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RESEARCH REVIEW - NORTH AND SOUTH AMERICA (WIND EFFECTS ON TALL BUILDINGS)

BY

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LES EFFETS DU VENT SUR LES EDIFICES ELEVES

L'auteur examine l'état actuel de la recherche effectuée en Amérique du Nord et en Amérique de Sud concernant la prévision du comportement des édifices élevés sous l'effet du vent, sous les rubriques suivantes: recherche météorologique concernant la structure du vent et le climat, essais à l'échelle naturelle, élaboration de techniques de soufflerie, formules de prévision simplifiées pour les effets des coups de vent. On insiste sur la necessité de coopérer à l'accumulation et à l'application des données obtenues tant à l'échelle naturelle que dans les souffleries. La bibliographie compte plus de quarante publications des dix dernières années, par ordre chronologique sous chacune des quatre rubriques principales.

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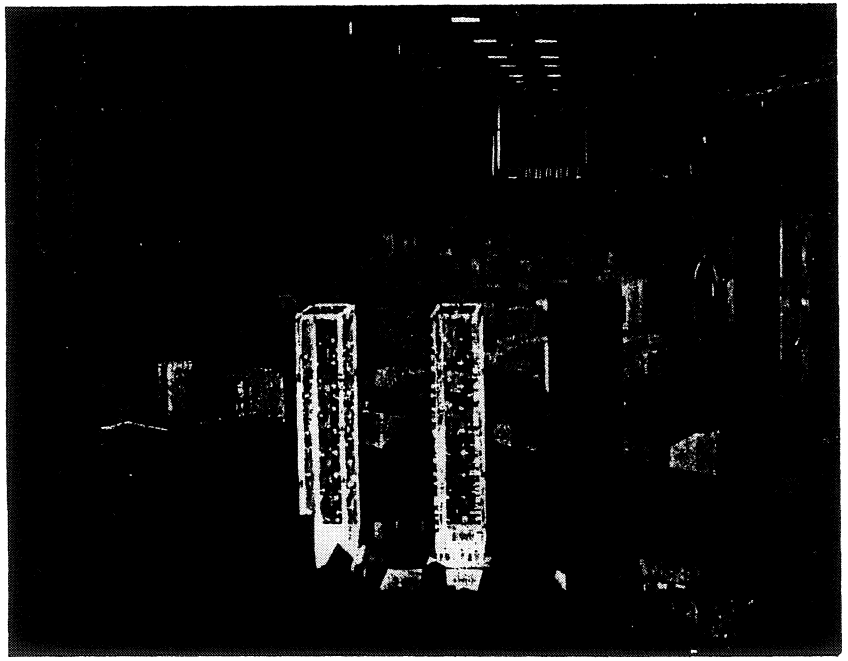

FIG. 3 INTERIOR OF METEOROLOGICAL WIND TUNNEL AT COLORADO STATE UNIVERSITY WITH 1:400 MODEL OF ATLANTIC-RICHFIELD TOWERS IN PLACE

