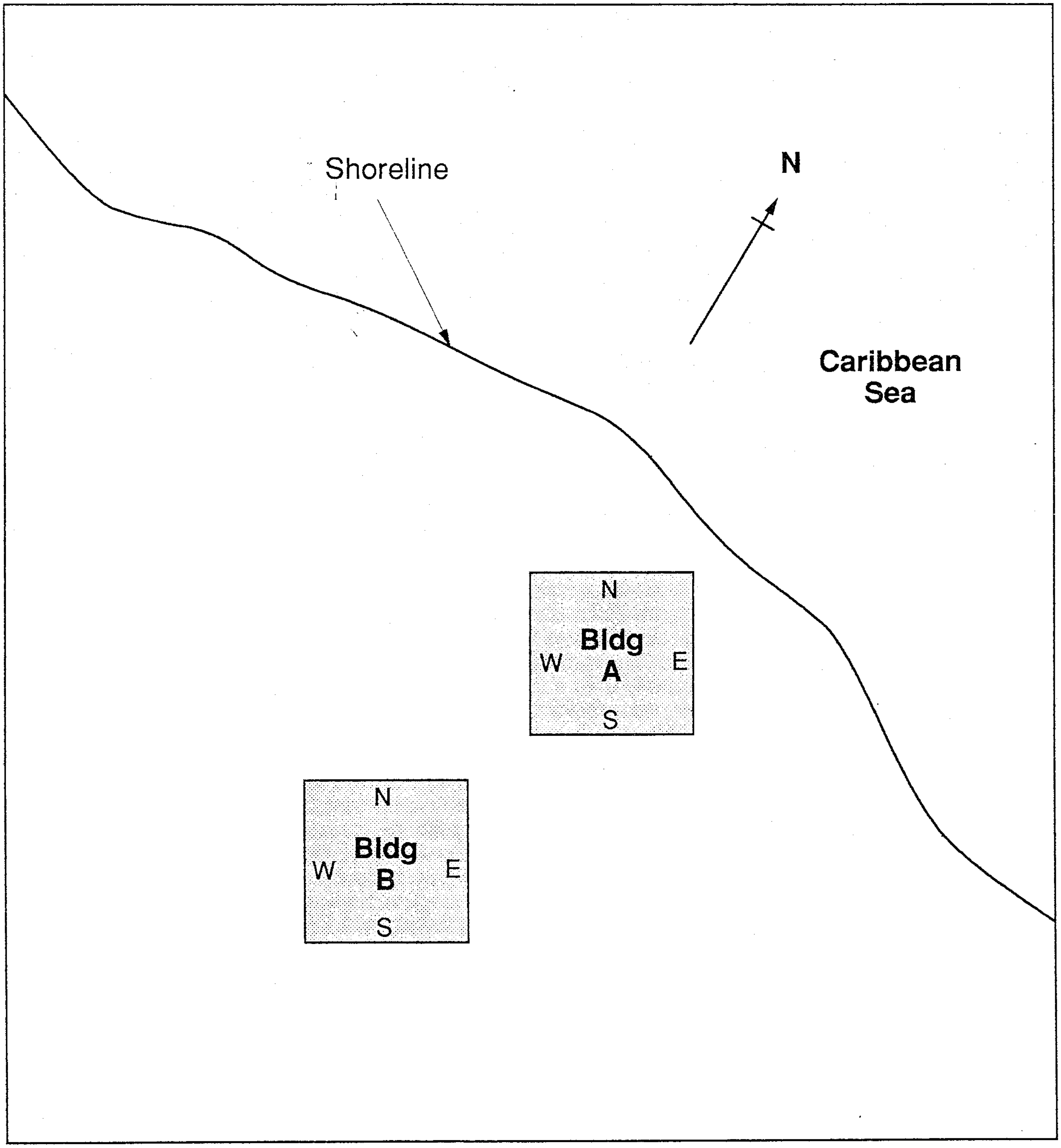


Figure 5. Location Plan of Site MB103

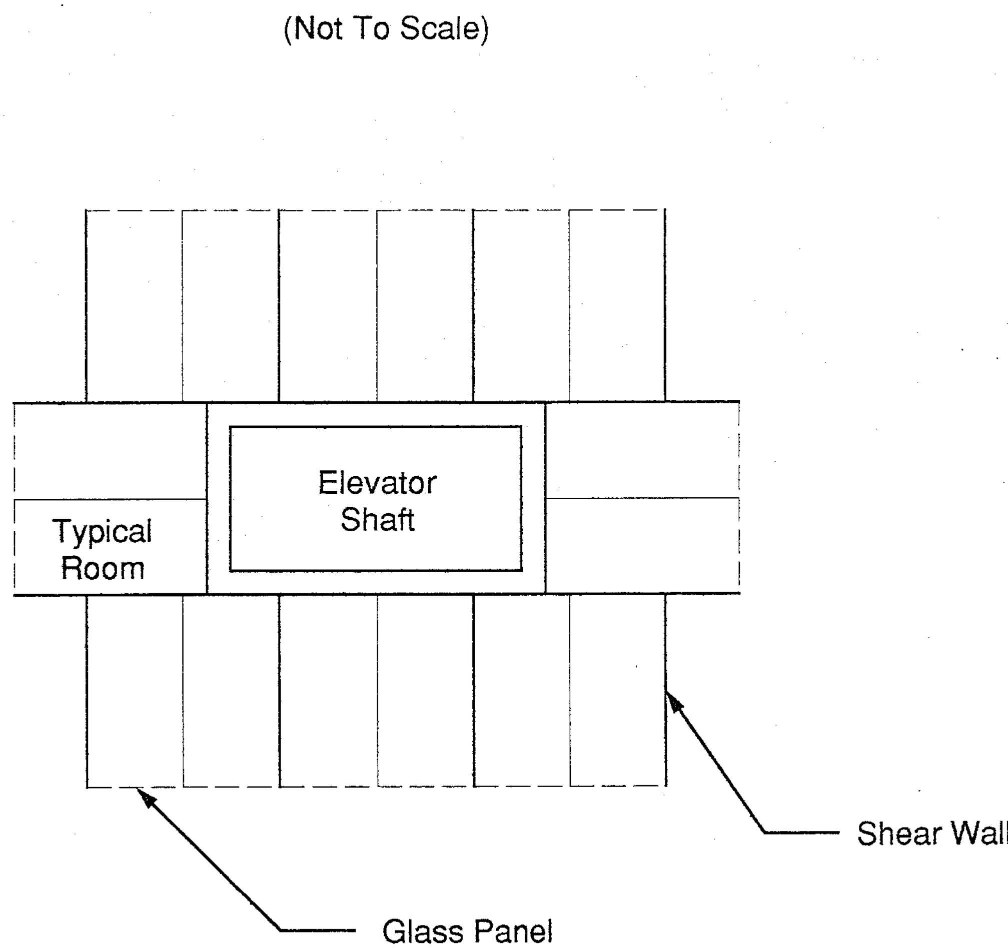


