SUMMARY REPORT

CONFERENCE ON WIND LOADS ON STRUCTURES

Held At

California Institute of Technology

Pasadena, California

December 18-19, 1970

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ORGANIZING COMMITTEE

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TORNADO PATH THROUGH BUSINESS SECTION OF INVERNESS, MISS.
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I. INTRODUCTION AND SUMMARY

An understanding of wind loading on structures is important for their economic design, increasingly so as high-rise construction activities increase and as design improvements lead to lighter and more flexible structures. Equally or more important is the problem of safety and protection from disastrous winds such as hurricanes and tornadoes. In this and in other aspects, there is an analogy with the problem of earthquake engineering. For example, there is the statistical nature of the loading, and the unpredictability of the occurrence (but the latter problem is not as difficult as for earthquakes, and questions of protection may be different).

Reminders of the seriousness of the problem of wind damage are constantly with us. Within the past year, three major storms, the Lubbock Tornado, Hurricane Celia and the Mississippi delta tornadoes of last February left over 100 dead, thousands injured and property damage totaling almost a billion dollars. Other, less spectacular storms add constantly to the toll.

While there are a number of individuals and groups in the U.S. who are active in research related to wind engineering problems, there has not been a national picture of vigorous research activity such as exists in some other branches of engineering. More active groups in the field are found in other countries, e.g., the United Kingdom, Canada and Japan. Practicing engineers seeking information, advice or other aid for their problems of design for wind are often at a loss as to where to find it. On the other hand, there is in fact a considerable amount of activity in the country, but it has tended to lack coherence and visibility.

Several people amongst whom the problem was discussed during the past year or more agreed that there was a need for examination of the situation from a national viewpoint and that a conference should be the first step. The National Science Foundation, through the office of Dr. Michael P. Gaus, agreed to sponsor the conference, and it was held at the California Institute of Technology on Friday and Saturday, December 18-19, 1970. This report is an account of that conference and its results.

To keep the conference size small enough for it to have a working atmosphere, and in keeping with the emphasis on research aspects, an effort was made to inform all university people known to be interested, but no attempt was made to have comprehensive representation from government agencies and engineering firms. It was estimated that the total attendance might reach 50, but in the event about 115 attended the meeting. Many more wanted to come, but were prevented by lack of travel funds, lack of time or lack of information about it. In addition to U.S. workers, a number of Canadians were invited to attend, taking advantage of their physical proximity and of other close ties in professional societies, etc.

The announced objectives of the Conference were: a) to identify and acquaint those interested in solving the problems of wind on structures; b) to learn the nature and scope of work presently underway; c) to discuss the various aspects of the wind engineering problem such as aerodynamics of bluff bodies, dynamic interaction of wind and structures, laboratory and field experimental work, wind forces and the design of structures, design criteria and codes, tornadoes and hurricanes; d) to consider the formation of a Universities Council on Wind Problems which could serve to identify the field and to provide continuity; e) to lay plans for the preparation of a comprehensive report on wind problems and research similar to the National Academy of Engineering Report on Earthquake Engineering Research; f) to prepare a summary report of the proceedings and findings of the Conference.

To try to realize those objectives in a two-day meeting, the following format for the program was adopted.

1) At three joint sessions of all participants, 41 individuals gave short accounts (varying in time from 5 to 10 minutes) of their research interests, activities and views. Detailed research results were not requested nor encouraged, the aim being to delineate the broad picture of research activity in the country.

2) Two other sessions were devoted to meetings of seven committees or discussion groups that were organized to discuss and report on the following areas: Public Safety and Protection, Tornadoes and Hurricanes, Meteorology and Climatology, Stochastic Methods, Structural Analysis and Design, Aerodynamics and Aeroelasticity and Wind-Tunnel and Full-Scale Investigations. All participants in the Conference were assigned to one of the committees. Because of the varied and multiple interests, some migration between committees occurred, and was encouraged. Brief reports from the chairmen of these committees were heard at the general discussion session of the Conference. More complete accounts, prepared jointly by the chairmen and co-chairmen after the Conference, are given in Part II of this report.

3) Brief written accounts of their interests and work were solicited from all the participants. These are collected in Part III. They include contributions from the speakers in the general sessions, and also from a number of persons who could not be accommodated in the tight program or who could not attend the Conference.

The Conference closed with a short business session at which the following steps were taken.

It was agreed that the Organizing Committee become the Steering Committee for a new Wind Engineering Research Council, with A. Roshko as Chairman and R. A. Parmelee of Northwestern University as Secretary. G. W. Reynolds of Utah State University also joined the Committee. A name with a connotation somewhat more general than that of "wind loading" was chosen when it became apparent that problems and interests are considerably broader. Problems include such diverse ones as ventilation, pollutant dispersal, environments in plazas, entryways, city streets. As one participant put it, "there are wind effects on structures but also of structures". It was decided not to include the name "universities" in the designation because research interests and activities in wind engineering extend considerably beyond the university community. In this respect, the field is somewhat different from that of earthquake research, which provided some precedents for this Conference.

Possible tasks for the Steering Committee include the following. 1) To formulate the future form and function of the Wind Engineering Research Council. 2) To consider how best to implement the desirability, much in evidence at the meeting, for continuing exchange of information and ideas amongst workers in the various disciplines related to wind engineering. 3) To consider what form future meetings might take. 4) To bring into focus problems that most urgently need research, possibly undertaking the preparation of a comprehensive report.

To summarize, the Organizing Committee was encouraged by the large and enthusiastic response of people interested in wind engineering research. There appears to be a real need and desire for better communication amongst workers in the different disciplines, and even amongst those in closely related subjects. The short papers presented at the meeting and included in this report are a representative but by no means comprehensive view of work in progress. The committee reports are an initial effort to define the areas most in need of additional research. No attempt will be made here to further summarize these findings.

It is hoped that this report will serve as a useful reference for those who participated in the meeting and a source of information for those who could not attend, and that the steps taken at the Conference will help to further clarify the needs and encourage cooperation in research on wind engineering problems.

A. Roshko
Secretary to the Conference

II. REPORTS ON DISCUSSIONS IN COMMITTEES

Each discussion group (Committee) was guided by a chairman and co-chairman, who also undertook to prepare a report summarizing the discussions and recommendations of their committee. Their reports were prepared after the Conference, largely by correspondence and, in some cases, incorporated further comments and suggestions by other participants.

The participants in the various committees are not listed since an accurate record of participation, which had been somewhat mobile, was not kept in all cases. The names of the chairman and co-chairman are given at the end of each report.

In the next pages, the committee reports are presented in the following order of topics.

Public Safety and Protection
Tornadoes and Hurricanes
Meteorology and Climatology
Stochastic Methods
Structural Analysis and Design
Aerodynamics and Aeroelasticity
Wind-Tunnel and Full-Scale Investigations

Summary of Discussions in the Committee

on

PUBLIC SAFETY AND PROTECTION

Introduction

The importance of designing against wind effects to provide for the safety and protection of the public was highlighted in 1970 by the Lubbock Tornado and by Hurricane Celia. In Lubbock 26 people were killed, 2,000 people were injured, and approximately $135,000,000 in damage occurred.* In the Corpus Christi, Texas, area 12 were killed, 1,000 injured, and the damage exceeded $500,000,000.† The impact of these storms on structures is summarized in Table I. As our population increases and population centers expand in size and number, it can be expected that the yearly incidences of significant wind damage will increase. It is imperative that the technical professions, constructors, universities, and governmental groups join together to undertake the required research, and to provide the design guidance required to achieve an optimum level of public safety and resistance to property damage.

TABLE I

SUMMARY OF STRUCTURES DAMAGED AND DESTROYED FROM MAJOR 1970 WINDSTORMS

	Lubbock Storm May 11, 1970	Hurricane Celia August 3, 1970
Residential Structures: (major damage or destroyed)	9,916*	22,800†
Commercial Structures: (small businesses, office buildings, industrial buildings, warehouses) (major damage or destroyed)	600*	562†

The following key recommendations are the outgrowth of the deliberations of the Committee on Public Safety and Protection; each recommendation is described in more detail in sections following the list:

1. A comprehensive program of development and installation of instru-

*Thompson, J. N., Kiesling, E. W., and Goldman, J. L., "The Lubbock Storm of May 11, 1970," National Academy of Sciences (for the National Academy of Engineering), Washington, D. C., 1970

†Barron (Ed.), ". . . and Celia Was Her Name," Boone Publications Inc., Lubbock, Texas, 1970.

mentation for measuring the loadings and response of selected types of structures, and for recording meteorological data, should be carried forward.