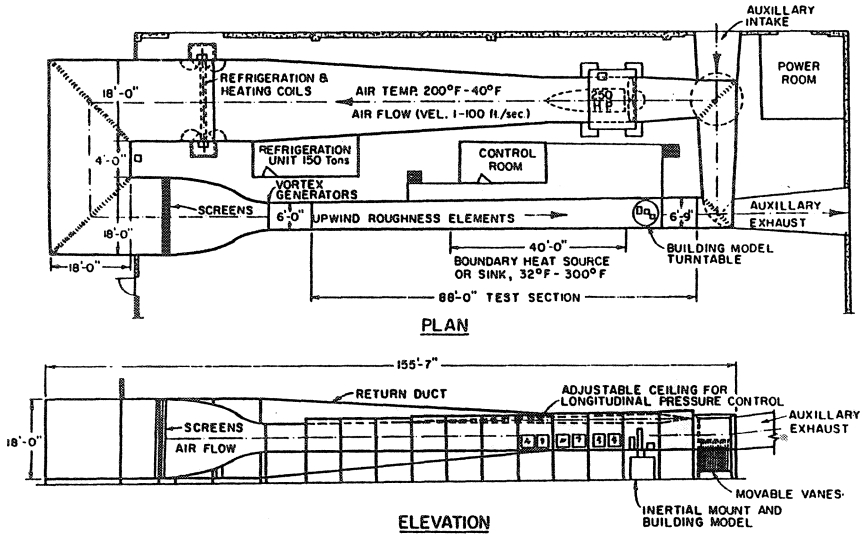

FIG. 4 METEOROLOGICAL WIND TUNNEL COMPLETED IN 1963 FLUID DYNAMICS AND DIFFUSION LABORATORY COLORADO STATE UNIVERSITY

Planning and Design of Tall Buildings
ASCE-IABSE/August 1972/Lehigh University

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Wind Loading and Wind Effects

State of Art Report No. 3

RESEARCH REVIEW—NORTH AND SOUTH AMERICA

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1. INTRODUCTION

The current status of research in North and South America relevant to the prediction of tall building behavior in response to wind is reviewed under four main headings:

Meteorological research - wind structure and climate
Full-scale investigations of wind action on tall buildings
Development of wind tunnel techniques for building aerodynamics
Simplified theoretical models of wind effects on tall buildings.

1.1 RELEVANCE OF RESEARCH TO DESIGN

These four aspects of research on the effects of wind on buildings represent the main links in the chain of reasoning by which one attempts to connect design predictions to actual behavior of prototype structures in real wind. Although each of the four links plays a major role in making a satisfactory design decision, the writers of this report have, in their opinion, discussed them in decreasing order of urgency with respect to need for additional research and collection of data.

Limited knowledge of wind structure within cities and its relation to meteorological data commonly recorded by weather stations at airports and of the effects of local topography, including the influence of particular groupings of buildings, appears to be the weakest of the links. The interdependence of all four areas makes progress in any one area difficult without corresponding advances in the others. This suggests the wisdom of a balanced approach to research, and points to a need for more effort in establishing the characteristics of wind structure in cities.

1.2 COLLECTING, COLLATING, AND SHARING OF DATA ON FULL-SCALE BUILDINGS

A second important limitation to understanding actual wind-induced phenomena is the scarcity of detailed field records taken on prototype buildings of surface pressures, structural strains, and building movements. According to a recent survey, several projects are either underway or in the detailed planning stage, which should provide considerable new data over the next three or four years. The potential benefits from these data can be realized only if they are made readily available to various workers in all of the afore-mentioned research areas. Those who responded to the survey questionnaire indicated willingness to cooperate, and in the writers' view, it is very important to ensure that effective means of communication are maintained.

1.3 COOPERATION IN THE DEVELOPMENT OF WIND TUNNEL TECHNIQUES

Much of the wind tunnel testing now being done involves specific projects on a contract basis and it is sometimes difficult to make the resulting reports generally available because of their proprietary nature. They often provide valuable information of a general nature which, if shared with other research workers, would accelerate improvement in wind tunnel techniques.

1.4 BIBLIOGRAPHIC REFERENCES

References selected as representative of recent research developments in North and South America are listed chronologically in each of four sections, corresponding to the four main headings. In the following, main points from the references have been assembled to give a brief, over-all review.

2. METEOROLOGICAL RESEARCH - WIND STRUCTURE AND CLIMATE

The variability of wind speed and direction at a given location involves two vastly different time scales: there is a peak of energy at a period of four days, usually a pronounced gap centered approximately at half an hour, and another energy peak at a period of one minute or less. The low-frequency peak is related to synoptic, or large-scale, weather disturbances which show up on a weather map as high or low pressure areas moving slowly across a whole continent, on average once every four days or so. The high-frequency peak is caused by the fluctuations about the average wind velocity during a particular storm. In strong winds (except possibly for local squalls or tornadoes) these fluctuations (turbulence) are of a mechanical rather than thermal origin and result mainly from drag. (3, 4, 5, 6)