Figure 6. Plan of Typical Structure at Site MB103

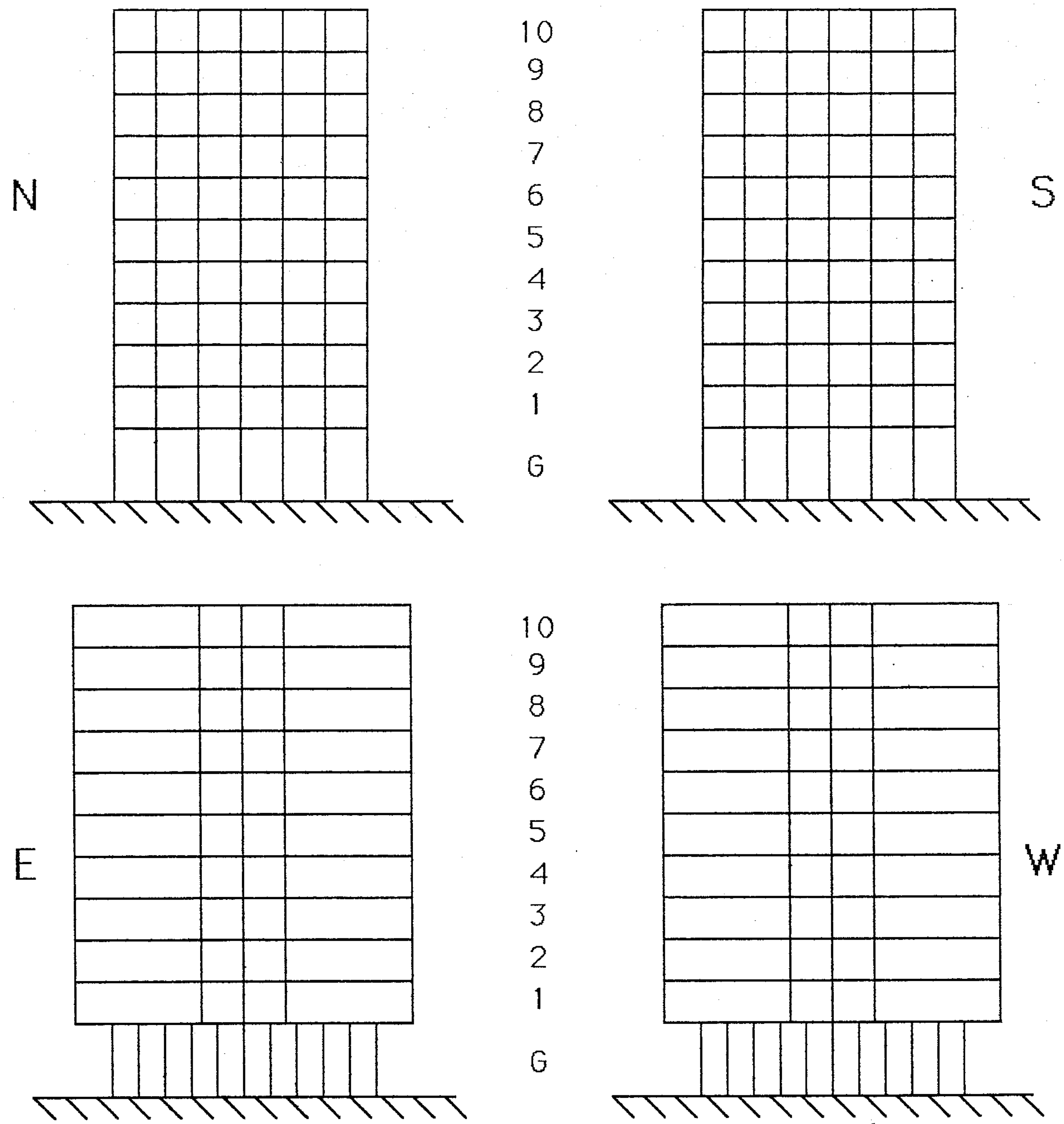


Figure 7. Elevation of Typical Structure at Site MB103