2. Post-storm inspections and studies should be carried out, followed by comprehensive reporting. In addition to a description and analysis of the physical damage, economic analysis should be conducted to provide the best basis for future planning and design.
3. Codes and specifications should be updated to reflect the best information available on loadings, on guides to provide resistance and protection from the wind, and on performance standards (including human comfort). Careful attention should be given to detail to insure the applicability of the codes, their acceptance, and enforcement of standards which are not less than the code.
4. Continuing effort should be expended to improve even further our forecasting of severe storms, and their areas of traverse. Better warning systems are badly needed. Design guides and criteria, to supplement codes, should be prepared and made available to the profession.
5. Further attention should be given to development of control, operations and management, before and during severe storms, and to development of recovery plans and stockpiling of supplies for recovery operations in the event of natural disasters.
6. The liability considerations associated with the design of structures to resist wind and other natural disasters should be clearly delineated. Also the basis for insurance protection against wind damage should be broadened.
7. A national data center should be established to provide a central base for obtaining information about meteorological storm data, storm damage and economic data, codes, design guides, regional planning and other items pertinent to providing a base for protection against natural disasters.
8. A research group should be organized to monitor and promote storm research with the goal of improving forecasting, design practice, recovery, etc.
9. National and international cooperation should be carried forward to the fullest extent possible to provide a basis for protection from natural hazards.
10. A comprehensive program of education should be developed for practicing engineers, architects, builders, contractors and code authorities, as well as for students, to present continually updated knowledge for design and planning aginst natural disasters.

1. Instrumentation

Instrumentation installed before storms occur, and measurements taken during storms, will prove in the future to be one of the most valuable sources of information for carrying forward research studies and for preparing design guides to reduce wind damage. Instrumentation for measuring wind loadings and structural response should be mounted on selected types of low- and high-rise structures for research purposes. In certain instances interference drag studies should be made where groups of buildings are clustered together.

At the same time there should be instituted a comprehensive program of measurement of meteorological data at various altitudes and locations as required. It may be possible to achieve some of these objectives to the degree required by the use of inexpensive instrumentation. Attention should be given also to possible photographic means of obtaining information on wind loadings and response.

2. Assessment of wind damage

A comprehensive program of post-storm inspection should be carried out along the line of that begun for several recent hurricanes and tornadoes. Such studies can be carried out under auspices of the NAE/NSF natural disaster survey arrangement and should be complemented by surveys sponsored by industrial organizations, governmental agencies, etc. Attempts must be made to obtain "perishable evidence" (that is, evidence which will be cleaned up almost immediately during the recovery phase after the storm) in order to be sure that certain valuable information is not lost. The goal of these inspections should be the factual reporting of data for future analysis -- a comprehensive survey will involve a team effort of engineers, architects, meteorologists, economists and others as required.

The studies carried out following major wind damage should involve not only an analysis of the physical damage but also should encompass an economic analysis of the storms, to provide a basis for other studies such as those involving recovery, insurance aspects, planning and design. Such studies should in part be concerned with the benefit-cost ratio analyses for providing various types of protection, and should be based on cost information involving such factors as loss of life, injuries, SBA loans, insurance company data, crop damage, lack of restarts in business, excess expense to those whose homes were lost or damaged, and other factors which result from storms. No such comprehensive studies have been carried out to date to our knowledge. Such studies would be of great value in developing and adjusting risk analysis evaluations, and in planning efforts.

3. Codes and specifications

Codes and specifications which affect the design and construction of structures which house the public, as well as critical facilities (such as nuclear reactors, power plants, chemical industries, etc.) should be reviewed and upgraded as necessary to insure that the best design practice is reflected in such documents. Such codes must encompass provisions relating to both loading and resistance, as well as performance aspects, and should include consideration of human comfort factors. Guidance should be provided for risk analysis and benefit-cost ratio studies, which may be pertinent to design, to the extent possible through supporting commentaries or other documents.

Codes, whether they be national, regional or state codes, are only as good as their acceptance for use in practice and their enforcement. Every attempt should be made to provide codes and design guides which are acceptable to both the private building sector, and governmental groups. Also more attention should be given to regional planning and zoning, to preclude placing of critical structures of housing developments in high-risk areas of damage such as that which might arise from tidal surge and wave action near shores.

4. Protection from wind and storms

The U. S. weather forecasting system, which has definitely improved in recent years, has indeed led to a significant decrease in loss of life from severe storms. In spite of the improvements in the forecasting situation, there appears to be an increasing amount of property loss, in part because of the increasing population and the spread of the population centers. Additional improvement in the forecasting of severe storms and their areas of traverse is still in order, especially in the case of tornadoes and highly turbulent winds. A better warning system is also called for. The goal is to minimize even further the loss of life from such storms, and to provide a basis for significantly reducing the property damage.

Every effort should be made through research and other means to arrive at rational design criteria and design guides, which can be made available to designers. Such guides should be developed to supplement codes, and to provide a basis for design in special applications where codes are not applicable. These guides should be concerned with not only the purely load-strength aspects of the design but should be addressed to such items as the effects of windborne debris, environmental effects on surrounding areas, interactive effects between buildings and the surrounding environment, and human comfort.

5. Post-storm recovery

As part of a national plan for recovery from all types of disasters involving natural hazards, it is recommended that national plans go forward for consideration of control and operations during storms and recovery immediately thereafter. Such activity should be coordinated through federal, state and local governmental groups, with assistance from other units and organizations as required. The recent recovery operations associated with the Fairbanks, Alaska, earthquake of 1964, Hurricane Camille of 1969, the Lubbock, Texas, tornado of 1970, and Hurricane Celia of 1970, suggest that our developments in this area are improving but can be accelerated with assignment of proper national priorities.

6. Liability and insurance considerations

With the increasing population base and areas covered by man-made structures, the matter of liability of those owning, constructing and designing structures needs to be examined more realistically in terms of social and personal liability implications. Owners and builders should be fully informed of their responsibilities with regard to public safety and protection, as well as liability, and the results of damage to their structures and the surrounding environment in the event their facilities receive damage. Recent lawsuits of downwind parties against upwind parties, as a result of damage sustained, suggest that much more attention must be devoted in the future to effects on surroundings.

One of the principal pressures for improved design and construction practice to preclude damage from wind will be that of improving the base for insurance underwriting in order to provide for insurance, when desired, against major catastrophes. It is hoped that the insurance industry will cooperate along with other cognizant groups in aiding with design research required to provide an insurance base for our country's facilities and structures.

7. National data

A national information and data center should be established to insure that meteorological data, storm damage and economic data, codes, design guides, regional planning documents, and other items pertinent to providing a base of protection against natural disasters can be accumulated in one place for use by government, university and private industry investigators. The importance of such a center is underlined by the fact that in recent years funding for handling of data and provision of instrumentation and other factors have not changed much.

8. Research

It is suggested that the Wind Engineering Research Council formed at this Conference be broadly organized to include the various professions and disciplines insofar as possible to insure the desired input is obtained. Such a group should draw on the various governmental agencies, national academies, and industrial groups, as appropriate, to provide a base for a strong research program to provide protection from severe storms.

9. National and international cooperation

In line with providing a basis for ongoing research and improvement in design guides, codes and specifications, planning, and other factors relative to improved wind design, it is recommended that every effort be made to foster cooperation among national and international groups to have an input to the problem. More than this, the cooperation should be broad-based in the sense of close cooperation between various disciplines such as that relating to earthquake, flood and other natural and dynamic hazards (including man-made explosions). In the long run, then, the basis for design and protection should be an all encompassing effort involving protection from natural and dynamic hazards in general.

10. Education

There should be undertaken, in conjunction with a forward-going program of research and improved design practice, a comprehensive program of education. This program should be directed to engineers, architects, builders, contractors, code authorities, and the general public, as well as students. Such an educational program should be presented for protection against natural hazards in general, of which wind would be one significant item. The aspect of education is extremely important in terms of gaining acceptance of design code provisions, and improvements in practice.

Chairman: W. J. Hall, University of Illinois
Co-chairman: E. W. Kiesling, Texas Tech University

Summary of Discussions in the Committee

on

TORNADOES AND HURRICANES

The prediction of the path, intensity, and lifetime of tornadoes and tropical cyclones (hurricanes) is a goal of great national importance to life and property, and study and experimentation are proceeding in these areas. In addition, efforts are underway by NOAA and DOD to modify the intensity of hurricanes by seeding. The purpose of this brief committee report is to highlight the areas of research which are relevant to wind effects on structures, describe the current status of knowledge in these areas, and to recommend further research and other activities directed toward improving our knowledge of severe storm phenomena in terms of improved design guides.