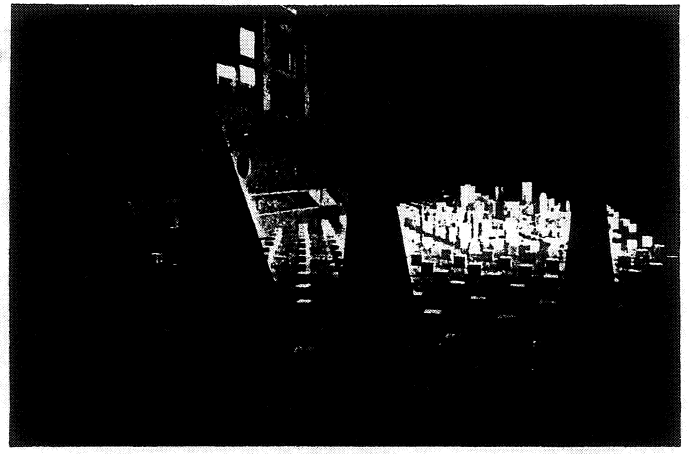

FIG. 1: SEVEN-FOOT SPIRES AND SIX-INCH CUBE ROUGHNESS GRID INSTALLED IN THE 30-FOOT SQUARE WORKING SECTION OF THE CANADIAN NATIONAL AERONAUTICAL ESTABLISHMENT'S WIND TUNNEL TO PRODUCE A SCALED TURBULENT SHEARED FLOW TO SIMULATE WIND OVER A MODEL CITY.

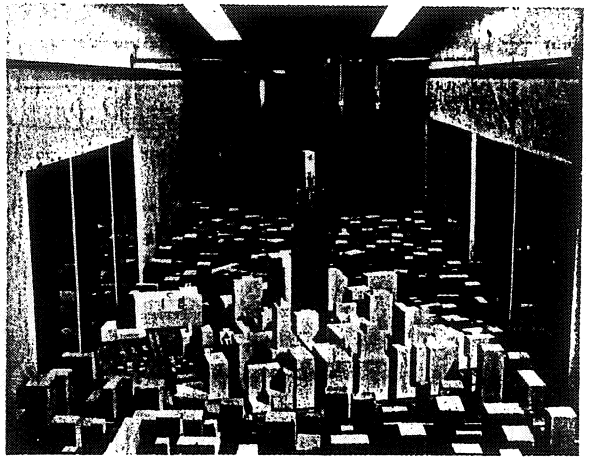

FIG. 2 INTERIOR OF BOUNDARY LAYER WIND TUNNEL LABORATORY AT THE UNIVERSITY OF WESTERN ONTARIO WITH 1:400 MODEL OF THE

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Severe local storms such as tornadoes, although having some statistical influence on the climatological records on which design wind speeds are based, pose special difficulties because of their short time duration, small spatial extent, and wide range of maximum forces. Some tentative estimates of maximum speeds in tornadoes have been made (1, 2, 10) and the tempo of research has picked up remarkably in the last few years. (11) As population growth causes urban areas to expand, the probability of losses due to tornado strikes increases and these losses can run into several hundreds of millions of dollars. The Lubbock tornado of 11 May 1970 provides one recent example, in which a twenty-story building received extensive structural as well as superficial damage, and in which another tall building experienced heavy financial losses mainly due to cladding damage. (13, 14, 15) Laboratory simulation of tornado forces has been carried out, with the development of promising techniques to aid in their study. (19)

The two main features of the structure of the wind in the earth's boundary layer (from the ground surface up to 1000 to 2000 feet) are the mean velocity profile and the turbulence properties, both of which are mainly dependent on the relative roughness of the ground surface for a distance of approximately one to four miles upwind of the site in question.

The existence of the so-called spectral gap separating the two scales of variability in wind velocity was instrumental in the development of design procedures for predicting wind effects on structures. First, mean wind velocity can be defined as an average over 5 minutes to an hour, preferably 10 to 30 minutes, and theory can be used to predict probabilities of recurrence of given mean velocity levels, based either on the total population of mean speeds or on a much smaller subset of yearly or monthly extreme mean winds. (7, 12) Second, the properties of the mean wind, in terms of its horizontal velocity variation with height above ground and of the amplitudes of turbulent fluctuations relative to the mean velocity, can be estimated as a function of the roughness of the terrain surrounding the building site.