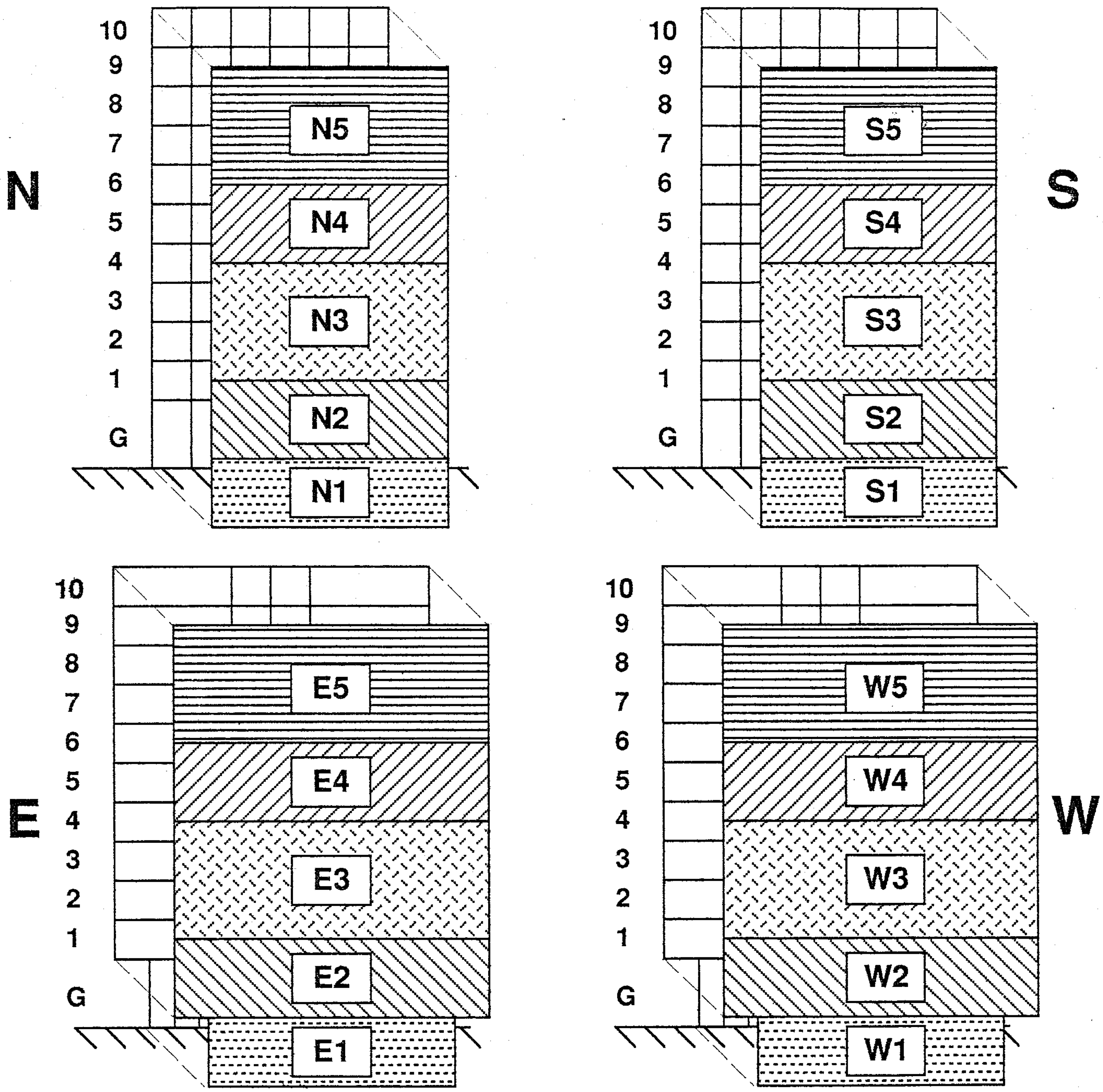


Figure 8. Assumed Areas of Constant Pressure

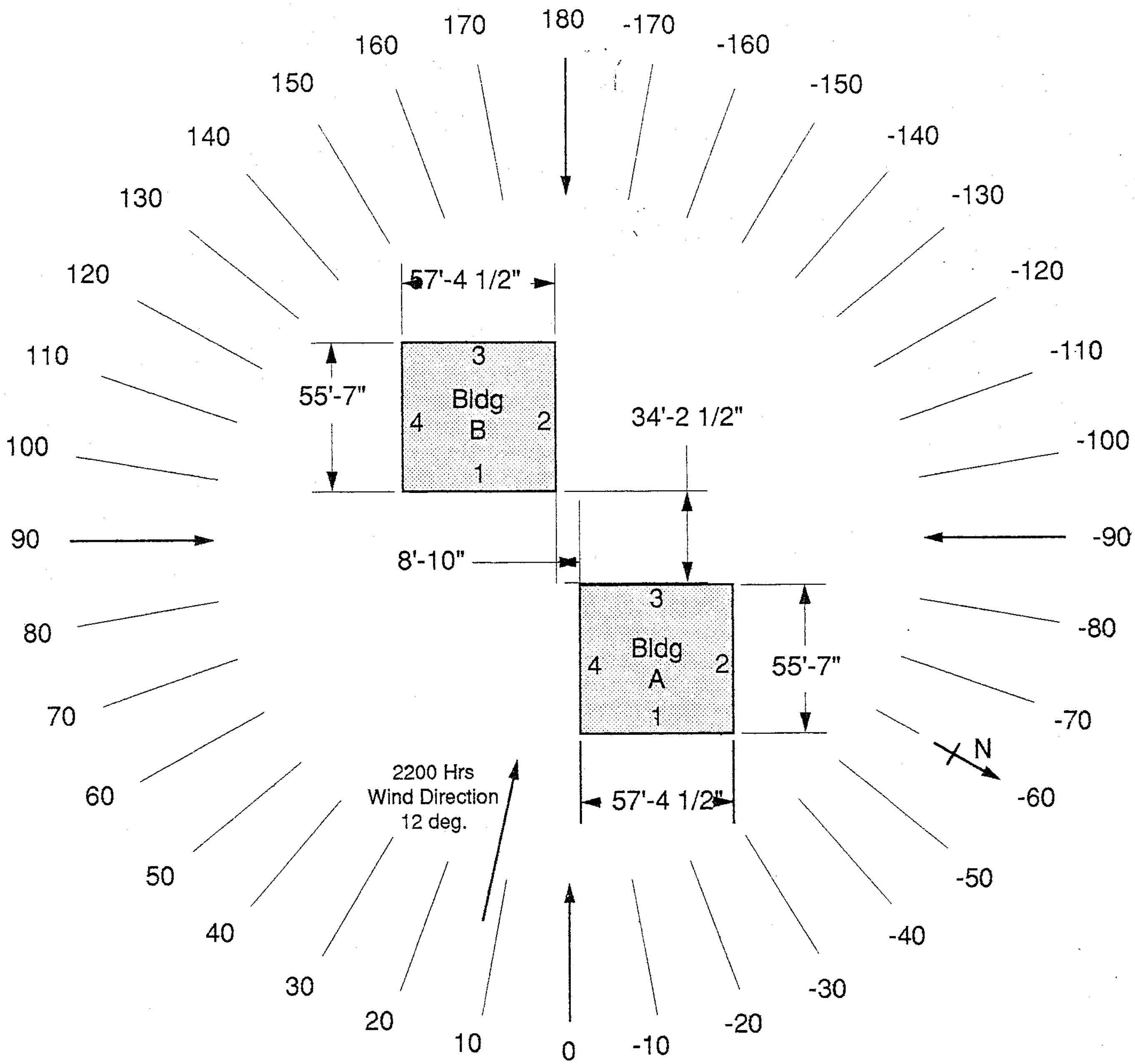