Since the lifetime of hurricanes is measured in terms of many days or weeks, whereas the tornado's lifetime is measured in terms of minutes or hours, data on maximum wind speeds, pressure distributions, size, etc., are much more voluminous and reliable for hurricanes than tornadoes. Improvements in knowledge for hurricane wind speeds are limited only in terms of data collection techniques and sensors, whereas the limitations for tornadoes are the result of their elusive character. An exception to this is the recent work at the National Hurricane Center in probing and photographing waterspouts, which appear to embody the essential properties of tornadoes and occur over water. Thus, methods for pinpoint forecasting would be required in order to gather data on tornadoes. The alternative would have to be a sensor system which could be delivered in the matter of minutes over great distances. The latter approach, for example, would require something like a radar-dispatched rocket system (very expensive) located near tornado-prone regions. For the near term, a combination of theoretical and laboratory models, photographic data on funnel clouds of tornadoes, and damage assessment can be utilized to estimate bounds for wind speeds and other related data on tornadoes. The previous discussion is not intended to leave the impression that mere knowledge of wind-speed distribution implies knowledge of the inception and behavior of either tornadoes or hurricanes.

The effective radial extent of a tornado is usually less that a mile, and often it is less than a few hundred feet, whereas the hurricane system is measured in terms of tens and hundreds of miles. This, combined with translation speeds from ten to sixty miles per hour (the higher values for tornadoes), means that the rate of pressure reduction becomes a design factor for buildings in a tornado path, whereas this is not the case for hurricanes. The crucial item for hurricanes is the reliable prediction of path with sufficient lead time to batten down structures. At the present time this capability provides a 24-hour prediction with an accuracy of nearly 75 nautical miles (1970) and long-term averages 50% higher. During this time the storm system has moved between 200 to 300 miles. It would be desirable to improve this accuracy to ± 50 miles or better. The National Hurricane Center has five models for path prediction (two statistical and three dynamical) and has worked out criteria for the selection of the appropriate model. While the reliability of the prediction method has been high, there have been notable breakdowns in accuracy.

A very vital phenomenon associated with hurricanes is the sea-state that results from the high wind speed. Recent experience of Hurricane Camille in the U.S.A., of the Bay of Bengal tropical cyclone in Pakistan and of the one in Mozambique attest to the utter devastation of life and property due to the sea surge. While considerable research could add much knowledge to the area, it was felt by the committee that predictions of sea states resulting from hurricanes are quite good.

The prospects of modifying hurricanes (diminishing intensity or changing path) while not an immediate possibility does bear upon the future importance of hurricane effects on structures. Even more remote would be the possibility of modifying tornadoes. Recent seeding experiments with silver iodide performed under Project Stormfury by NHRL on Hurricane Debbie have produced results which have been interpreted (with cautious optimism) as producing measurable reduction in the wind speeds as inferred by measured pressure increases near the center of the storm. The development of optimum seeding strategies can be guided by numerical simulation (computer models) of hurricanes. The answer to the question of seeding having any significant effect at all could be materially improved by the joint efforts of field experiments and computer simulations. The question of atmospheric contamination while not of consequence to structures is of ecological importance and should be considered.

The major research area then for severe storms in relation to wind effects on structures is the study of tornadoes. Recent theoretical studies utilizing photographs of tornado and waterspout funnel clouds, correlated in some cases with some speed estimates from motion pictures of waterspouts, seem to indicate maximum tangential wind speeds of 200 mph or less for most of the tornado examples studied. These values are not conclusive nor universally accepted. The committee felt that we need to do sufficient research to describe the space gradients of speed and pressure both vertically and horizontally and the behavior with time of these quantities for tornadoes. This is also true of hurricanes but to a lesser degree. Since waterspouts are numerous and readily observed near the Florida Keys, field work with airplanes and sensors should be continued since much can be learned that is useful to the theoretical modeler of tornadoes. In the case of the less predictable land-locked tornadoes, the public should be encouraged to photograph funnels and make the photographs available to the researchers in the field. Laboratory models are an important part of the research. Since a swirling funnel can be produced by draining a tank of water, the relevance of parameters of the lab models to the atmosphere need to be clearly demonstrated. An important study area for tornadoes is in the ability of hurricanes to spawn tornadoes. In this regard, the duration and intensity of hurricanes as they move inland is a relevant question. Another important area for study is the gusting of winds above an average maximum speed. Preliminary analyses of photographic data indicate that there could be a natural variation of speed with time which, if fast enough, could be interpreted as gustiness. The role of the boundary layer for both tornadoes and hurricanes is being analyzed by theory and laboratory models. The usefulness of a wind tunnel in this regard should be examined and could be a very useful experimental tool.

It is felt that we have reached a plateau in tornado forecasting, are really forecasting only the intensity of a thunderstorm, and further improvement in tornado forecasts can only be realized by additional work in this field. The committee felt that the funding level for research on tornadoes be increased by an order of magnitude, that is, from a few hundred thousand dollars a year to a few million dollars annually. This would include experimental work on waterspouts, analysis of photographs, laboratory and theoretical modeling, and the formation of interdisciplinary field teams (part of a National Disaster Institute) to move quickly into a tornado disaster area to assess the damage for useful data relating to intensity and extent. The picture of a twisted sign post is evidence enough to indicate that the evaluation requires a meteorologist, an aerodynamicist, and a structural engineer. Since there will be interfacing with city officials and distraught citizens, members of the team should include people with legal and social science background.

One of the characteristics of research in tornadoes and hurricanes is the fact (not uncommon to other fields) that many independent agencies, institutions, and companies are studying bits and pieces of the problem under many small contracts. It is recommended that NSF fund a review group to prepare a single document concerning the status of this work, its relevance, and recommendations for better coordination, nationally, of all this activity. Again, while major participation would be by meteorologists, the structures and aerodynamics disciplines should be represented. Among the output would be intensity criteria, the classification of other related phenomena such as fire storms, Chinook and Santa Ana winds.

At the present time the AEC nuclear reactor installations need this data most desperately and would actually utilize it in building design. Eventually this data would be available in the form of design criteria and could influence other major building designs. The documentation and dissemination of definitive information would influence the building industry as a whole to utilize data on intense winds.

As a final summary, the specific recommendations are listed below:

1. Improve the forecasting of hurricane paths.
2. Establish the modification effects of seeding hurricanes by a combined effort of field experiments and computer simulations.
3. Investigate the economic feasibility of a sensor system for gathering data on actual tornadoes.
4. Encourage the public to take pictures, especially moving pictures, of tornadoes and make them available to experts in the field.
5. Continue and expand the joint efforts of meteorologists and engineers to gather observational data on real tornadoes, such as that from photographs, damage inspection and field work on waterspouts.
6. Fund a review group to prepare a single document concerning our knowledge of tornadoes and hurricanes and the relevance of this knowledge to structural design problems.
7. Form an interdisciplinary field team (as part of a National Disaster Institute) to assess wind damage for useful data relating to tornadoes and hurricanes.

Chairman: Paul Dergarabedian, TRW Systems

Co-chairman: Tony Maxworthy, University of Southern California

Summary of Discussions in the Committee

on

METEOROLOGY AND CLIMATOLOGY

1. Wind Profiles Above the Roughness Elements in Stationary Flow.

A. Introduction

For the purpose of this discussion we divide the lower atmosphere into three regions: The surface layer up to about 100 feet, the "tower layer", up to about 500 feet, and the planetary boundary layer up to about 3000 feet.

In the surface layer, the horizontal stress can be regarded as constant height; in the tower layer the wind direction is nearly constant with height, except in very stable air (Richardson number $> .15$); and in the planetary boundary layer above 500 feet the wind speed changes little with height but the wind vector usually turns clockwise with height in the northern hemisphere.

B. The Surface Layer

The wind profiles in the surface layer are quite well understood over homogeneous terrain. For most purposes the terrain can be assumed homogeneous if the upwind fetch is over a uniform surface to a distance about 20 times the height.

Over uniform terrain the surface layer profiles are completely described by the terrain roughness length, the surface stress and a quantity related to the vertical temperature distribution, such as the vertical heat flux or the Richardson number. The actual equations, though well understood, are quite complex; and particularly in view of the relatively rare occurrence of homogeneous terrain, it is not often desirable to use these expressions in calculations of wind loads. Instead an engineering approximation of the form

$$\frac{V}{V_1} = \left[\frac{Z}{Z_1}\right]^P \tag{1}$$

is quite adequate. Here V and V_1 are the winds at heights Z and Z_1. P is a variable quantity for which quite good estimates can be made from meteorological theory. For example, in strong winds P is $(LN\ \bar{Z}/Z_0)$ where $\bar{Z}$ is the geometric mean height over which the law is to be applied and Z_0 is the roughness length, which is typically a few inches over flat country, 1-2 feet over the suburb and 10 feet or so in downtown areas. In unstable air (temperature rapidly decreasing with height, or $Ri < .10$), P becomes smaller.