The wind conditions thus specified reflect the nature of the location (for example, lakeshore, rolling country, city center) as well as the geographical variations of climate. For tall buildings, the separation into mean wind and superimposed turbulence facilitates evaluation of dynamic response of the structure to the unsteady loading produced by turbulent wind. (8, 9, 16, 17)

A significant recent advance in structural design is the recognition of the damaging effects of repeated loading. Experience suggests that unserviceability of tall, slender structures is more likely to result from some effect of recurring loading than from a single application of an exceptionally large load. Possible effects include excessive deflections, fatigue damage, and excessive building motion.

In order to predict the expected number of occurrences per unit of time at any given level of excitation (stress, deflection, acceleration, wind speed at street level), it is significant to note that, first, maximum responses tend to be clustered within bursts during a storm, and second, the bursts themselves are

clustered within storms if one considers the whole time history of building behavior. (18) This suggests that the assumption of a stationary Gaussian process to represent the response of the structure to wind excitation may require some modification or refinement to improve design predictions of peak load effects.

A further refinement that is employed in current consultative work in this field is to treat combinations of loading through the use of interaction diagrams. For example, under actual wind loading, a column may be forced to resist bending about two axes rather than one and this involves knowing the interaction of simultaneous building displacements in the along-wind and the cross-wind directions. Although a systematic approach is available for the utilization of wind data in the design process, there is a very definite need for more information on wind climate in city centers where field measurements are inherently difficult. Another important problem is the effect of surface roughness discontinuities on wind structure. This is the subject of a field study recently initiated by the National Aeronautics Space Administration at Huntsville, Alabama.

3. FULL - SCALE INVESTIGATIONS OF WIND ACTION ON TALL BUILDINGS

The next step after wind conditions have been specified for the building site (wind structure, design levels for mean wind velocity and so on) is to determine the behavior of the building in response to the stated wind action. Although it is not generally practicable to generate sufficiently detailed information by full-scale investigations to satisfy the designer's needs, field tests play an essential role in providing information about a limited set of wind conditions (moderate wind speeds, small range of wind directions) on a few specific buildings in particular topographic settings.

Such information is used to aid the development of wind tunnel techniques for simulating real wind conditions and actual responses of prototype structures to that wind. Similarly, simplified theoretical models of the wind process can be checked by comparing the prediction of building behavior with field measurements.

The special problems faced in making full-scale investigations include the need for various types of references against which to make measurements. Firstly, surface pressures on the building generally have to be measured with reference to a common internal pressure, which is unfortunately affected to varying degrees by the wind itself, chimney effect during cold weather, operation of the air-handling equipment in the building, and so on. (22) Secondly, to compare pressures measured on the building with corresponding measurements on a model, a link has to be established with the mean wind speed, or rather, the mean dynamic pressure, at some specified reference position. This is usually some point at or above the top of the building in line with the approaching flow. (23, 24, 25)

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DEVELOPMENT OF WIND TUNNEL TECHNIQUES FOR BUILDING AERODYNAMICS

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Building motion as represented by displacement of the top relative to the base would be an excellent parameter for comparison, but here again the difficulty lies with the establishment of a reference position. Various forms of seismic instruments have been employed, including velocity, acceleration, and displacement types involving a critically damped spring mass system, but all are responsive to tilt as well as to translation of the slab on which they are mounted. (20, 21, 26, 27, 28) One promising solution is to obtain direct measurements of displacement by the use of a beam of light transmitted from the building foundation to serve as a reference for a servo-controlled receiving device at the top of the building. (29) A disadvantage of this technique is that horizontal temperature gradients can produce apparent displacements because of changes in the refractive index. Prototype instruments are under development for use in two or three field installations now being set up and preliminary results are very encouraging.

Very little correlation has been carried out between field data and corresponding data from wind tunnels, but any that has been done has generally yielded encouraging results. Power spectra of horizontal wind speeds and of wind pressures at various points on building surfaces of two different high-rise buildings showed reasonable agreement between model and full-scale data. Mean and root-mean-square pressures have shown qualitative agreement (shape of pressure distribution) and in some cases quantitative agreement as well.