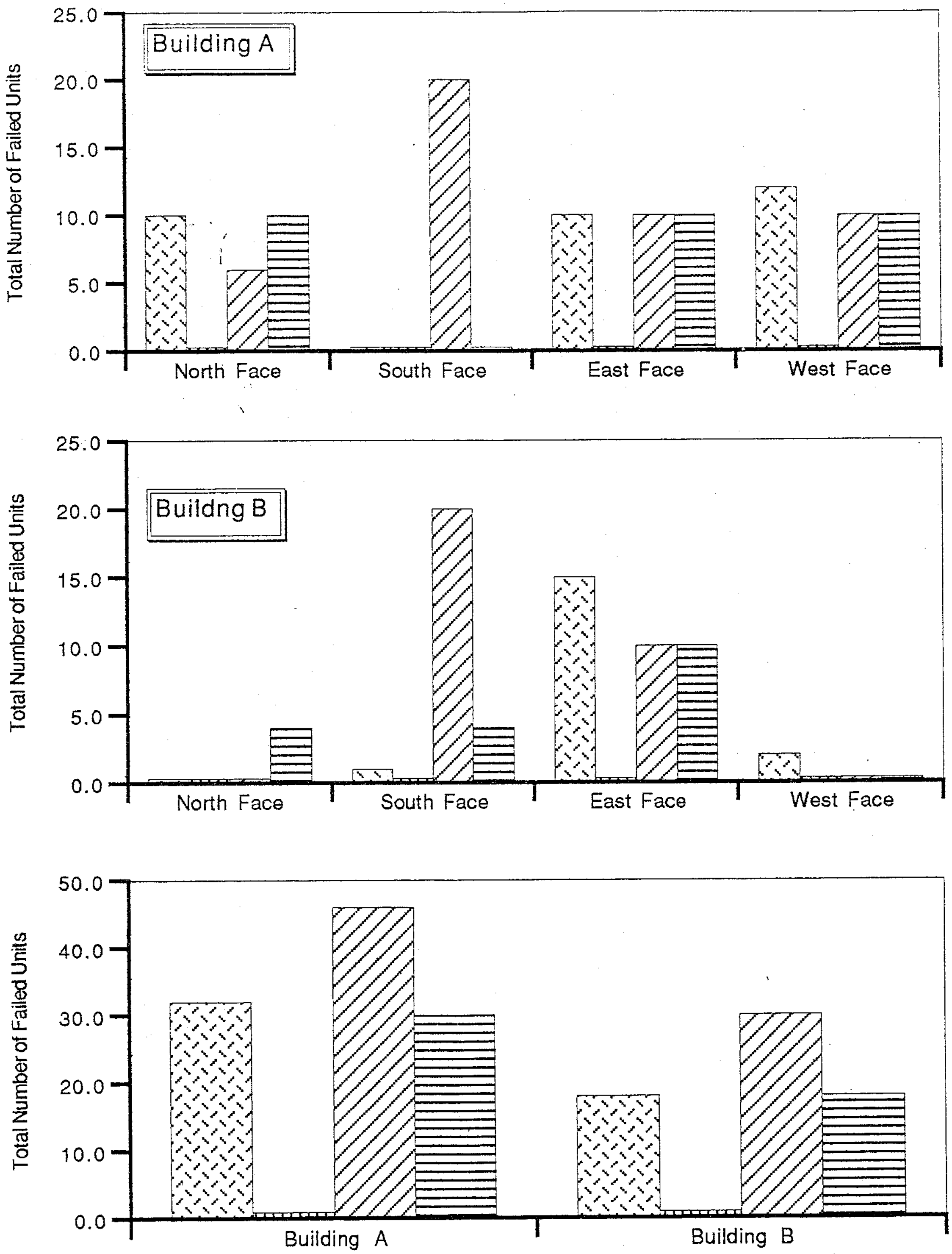


Figure 9. Layout of Wind Tunnel Test



Observed
Predicted: Resistance (From Engineering Judgement) and Pressure Coefficient (Assuming Isolated Building)
Predicted: Resistance (From Calibration) and Pressure Coefficient (Assuming Isolated Building)
Predicted: Resistance (From Calibration) and Pressure Coefficient (From Wind Tunnel Tests)

Figure 10. Graphical Presentation of Results