Only one form of heterogeneous terrain has been studied so far, a change of roughness along a line at right angles to the air flow. The results are most reliable in strong winds ($Ri \sim 0$), and still qualitatively accurate in unstable air. In particular, a terrain change produces an internal boundary layer causing kinks in wind profiles. The height and strength of these kinks can be estimated accurately and can be taken into account in calculations of loads. Unfortunately, such simple geometry is rare. The theory is also still valid more qualitatively above the surface layer. As an approximate rule of thumb, the kink in the wind profile occurs at a height about one tenth of the distance to the roughness change.

C. <u>The Tower Layer</u>

Various models for wind profiles in the tower layer now exist. It is clear that wind speeds above the surface layer are faster than those expected by extrapolating vertically the formulae used in the surface layer. Similarly, P in equation 1 is somewhat larger than expected from that equation. It is known that the Coriolis force begins to influence the profile and the general form of the equations has been determined. However, the equations contain one or more coefficients which are not well known, and the exact determinations of which are essential.

D. <u>The Planetary Boundary Layer</u>

Above the tower layer, the wind speed can be assumed independent of height under many conditions. If horizontal temperature gradients are strong, corrections to this assumption can be estimated. Also, in very stable air, wind shears can be large (especially between midnight and morning). It remains to be determined whether this effect is important for very tall structures (higher than 500 feet).

Also above the tower layer, the wind turns clockwise by about 1° every 100 feet, but this number is quite variable, and can, if needed, be estimated from basic theory.

2. <u>Spectra in Stationary Flow</u>

A. <u>Wind Speed</u>

The spectra of wind speed are well determined for frequencies (cps)

$$N \geq \frac{0.2V}{Z} \tag{2}$$

where V is the mean wind speed at height Z over an hour or so. Usually this range covers most of the frequencies of importance for structures.

The spectrum is then given by

$$S(N) = 1.14\ E^{2/3}\ N^{-5/3} V^{2/3} \tag{3}$$

Here E is the dissipation of turbulent energy into heat. In order to use equation 3 in practice, E must be estimated from easily available parameters. Such estimates are usually based on the turbulent energy budget, which is still controversial. Additional measurements of the components of the energy budget are <u>urgently</u> <u>needed</u>.

Still, in strong winds (small Richardson numbers), the following estimate of E seems valid to 500 feet or so:

$$E = \frac{0.16\ V_1^{\ 3}}{Z(LN\ Z_1/Z_0)^3} \tag{4}$$

(Note that LN is the natural logarithm of X).

Here V_1 is the wind speed at a low height Z_1 corrections for unstable conditions (sunny periods) may be large, especially at high levels. These conditions also are quite well known.

For $N < 0.2V/Z$ the spectra of wind speed vary greatly from place to place, and much more work is required to understand these differences. For spectra down to $0.05V/Z$, equation 3 may be barely adequate and will overestimate the spectra somewhat.

B. <u>Lateral and Vertical Spectra</u>

For lateral spectra if $N > 0.4Z/V$, equation 3 applies, except that the 0.14 should be replaced by 0.18. For $N < 0.1Z/V$, the spectra become extremely sensitive to changes in stability, and estimates become uncertain.

For spectra of vertical velocity equation 3 with the constant 0.18 is valid only for $N < Z/V$. Fortunately, for lower frequencies, good estimates can be made (see Busch and Panofsky, 1968) from equations of the form

$$N\ S\ (N) = U_*^{\ 2} F(NZ/V,\ Ri) \tag{5}$$

where the friction velocity, U_*, can be obtained from wind profile theory. For details, see original paper. Suffice it to say here that enough is known about vertical velocity spectra to solve structural problems involving them where the terrain and flow can be treated as being homogeneous.

3. <u>Extreme Velocities</u>

Profiles of extreme velocities are often handled entirely empirically, separately for each location. More will be said about this later. However, known turbulence characteristics in the surface and tower layers can also lead to such estimates at locations where no special studies have been made.

The velocity which will exceed X % of one hour will be called

V_X. We now write:

$$V_X = V + N_X \sigma$$

where V is the one-hour mean velocity discussed earlier, σ is the standard deviation of velocity and N_X is a pure number depending on the probability X. Since velocity components are nearly Gaussian, but have kurtosis slightly larger than Gaussian, N_X should be slightly larger than the corresponding Gaussian value. More accurate work needs to be done in this matter, but, for example, if X = 0.5%, $N_X = 3.3$.

Up to 20 m height in strong winds, σ is well described by:

$$\sigma = \frac{V}{LN\ Z/Z_0} \tag{6}$$

At larger heights, σ's are slightly smaller.

Actually, for the same V, Z and Z_0, σ may vary in a not yet understood manner by 20% or so in either direction. This variation is probably larger than the systematic vertical variations throughout the tower layer.

Standard deviations of lateral and vertical velocities are about 85% and 50% of that of longitudinal velocity, in strong winds.

3. <u>Cospectra with Spatial Displacements</u>

Coherence and phase delay have apparently simpler properties than quadrature and cospectra, or than cross correlations. Given the first pair of statistics and the spectra the others can be found from basic relations. According to Davenport, the coherence (analogous to the square of a correlation coefficient) between like components of the wind is related to the non-dimensional frequency $N\Delta X_I/V$ by:

$$COH(N) = E^{-A_1\ N\Delta X_I/V} \tag{7}$$

Here A is a constant, and ΔX_I the displacement between the observing points in any of the three Cartesian directions. In strong winds, with the displacement at right angles to the wind, A_I is about 18. Since $N\Delta X_I/V$ is effectively the ratio of displacement to wave lengths, the coherence is substantial only if the wave length exceeds 10 times the separation. In unstable air (negative Ri) coherence generally increases. So far, information on these matter is spotty and needs much more investigation and virtually no information is available concerning the coherence phase delay between unlike components of the wind.

If the displacement is in the direction of the wind, A_I is much smaller and not well known; a value near 2π has been suggested.

The phase delay for optimum correlation signals at two points can be expressed by

$$S_i = \frac{1}{2\pi N \Delta X_i / V} \arctan\left[\frac{\text{quad }(N)}{\text{CO }(N)}\right] \qquad (8)$$

where quad (N) and CO (N) stand for quadrature and cospectra, respectively. The quantity S_i actually represents the ratio of the displacement in wind direction for optimum correlation, divided by the separation between stations. If the line connecting the stations lies in the wind direction, S_i must be one. In general, S_i appears to be not significantly affected by changing frequency N. For vertically separated observations, S_i is about one for the longitudinal and 2 for the lateral component of the wind, up to perhaps 200 feet. At greater heights, S_i decreases.

For horizontal separations at right angles to the wind, $S_i = 0$.

5. Other Relevant Properties

For more sophisticated applications to load problems, the spectrum of the square of the wind speed may be required. Kolmogorov's theory implies that this spectrum varies as $N^{-7/3}$, but observations suggest $N^{-5/3}$ law instead. The behavior of the coefficient in this relation has not yet been analyzed, but it appears to be proportional to $E^{2/3}\ \sigma^2$.

In many applications, wind fluctuations are assumed to be Gaussian. This is approximately true under neutral conditions (strong winds) though even then the kurtosis exceeds 3 by a small but significant amount. The kurtosis of time derivatives of wind components is huge, suggesting intermittence of the turbulent flow.

The skewness of the wind components is near zero in strong winds. In unstable air, the longitudinal components of the wind speed have significantly negative skewness, vertical winds are positively skewed (for experimental results, see Pries JAM 1970).

6. Statistical Wind Profiles

When sufficient data exist in the vertical (height of structure) and in time (a few years, say) it is possible to describe the wind profile statistically in such a way that the design wind profile is immediately specified once the engineer specifies the risk he is willing to accept of compromising the structure if the design wind condition occurs. The procedure is based on the climatological annual conditional distribution function of p in equation 1, where the conditionalizing parameter is the wind speed V_1 at the reference level which is located at the base or at the top of the structure. The engineer specifies two risks, namely (1) the risk he is willing to accept of exceeding the design wind speed at the reference level, and (2) the risk he is willing to accept of compromising the structure if the design wind speed should occur at the reference level. The first risk specifies V_1 through the appropriate climatological distribution function of V_1 and the second risk specifies the value of p consistent with the design wind speed V_1 at the reference level. The procedure can be used for mean wind speeds and for peak wind speeds over a given period, like one hour. In the case of the peak wind speed profile it is assumed that the peak wind speeds at the various levels in the vertical occur simultaneously. This assumption is somewhat conservative but not excessively so. If the peak wind speed profile is used then gust factors must be specified to obtain a mean wind speed in order to apply the available power spectral models of turbulence. Statistical wind profile descriptions of the wind in the atmospheric boundary layer are now being used by the National Aeronautics and Space Administration for the design of space vehicles. The procedure provides a rational approach to the design problem; however, the wind data from a number of levels over the vertical extent of the structure must be available in sufficient quantity (at least one year) to calculate the conditional distribution function of the parameter p.