There are some indications of possible scaling effects involving the sizes of small surface roughness features such as mullions on a building. Pressures at certain locations on a building surface seem to be affected, both in terms of mean and root-mean-square pressure levels. This leads to concern over the applicability of contemporary wind tunnel results for window glass and curtain wall cladding design. (41)

Measurements of structural vibrations induced by wind permit estimates to be made of natural frequencies, mode shapes, and damping. Amplitudes of vibration can also be deduced, but to determine even an approximately correct estimate for the deflection including the drift (displacement in response to gusts that are long relative to building period) is extremely difficult. Nevertheless, a few estimates have been made and both wind tunnel evaluations of structural response and calculations using simple theoretical models seem to be consistent with estimates based on field measurements using accelerometers and seismometers in tall buildings.

In addition to the full-scale investigations reported in the bibliographic references, at least three other projects are in advanced stages of planning or instrumentation as follows: Georgia Institute of Technology, three buildings ranging from 290 feet to 375 feet in downtown Atlanta are being instrumented to record surface pressures, structural strains, building acceleration, velocities and displacements, in addition to reference wind velocity; Escola de Engenharia da UFRGS, Porto Alegre, Brazil, a 353-foot-high reinforced concrete building will be used to measure displacement, acceleration, strain, surface pressures and reference wind velocity; Division of Building Research, National Research

Council of Canada, a 784-foot-high steel-frame office tower is being instrumented to measure wind pressures at four levels, strain and reference wind velocity.

4. DEVELOPMENT OF WIND TUNNEL TECHNIQUES FOR BUILDING AERODYNAMICS

Although much development work has been done in the past ten years on specialized instrumentation, apparatus and techniques for studying wind effects on structures in the earth's surface boundary layer, the main portion of aerodynamic information used by designers is still based on tests done in low-turbulence, uniform-velocity fields. Unfortunately, even under such supposedly reproducible conditions, significant discrepancies have been discovered among comparable test results from different institutions. This fact underlines the necessity for a painstaking approach to the definition and fulfilment of modelling requirements. (30, 31, 37)

The major innovation required for studying the structural behavior of tall, slender buildings is to model the approaching flow to achieve an appropriate scaling of wind structure, in particular the mean wind profile and the turbulence properties. Various techniques have been investigated to produce the required turbulent shear flow, including curved screens, coarse grids, horizontal graded rods with increasing density near the tunnel floor, vertical spires, and others. (33, 34, 35, 36, 38, 39) One of the more promising techniques has been the use of a boundary layer wind tunnel. A typical boundary layer wind tunnel has a long upwind section, the floor of which is coated with roughness elements to develop a boundary layer with the desired scale properties and sufficient depth for testing purposes by the time the working section is reached. (32) (See Figs. 1 - 4.)

The degree of success achieved in simulating surface winds is gauged by comparing power law profile exponents, velocity spectra, and scales and intensities of turbulence, with data gathered in field experiments. Usually it is implied that if certain fundamental features of the flow coincide with field measurements, other properties of the flow that have not been compared also have a reasonable chance of being in agreement. In fact, no definitive statement has yet been made as to what constitutes a properly modelled shear flow to represent the entire atmospheric boundary layer. In the case of a very rough terrain, such as the centre of a city, the building under consideration tends to be of comparable height to the roughness and it seems probable that some of the more theoretical requirements will be swamped by other considerations, for example, wake interference effects among the various members of a grouping of buildings. (40)

Measurements on a model in a turbulent shear flow resemble field measurements more closely than do smooth flow studies and generally it is concluded that the fluctuating effects of wind cannot be ignored.

A wind tunnel study of a tall, slender, office tower involves at least two or three phases. In one, a partial aero-elastic model, usually with only two degrees

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FULL-SCALE INVESTIGATIONS OF WIND ACTION ON TALL BUILDINGS

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of freedom, is tested, since most of the building response to strong winds is usually confined to the fundamental mode. Parameters such as instantaneous bending moment, or tip deflections in the x- and y-directions are recorded for a range of wind speeds, directions, building frequencies and damping to obtain design parameters for the structure as a whole.

A second distinct phase of wind tunnel testing to assist in the design process involves a rigid, pressure-tapped model. This model is used to determine the envelope of maximum positive and negative pressures over the building surfaces for the whole range of possible wind directions for use in the design of glass and cladding.