A more detailed discussion of this approach can be found in Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development, 1969 Revision, National Aeronautics and Space Administration Technical Memorandum 53872 edited by Glenn Daniels.

7. Conclusions and Recommendations

The sections above show that considerable information exists about the mean wind and wind fluctuations under stationary conditions. Many of the most important effects of wind on structures occur with transient phenomena, such as thunderstorm gusts and tornadoes, or the wind may be very local as in the case of mountain winds. In these cases, time histories of winds must be studied empirically, and frequently local observations are required. The most significant recommendations discussed at the Committee Meeting were the following:

(1) High Velocity Winds. Much of the available data on the fine scale description of the wind is for low speeds. Indications are that the characteristics of turbulence may be quite different at speeds affecting the design of structures. Much more data is needed at such speeds.

(2) Stationarity Problems. Wind speed time series at high speeds appear to exhibit departures from stationarity which may be critical in the analysis of the data. Better statistical methods should be applied in analysis in order to assure that results are meaningful.

(3) High Frequency of Response. Wind speed observations are needed at higher frequencies down to one-tenth second or lower. The present available instrumentation is not capable of such observations. Some new instrumentation is needed.

(4) Channeling Effects. Some results are needed which can give some general answers. Although wind tunnel tests may be the answer in some cases after the problem of simulation of atmospheric turbulence has been solved, approximate analytical methods would be very useful.

(5) Monte Carlo Methods. There appears to be little doubt that Monte Carlo methods will eventually be applied to the weather factors (especially wind in structural design) because there is more and more interest in the total performance of structures. For this purpose, magnetic tapes of detailed observations will be needed especially under critical conditions. Those should be made available from observations proposed above.

(6) Meteorological Studies. Meteorologists devote almost all their efforts at present to real time or forecasting problems which are next to useless to engineers. They should devote more effort to the non-real time or climatological problems with special emphasis on the internal characteristics of storms which would assist in climatological interpretation where, unlike in forecasting, the prediction of what happens from time t to t + 1 is of little importance to the engineer.

(7) A survey report could be prepared which summarizes the existing meteorological knowledge which is relevant to an engineer.

(8) More information and communication with structural engineers on their needs and requirements is needed as there is a lack of expertise in general in bridging the fields of interest.

Chairman: Hans Panofsky, Pennsylvania State University

Co-chairman: Irving A. Singer, Brookhaven National Laboratory

Summary of Discussions in the Committee

on

STOCHASTIC METHODS

1. Structure-Related Problems

It is agreed that the major goal of stochastic analysis associated with wind loads on structures is to establish a reliability methodology or a methodology for risk analysis by which we can assess structural integrity and weigh economic consequences of possible structural damage under the wind environment. We expect that such a methodology will eventually be incorporated into design codes and thus into engineering practice. Such a methodology must reflect the current state of art of the reliability analysis and must be compatible with the quality as well as quantity of information available at present both on nature of wind loads and on dynamic characteristics of structures. We must recognize, however, that there are a number of distinct types of structures to be considered under different wind conditions. For example, high-rise buildings, smoke stacks, offshore or coastal structures, transmission towers, special structures such as a deep-space ground antenna and a space shuttle vehicle standing by for a take-off, etc. have their own unique wind-structure and/or wind-induced wave-structure interaction problems to be dealt with. Although some work has been done toward the establishment of such a methodology dealing with specific types of structures, a more unified study appears to be in urgent need.

In view of extensive studies carried out by climatologists on wind properties, hurricanes and tornadoes and studies carried out by engineers on wind effects on structures using wind tunnels as well as performing full-scale testing, we strongly feel that a considerable amount of pertinent information is already in existence without being fully utilized. It is recommended therefore that a coordinated effort be made to gather the data derivable from these studies that are useful in the reliability analysis. Such effort will hopefully result, for example, in code-oriented input data such as the mean and r.m.s. wind pressure at various locations and localities. At the same time, it is equally important to identify specific information needed for such a reliability analysis for future study. For example, it cannot be overemphasized that engineers need much more information on wind force distribution on the structure rather than on wind velocity distribution, suggesting the importance of full-scale testing including measurement of space correlation. The data thus obtained, particularly under turbulent conditions in urban areas, must be treated within a general framework of stochastic method. Also, statistical variability of observed parameters due to difference in site locations as well as due to different levels of storm intensity should carefully be studied.

Speaking now specifically about tall buildings, we feel that, given wind pressure distribution and its time history, our present analytical capability is adequate to perform dynamic analysis for the structural frame (1) for the purpose of evaluating response variables (such as acceleration spectrum) of building motion which can be used as a measure of phyco-physiological effect and (2) for the purpose of assessing, in first approximation, the over-all structural safety, particularly of asymmetric buildings.

We also feel that we have analytical capabilities (probabilistic as well as structural) to evaluate, in terms of probability failure, the safety of well defined structures such as transmission towers, and substructures such as window panes, if the excitation process is described as a stochastic process, whether stationary or nonstationary and whether Gaussian or non-Gaussian. It is therefore recommended that an immediate attempt be made to perform design-oriented reliability analysis for these well defined structures and substructures as a first major step toward the rational structural design under wind environments. This type of analysis appears particularly appropriate to problems associated with claddings to a structure. One of the major difficulties in such an attempt will most likely consist of high degrees of uncertainty involved in the stochastic process model as well as in parameters describing such a model. We must resolve such a difficulty at least in engineering sense, if the credibility and integrity of the reliability analysis is to be maintained.

It is pointed out that although failures of such items as window panes may not lead to a collapse of the structural frames, the damage can be catastrophic in order of magnitude in terms of dollars and possibly, human lives.

In performing such a reliability analysis, statistical nature of structural resistance must also be taken into consideration, since it is well known that yield strength of structural steel, fracture strength of window panes, strength of reinforced concrete, resistance of structural joints, fatigue resistance of most structural materials, etc. exhibit considerable statistical dispersion.

In passing, we state that the cross-correlation analysis, which is an analytical tool originally developed in conjunction with stochastic process theory, may be very useful for structural identification purposes and therefore it is recommended that an effort be made in this area.

In summary,it is emphasized that the immediate and essential contribution the stochastic methods can provide in structure-related wind problems consists of (1) the reevaluation of the traditional view of factor of safety in favor of incorporating dynamic considerations into design and (2) the establishment of specification of wind loads in terms of the probability distribution of surface pressure in an urban environment.

Finally, a word of optimism. The advanced warning for severe winds is increasingly reliable thus reducing the possibility of the loss of human lives. It is this fact, the committee felt, that present a unique and promising opportunity to the probabilistic approach for a wider recognition and adoption by the profession.

2. Non-Structural Problems

As to those problems not directly related to structures, we recognize for example, that stochastic methods are vital (1) to the air pollution problem involving statistical treatment of wind velocity, direction and their spacial distribution, (2) to the statistical treatment of terrain-wind interaction, (3) to the problem of air and heliport operation under gusty wind, and (4) to the statistical description of missile characteristics including their size, speed and origin.

3. A Comment on Engineering Education

In view of the growing importance of stochastic methods in civil engineering applications, particularly in those involving natural forces such as wind forces, it is recommended that an undergraduate or graduate course be established in civil engineering curriculum in which students will be exposed to the probabilistic and statistical methodology and the philosophy of structural reliability analysis associated with natural forces.

4. A Suggestion for a Future Conference

In a future conference, interaction of stochastics group with other specialities represented in the conference would be extremely helpful in exchanging ideas as well as in disseminating stochastic methodology of structural interest among climatologists and engineers attending the conference and eventually among practicing engineers.

Chairman: Masanobu Shinozuka, Columbia University

Co-chairman: Aushel Schiff, Purdue University

Summary of Discussions in the Committee

on

STRUCTURAL ANALYSIS AND DESIGN

Building codes tend to overemphasize the details of design requirements beyond the scope of knowledge concerning basic load data. The design profession is in need of a more complete description of wind loading on structures and their component parts. In addition, there is a need for more detailed information of local climatology in order to assist the engineer to properly design structures for a particular location. Today many designs for wind effects are based upon a thirty year return period. Possibly a longer return period should be used together with a lower load factor. The statistical approach to loading seems to be the most promising and realistic method.

Building codes are tremendously important and are very useful tools for the designer. Although simplicity is desirable for a building code, care must be taken to insure that this simplification does not lead to a gross misinterpretation; e.g., many persons interpret the "static equivalent wind loads" as maximum values which will never be exceeded. It is recommended that the codes should be reduced in size and detail, and that more supplemental and background material be placed in Commentaries which accompany the code.

Research into wind effects on structures that does not influence a code is nonproductive effort and can be likened to a dog chasing its tail. Research efforts should be directed toward broad classes of buildings rather than concentrating on specialized buildings.

A great deal of basic information regarding wind loading for tall buildings has been documented; however, it is not readily available in the open literature. Efforts should be made to correlate and publish these data so as to make them available for the design profession.

Although the level of confidence which can be placed on the results of wind tunnel tests is reported to be "rather good" for square edged structures, there is still a need for additional full-scale test results in order to correlate the data with that obtained from wind tunnel tests and thereby increase the level of confidence.

The designer of tall buildings is in need of additional information (with respect to wind effects) in the following areas:

1. Effect of surface roughness
2. Effect of shape of the building
3. Damping (structural and aerodynamic)

4. Design of cladding
5. Stack effect
6. Effect of the building on the world (and people) around it.

The proper evaluation of damping is an important and complicated problem. Tests have shown that damping is nonlinear and not really viscous. For the purpose of design, it would be desirable to be able to evaluate an equivalent value of damping for the structure when its materials are functioning at their working levels of stress.

The effects of interfloor drift are dependent upon the structural materials and construction techniques used, and therefore research into the establishment of a design criteria for this type of drift is not considered to be critical, especially since the data can become obsolete with the development of new materials and/or methods. In contrast, the effect of the total drift of the structure is considered to be of prime importance, since this is directly related to human perception of motion and occupancy comfort.

To date some tests have been conducted in an effort to establish limits of human perception of motion; however, the reports of these studies have not yet been released. It is hoped that these results will be published in the near future, and that additional research into this important topic will be undertaken. The design profession is in need of documentation and guidance concerning criteria for human perception of motion in buildings.

In summary, as currently practiced, the analysis and design of structures for wind effects is an art, and the designer must rely heavily on his "engineering judgment." A great deal of research is required to clarify the situation and provide the designer with simple, yet reliable, solutions.

Chairman: R. A. Parmelee, Northwestern University

Co-chairman: P. C. Jennings, California Institute of Technology

Summary of Discussions in the Committee

on

AERODYNAMICS AND AEROELASTICITY

The chief problems of an aeroelastic nature in the present context center about the fluid and mechanical instabilities associated with bluff bodies, since in the main the structures in question are not streamlined or designed primarily for aerodynamic efficiency. Flow-induced mechanical oscillations, and flow instabilities may be considered the focal points of interest here. In the former category are the numerous galloping and flutter phenomena; in the latter are the velocity and pressure variations associated with vortex shedding, edge flow instabilities, flow through gaps, etc., associated with fixed bluff objects.

The influence of wake conditions upon the forces on objects in the flow is great in the present context, in which all flow is subsonic and essentially incompressible. The effect of Reynolds number upon wake conditions and wake-body interactions is not well explored, so that the ranges of validity of scaled testing become an important consideration. In particular there is a need for Reynolds number effects to be quite "locally" appreciated, rather than merely globally, in order for physical insight into instabilities to be gained.

The study of flow over various simple bodies of sharp-cornered cross-section may well prove to be of greater general interest in the context of structural wind problems than is the still formidable problem of flow over the circular cylinder.

Suitable theoretical models of instability are few in number, due to the relative analytical intractability to date of flow configurations involving broad wakes containing organized vortex systems. There does, however, appear to be some promise in the use of potential flow models of bluff bodies in the presence of wake vortices, and generally, the judicious use of computer models of flow can lend insight into certain instability phenomena, although this is usually a painstaking and relatively costly process. Thus the area of interest will probably remain strongly experimental for a period into the future. It will be important in research in this area to examine those typical kinds of cases in which the alert experimental aerodynamicist can observe key "unitary" flow characteristics of importance to the engineer and theoretical analyst. The need exists for identifying and classifying those flow phenomena (such as separation phenomena) which are present in the various classes of instability, so that an ordered picture can emerge of the aeroelastic phenomena of bluff bodies. Much recent research has been concerned with identifying the actual nonlinear nature of galloping and vortex-induced oscillations of bluff bodies, and it seems likely that sound dynamical models of these oscillations, with the aerodynamics as empirical inputs, will be available before the aerodynamic excitation can be modelled theoretically.

The effect of upstream turbulence upon flow over bluff objects is also of fundamental concern. It becomes necessary to establish experimental methods for adequate simulation of the full-scale atmospheric turbulence in the earth's boundary layer. It has been observed, for example, that oncoming turbulence can delay the onset of certain aeroelastic instabilities either because of important changes wrought in the two-dimensional flow over the body in question or because of the reduced correlation between random flow effects at physically separated points of the body.

Those classes of instability which persist in the presence of streamlining (such as flutter in coupled translations and torsion) presently require somewhat less attention because of the strong emphasis already given to them by aeronautical investigations. However, they remain of fundamental importance as a background for further analytical efforts in the new areas.

Continued development of representative test and simulation methods, so that similarity to full scale is enhanced, is necessary in regard to forecasting the performance of complex aeroelastic models in specialized environments. Such methods are presently the last effective resort in particular cases where existing analytical techniques cannot follow the complexities of the actual full-scale environment.

Chairman: R. H. Scanlan, Princeton University

Co-chairman: G. V. Parkinson, University of British Columbia

Summary of Discussions in the Committee

on

WIND-TUNNEL AND FULL-SCALE INVESTIGATIONS

Because of the breadth of the subject considered and the limited time that was available for discussion, this report must be considered as limited in scope. It is anticipated that additional communications will be received in the future, introducing new topics and amplifying those discussed herein.

Wind Tunnel Investigations

In discussing the general problem of model testing, the committee felt that the scaling criteria required to achieve dynamic similitude between models and prototypes are known, but that they are extremely difficult to satisfy, even when special-purpose tunnels are used. It was suggested that the following guide criteria be adhered to whenever possible in conducting wind tunnel investigations of prototype structures or atmospheric flows.

1. Characteristics of the approaching flow should be simulated as closely as possible (initial conditions). This should include mean-velocity profile, distributions of scale and intensity of turbulence, and thermal stratification.

2. Geometry of the structure under investigation should be carefully scaled and surrounding structures and terrain which influence the flow should be reproduced in the model.

3. For those structures whose dynamic response is important, suitably scaled dynamic models should be used.

In general, the committee felt that a naturally generated turbulent boundary layer of sufficient thickness was a highly desirable method of simulating surface winds. However, objections to this technique were expressed, and it was pointed out that graduated grids and screens have been successfully used to generate both mean velocity profiles and turbulence. Air jets and shutters have also been used to simulate wind gusts, and wind tunnel turbulence has been augmented by using vortex generators and vertically distorted scales of surface roughness. It was also noted that while thermal stratification can usually be ignored under strong-wind conditions, there are cases in which unstable stratification is a significant source of turbulence.

It was concluded that much more effort should be made to establish correlations between model and full-scale results, particularly where the effect of the Reynolds number is thought to be significant. The level of agreement that can be expected using state of the art modeling techniques was discussed. Results of wind load investigations conducted in Canada within the past five years show differences in mean surface pressures between model and prototype ranging from 10 to 20 percent. This is quite acceptable for many practical applications, in view of other uncertainties. It was noted that a number of studies contained proprietary information and therefore could not be reported.

To evaluate the state of the art in wind tunnel modeling and to identify existing special-purpose facilities, the committee divided modeling applications into the following six categories. Aeronautical problems were specifically excluded and consideration was restricted to that area which can broadly be defined as environmental aerodynamics. The six categories were:

1. Environmental studies
2. Static forces on structures
3. Dynamic loading of structures
4. Diffusion and heat transfer
5. Air-sea interaction problems
6. Special problems.

Discussion of each of these categories is summarized in the following.

Environmental Studies. This category includes the study of mean flow patterns around buildings and structures, the effect of proposed buildings on neighboring structures through shielding and channeling and the determination of optimum configuration and orientation. It also includes occupant comfort, investigation of turbulence intensities in plaza areas and courtyards, downflows on windward building walls, etc.

It was felt that the degree of similitude required to obtain acceptable results in studies of this type is not sufficiently defined, particularly where quantitative results are of interest. As models of urban areas can be extremely expensive to build, the amount of detail required to adequately simulate full-scale conditions is a very important question. In this vein, the committee emphasized the need for more information on wind characteristics in urban areas and city centers.

Static Forces on Structures. As in the previous category, the Reynolds number is seldom equal in model and prototype. It is believed, however, that results from sharp-edged structures are reasonably reliable because of the fixed position of flow separation. A wide range of model scales has been used, but scale ratios of from 1/300 to 1/500 seem to be the most common.

Larger scales have been used in investigating the effects of local architectural features such as mullions, parapets, etc. The problem of tunnel blockage was also discussed. While corrections can sometimes be applied to test results, it was felt that these corrections are difficult to determine and that solid blockage should not exceed 5% of the tunnel cross-section.