Research is just beginning into the details of pressure patterns over building surfaces. It appears that modelling rules may need further refinement, and that scaling effects may occur in relation to flows along a building surface. One possible outcome of such investigations may be the use of a different length scale for surface details such as mullions than for the building as a whole. The interaction of turbulence in the oncoming flow with the turbulence and flow distortion produced on the building surface at separation and reattachment lines has yet to be explored, but there are indications of significant increases in the severity of surface pressure fluctuations. (38, 41)

A third important aspect to the problem of synthesizing design data is the integration of aerodynamic coefficients with meteorological information. Often a model of extremely small scale is tested to permit a correlation to be made between wind structure at the site and wind structure at the nearest meteorological station. Local topographical features may result in sizable modifications in wind velocity and turbulence characteristics.

A further refinement becomes possible if enough climatological data are available to define the probability distribution of wind speed as a function of direction; in computing the probability of exceeding a given response (say, tip deflection), the directional properties of both the structure and the wind for the site can be taken into account. In general, structural response depends on the angle of attack of the wind. This dependence can arise either from a variation of structural properties such as stiffness or damping or from the variation of aerodynamic effects (surface pressures, vortex shedding, aerodynamic damping, etc.) as a function of wind direction. As far as the wind itself is concerned, climatological evidence coupled with a knowledge of local topographical effects might permit a more accurate assessment of risk levels for the attainment of a given wind force by taking prevailing strong wind directions into account instead of taking the most critical direction for each design aspect regardless of the reduced probability of the combination of a strong wind and a particular wind direction.

5. SIMPLIFIED THEORETICAL MODELS OF WIND EFFECTS ON TALL BUILDINGS

Analytical methods based on the same statistical concepts that are basic to the wind tunnel approach have been developed to compute the structural response of tall, slender structures. (42, 43, 44) These methods make use of available field data on wind structure, and comparisons of measurements in wind tunnels and on real buildings with analytical predictions have shown satisfactory agreement.

The basis for the simplified analytical approach is to consider the wind loading to be a stationary Gaussian process for which the mean and variance of the approaching wind can be obtained, along with estimates of the correlation, between any two points on the structure as a function of the distance between them. The power spectrum of the input loading is calculated as the product of the spectrum of the free wind velocity and a transfer function (called aerodynamic admittance) appropriate for the building in question. The spectrum of the output parameter of interest, say tip displacement, is then found by multiplying the input loading spectrum by the mechanical admittance of the structure (the dynamic amplification as a function of frequency). The area under the output spectrum then gives the variance of the output parameter, so that both the mean and variance are defined. This allows an estimate to be made, for example, of the expected maximum deflection during a storm of a given duration. (45, 46) The result is usually expressed as a gust loading factor to be multiplied by the mean loading to give the equivalent static design value.

These simplified analytical procedures for assessing the contribution of wind turbulence to building response are in the latest editions of building codes in both Canada and the United States. Unfortunately, there is as yet no similarly satisfactory extension for use in cladding design that takes into account the effects of turbulence on local pressures. This is largely due to the complexity of local pressure fluctuations generated by flow separation and reattachment over the surfaces of a building.

6. CONCLUDING REMARKS

The advances achieved in the past ten years have been remarkable not only in terms of a better understanding of wind phenomena, but also in terms of refined design methods and more sophisticated design criteria. In other words, not only has knowledge been acquired, it has been put to work in design and construction practices. The amount and extent of pertinent research is increasing, so much so that there is now a serious need to provide for coordination of efforts and sharing of results among researchers in a given area and from one area to another.

Recognizing the need for coordination and organization of research efforts, the National Science Foundation of the United States sponsored a conference at Pasadena, California in December, 1970 which resulted in the formation of the Wind Engineering Research Council. (47) The main conclusions drawn at this

conference stressed the desirability of a) interdisciplinary approaches (structural engineers, aerodynamicists, and meteorologists), b) meteorological studies directly related to engineering needs rather than forecasting type problems, with emphasis on studies of strong winds, statistical aspects and topographical influences, c) documentation of correlations between model and full-scale research as well as "standard building model" comparative testing among different wind tunnel facilities, d) long-term studies on full-scale structures for the purpose of establishing probability distributions of extreme loads and evaluating the effects of repeated loads, and e) the free and timely distribution of test data, both model and prototype.

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