The Commonwealth Advisory Aeronautical Research Committee has proposed a round robin of tests using a standard prismatic body to aid researchers in comparing results obtained from various wind tunnels. This body is similar to a full-scale building on which surface pressures have been measured so that wind tunnel results can also be compared with prototype results. It was recommended that a similar program be established to aid researchers in the United States.

Dynamic Loading of Structures. In addition to simulating the natural surface winds, this application requires that the geometric and dynamic characteristics of the structure be modeled. A serious limitation is the availability of modeling materials with the required physical properties. In the case of tall, slender structures, one approach has been to utilize a single degree of freedom system in which the model is permitted to rotate about the base on a gimbal and to use springs and electromagnetic dampers to simulate full-scale stiffness and damping. As the effective structural damping is not generally known for unique structures, a range of probable damping coefficients is covered in the testing program to identify worst-case conditions.

While the above approach appears to be satisfactory for many structures, there are cases where rotations and damping must be distributed throughout the structure. Shell structures such as cooling towers and membrane-type roof structures are examples in which particular attention must be paid to detailed modeling of mass, stiffness and damping. Although certain analytical procedures have been used with success, the wind tunnel model appears to be the best way to identify potentially dangerous combinations of structural properties, wind speed and wind direction.

Diffusion and Heat-transfer. Generally, these problems require that thermal similarity as well as dynamic similarity be satisfied. Included in this category are the effects of forced convection on heating and cooling loads, inversions, diffusion of gases and layout of air intake and exhaust systems. It is believed that special-purpose facilities now exist which can adequately simulate full-scale conditions. Model scales on the order of 1/2000 - 1/4000 have been used to study large metropolitan areas and gross topographical features such as mountain ranges. Experience has indicated that distorted vertical roughness scales (with distortion ratios on the order of two) are sometimes required because of the large lateral extent of the prototype area. This technique has long been used in hydraulic models.

Air-Sea Interaction Problems. This category has assumed increasing importance in recent years with the advent of major offshore structures such as drilling platforms. A number of highly sophisticated air-water tunnels have been built in recent years or are now under construction. Despite advances that have been made in this field, the committee was of the opinion that model results must be treated with due circumspection until verified by full-scale tests. Of particular concern was Reynolds number distortion and the highly complex problems of modeling wind characteristics, wave structure and soil-pile interaction. Another area indicating a need for more research is that of storm tide or surge.

Special Problems. This category includes the simulation of dead air conditions in city centers, vortex flows, pulsating flows, blast effects and sonic boom. Unfortunately, the committee did not have sufficient time to consider at length current research efforts and to recommend future research in these areas.

Although not specifically recommend by the committee, significant benefits would probably result from an in-depth survey of existing special purpose facilities by a task committee. To be effective, such a survey should not be restricted to facilities within the United States and should also include a study of modeling techniques used by various researchers.

Full-Scale Investigations

The second general area of research discussed by the committee was that of full-scale testing. This is an area in which considerable effort has been expended within the past three years.

Various types of instrumentation and measurement techniques were reviewed with particular emphasis being placed on anemometers and pressure transducers. Hot-film anemometers and Doppler radars are now being used in atmospheric studies but they are still in a state of development. Considering their cost and long-term stability, mechanical anemometers and drag spheres will probably continue to be widely used in these studies. The committee felt that much improvement could be made in pressure transducers and that greater use should be made of laser devices.

The problem of obtaining adequate field data on mean velocity profiles and turbulence, particularly in urban areas, was felt to be extremely important. In reviewing past and current research efforts, the committee concluded that much useful information already exists and should be compiled. To accomplish this, it was recommended that a task committee be established and that this committee act on a permament basis, assembling information on wind characteristics as it becomes available and coordinating new research programs.

Concerning full-scale studies of wind forces on buildings and structures, it was recommended that companion wind tunnel studies be carried out whenever possible. Those structures in which the Reynolds number makes modeling difficult (such as rounded bodies, for which separation points are not fixed) were especially emphasized. Full-scale studies of drilling platforms and the response of structures to blast loading were also reported.

While the primary motivation for full-scale studies has been the correlation with wind tunnel investigations, it was pointed out that information necessary to establish distributions of extreme loads can also be obtained from these studies. In addition, wind excitation provides an opportunity to evaluate the performance of complete structural systems, particularly with regard to damping coefficients and with respect to question of low-cycle fatigue due to the action of repeated loads. The committee felt that in addition to the data obtained from "high-density" instrumentation of specific structures there is a need to obtain limited, long-term field data involving minimal instrumentation on a given structure, but at a number of sites within a given region.

Summary

The major points made by the committee during its discussion of wind tunnel and full-scale studies may be summarized as follows:

1. Because of the great difficulty in achieving dynamic similarity, correlation between model and prototype must be documented.

2. A standard model test body for comparing results obtained in different wind tunnels would aid researchers.

3. A survey of existing special-purpose test facilities and modeling techniques should be conducted.

4. A task committee should be established to compile existing wind data relevant to structural design and to report on and coordinate future wind research programs.

5. More full-scale studies should be conducted on structures such as stacks and hyperbolic cooling towers for which scale effects are known to be significant.

6. Long-term studies should be conducted on full-scale

structures for the purpose of establishing distributions of extreme loads and evaluating the effects of repeated loads.

7. The free and timely distribution of test data, both model and prototype, should be encouraged.

Chairman: R. D. Marshall, National Bureau of Standards

Co-chairman: J. F. Kennedy, State University of Iowa

III. SUMMARIES OF INDIVIDUAL RESEARCH INTERESTS

WIND EFFECTS ON HIGH-RISE BUILDINGS IN CHICAGO

Richard A. Parmelee
Northwestern University

Research directed toward wind effects on tall buildings originated over 75 years ago in the "Windy City" of Chicago. In spite of an early start in this direction, it was not until the past five years that extensive studies of wind loading and wind-structure interaction have been undertaken in the Windy City.

As taller buildings were designed and built in Chicago, the deflections and oscillations of such buildings under wind loadings became of increasing interest to structural engineers. Within recent years, research activity in this area has shown a steady increase, since the rapid growth of the construction of high-rise buildings has brought about the need for a better understanding of wind effects on tall buildings.

In 1966 the Reinforced Concrete Research Council sponsored a study of the dynamic motion of a high-rise building due to wind forces. Two types of compact instrumentation were developed and installed in the building: tiltmeters sensitive to a few thousandths of a degree, and horizontal seismic pendulums having very low natural frequencies and large amplitude capabilities. This instrumentation was used to record the motion and tilt of the 55-story building for a period of 30 days. The natural frequencies of the several modes were measured as well as the magnitude of the drift deflections and the oscillatory displacements.

A year ago the instrumentation was installed on the John Hancock Center in order to monitor the response of the structure under the action of wind loading. The framed-tube type of construction of the four exterior walls of "Big John" make it possible to evaluate the static "overturning moment" at the base of the structure by means of instrumentation on only four of the columns. A total of sixteen strain gages were affixed to the test columns at the basement level prior to the application of the fire proofing material, and all of the gages are functioning properly. The data from these gages will be correlated with the wind velocity and direction data from instruments located on the roof, and the resulting relationship can then be used as a check on wind tunnel data and testing procedures.

Recently this instrumentation was used in combination with the previously described seismic pendulums and tiltmeters (installed near the top of the building) to obtain data for evaluating the damping of the structure. Preliminary analysis of the data indicated that in the 30 to 40 miles per hour winds experienced during the testing program the structure exhibited an effective first mode damping rate of less than one percent of critical. Additional studies of this effect are planned for the winter season of high wind activity.

The results of the research efforts in the area of wind loading and wind effects on tall structures in the "Windy City" have been encouraging, and Northwestern University, in cooperation with the Chicago Committee on High-Rise Buildings, has prepared short-range and long-range plans for more extensive programs. At the present time plans are being completed for the establishment of an instrumentation capability for measuring the response of full-scale high-rise buildings in a wind environment. It is anticipated that this instrumentation package would be sufficiently flexible and portable such that the transducers and data acquisition system could be installed in any existing building as desired. In addition to measuring and recording wind pressures, strains, deflections and movements at key positions throughout the building, it is planned to position a network of wind measuring instruments in the vicinity of the test building. This data will be of assistance in establishing the structure and nature of the wind before, during and after it encounters the tall structure.

All of these data will be recorded and stored on magnetic tape, and then will be transferred to a high-speed electronic digital computer for statistical treatment and evaluation. The aim of this long-range program is to provide the design profession with a better understanding of the wind-structure interaction phenomena, and thereby assist the structural engineer to assess the structural safety and reliability of high-rise buildings with respect to the action of wind forces.

AN APPROACH TO THE WIND PROBLEM IN ATLANTA

D. C. Perry
Georgia Institute of Technology

Early in 1970, members of the Atlanta Committee on Structural Design (ACSD) concerned with provisions in the new 1970 City of Atlanta Building Code pertaining to wind loads, formed a Wind Task Force Committee constituted of local practicing structural engineers, architects and this writer, representing the Georgia Institute of Technology. Following a meeting on June 10, 1970 between this committee and the BUILDING CODE ADVISORY BOARD OF ATLANTA it was decided that the two groups would collaborate in a broad program aimed at developing a more rational approach to the wind problem. In order to achieve this objective it was agreed that the efforts of the ACSD Wind Task Force would be focused on the following immediate activities as funding permitted:

1) A "high density" correlation of wind velocity profiles, pressure distribution and the resulting structural response to be conducted at 100 Colony Square, a new 26 story steel office building isolated from the "built-up" areas of downtown Atlanta. A 1100 ft. TV transmission tower situated a short distance from the Colony Square Site will be instrumented to determine the structure of the wind approaching the "built-up" areas.

2) A study of the changes in local wind characteristics which occur during the erection of additional high-rise buildings in a compact area, also to be conducted at the Colony Square Site (Atlanta's first micropolis).

3) An investigation of the variation of wind structure and resulting pressure distributions and structure responses throughout the City of Atlanta. Two or three key parameters (wind velocity, cladding pressures, accelerations or gross displacement) will be monitored at one or two specific elevations on a particular building at as many locations in the city as practical on both new and existing construction. It is intended that this phase of the program will be established on a long-term basis for the purpose of determining distributions of extreme loads and evaluating the effects of repeated loadings.

With the support of the City of Atlanta and the enthusiastic cooperation of a large number of local building contractors and developers, sufficient funding has been gathered to initiate phase 3) of the program on a limited basis. The American Iron and Steel Institute initiated support of the Colony Square Study in 1969 and is continuing to fund this portion of the investigation (AISI Project 130).

The writer wishes to acknowledge the close collaboration of Dr. R. D. Marshall, NBS; and the many valuable suggestions and criticisms

received from Professor A. G. Davenport, University of Western Ontario; Professor J. E. Cermak, CSU; and Mr. H. C. S. Thom, NOAA.

PROBLEMS IN ASSESSMENT OF WIND LOADS

Edward Cohen and Joseph Vellozzi
Ammann & Whitney - Consulting Engineers

Specific areas of Ammann & Whitney's current interest and efforts related to wind loads involve: (1) assessment of loads and dynamic response for wind sensitive structures such as tall buildings, radio and communication facility towers and antennas, plus stacks; (2) the dynamic response of suspension bridges (full scale experiments) and (3) preparation of standards for inclusion in building codes. Important problems are (1) the measurement of wind speed data in a form suitable for design use; (2) the effects of shielding and channeling plus topographical features in general on design wind speeds; (3) the assessment and distinction between high local pressures on a structure and lower overall pressures for design of the main frame and (4) dynamic response due to vortex shedding, gusts, buffeting from adjacent structures and instability due to galloping and flutter. Although these problems cover a broad range of wind effects, it is felt that each of these areas require additional research in order to continually improve our assessment of wind loads and effects.

A major innovation in recently proposed building codes and standards on wind loading is the concept of varying load requirements both with the dynamic properties of the building and with the roughness of the terrain. Although the gust factors and wind velocity height profiles given in these codes are based on the best information available, more measurements of gust effects and wind speed profiles, particularly for built-up exposures, are required. Since mean wind speeds are known to be lower in the centers of large cities compared to speeds in flat open country, accurate information on the transition in the wind speed profile between smooth and rough exposures is required in order to transfer meteorological data for open exposures to city centers. "Regional" or micro wind maps are required in areas where the transition in the wind speed can have a major effect on relative construction costs. These maps should give the annual probability of exceedance on wind speed as a function of wind direction and should be continually updated as the terrain becomes more heavily populated. For some structures the combined probability of wind speed, icing and air temperature is also required for design purposes. There is considerable doubt as to whether simple power law equations are valid under all conditions for predicting the variation of mean wind speed with height in large cities and more measurements in actual cities are required to resolve this difference.

Although power spectral techniques have proved to be powerful tools for analyzing the dynamic response of structures to random wind loads, the application of these techniques in the prediction of gust factors has resulted in major differences between the results obtained among several investigators. The major reason for these differences is the area in which the gust loading is correlated over the structure as a whole. A resolution of these differences requires a better understanding of the mechanism of how free field wind fluctuations are related to the fluctuating loads on the windward and leeward faces of a structure. Although wind tunnel tests in boundary layer wind tunnels have provided significant insight into this problem, the correlation between such tests and full-scale measurements is relatively poor.

Since wind, live and dead loading and structural strength are all probabilistic, a great deal of work is required in order to establish realistic design criteria for combined loading and to deduce more nearly predictable probabilities of failure. In view of the current trend towards taller and lighter structures utilizing high strength materials and overall lower safety factors, it would be unconservative to rely solely on favorable unevaluated experience with the structures of the past in establishing wind design criteria for future structures. Even the experience for modern, wind sensitive structures is very limited since the loading and design criteria have been in a state of flux over the past 20 years. Information on occupancy comfort in tall buildings and in the determination of damping ratios and their variation with amplitude and duration of load are far from accurate.

There is a need for more full-scale measurements of wind loads and dynamic response of structures in order to provide statistics of the physical quantities required in design. Such tests should determine as a minimum the relationship between the wind speed fluctuations in the free flow and the pressure fluctuations on the structure. Supplementary measurements of the dynamic response should be correlated with the wind speed and pressure data using power spectral techniques.

Full-scale measurements on cylindrical structures of vortex shedding effects are also required, particularly for very high Reynolds numbers which cannot be achieved in wind tunnels, using reduced scale models.

RELATION OF WIND DESIGN TO SEISMIC DESIGN FOR TALL BUILDINGS

Edward J. Teal
Albert C. Martin and Associates

This discussion is from the viewpoint of the structural designer of high-rise buildings. Our office has designed several office towers with heights ranging from 400 to 700 feet, and we are now designing another tall building and a tall free-standing TV tower. All of these structures are in the Los Angeles area which has high seismic risk and relatively moderate wind storm hazards.

In the southern California area the building code specifies static wind forces to be used for the design of a building and also specifies minimum equivalent static earthquake forces. For tall buildings the code wind forces exceed the code earthquake forces. However, the large investment in a tall building and the cost of repairing earthquake damage dictates more thorough dynamic analyses of the response of the structure to earthquake ground motions of realistic intensity. Because of this, the strength and form of the structural frame is determined by the earthquake-induced deformations rather than by the code prescribed wind forces.

The fact that wind does not control the design of the structural frame in earthquake country does not mean that there is no concern for wind or that the design is not pertinent to wind. As a matter of fact, the design for seismic forces had led to a detail of dynamic design, analysis, testing and instrumentation which should be of great help in wind design studies. Consider the following dynamic factors.

Period - Only in seismic areas are extensive studies of building periods being made. Periods are being estimated on an empirical basis and on detailed (computer modeling), and semi-detailed (analogy) analyses. Periods are being measured by means of vibrators, microtremor instruments and accelerographs. Analytical studies are indicating the effect of forms of structural frames on periods and the limited band of period control which is possible.

Damping - The importance of damping and the limited amount of damping present in the usual structural frame are being explored by analysis and field testing.

Accelerations - Dynamic response computer programs developed for earthquake motions will provide a basis for future work on wind response. Shaking tables being built for seismic testing may also provide basic and important information on human response to motion.

Drift and Distortions - The prediction and control of drift is critical to estimating dynamic response and damage control for buildings in an earthquake area. The detailed analysis, testing and evaluation of this problem which is being pursued because of the earthquake problem is providing a better basis for wind design.

Overturning Forces - These forces are not only a considerable concern in regard to safety, but are very significant in their effect on building drift. Reliable prediction of these forces is essential to providing building economy and performance for both wind and seismic exposure. Column strain instrumentation on buildings can and should be promoted on the basis of combined needs for wind and earthquake safety and performance.

For wind design of major structures, we can and do get meteorological and wind tunnel studies made if the wind conditions for the general area of the site need definition, or the shape factors are unusual. Of course the effectiveness of the meteorological study is very dependent on the wind records for the area. It usually comes as a great surprise to designers that they are very lucky if there are maximum wind speed records which provide even a reasonable prediction of gradient winds for a particular site. United States maps showing maximum wind speeds related to height and frequency are misleading in this respect.

In this regard, designers are generally very concerned over the trend to introduce voluminous, binding code wind provisions, expanded well beyond the accuracy of the basic data and real design needs. As reference data this material can be very useful. As binding code provisions it can force irrational and uneconomical design.

We need much more field instrumenting if the prediction of frequency and height-related wind speeds for a given site is to even approach the analytical and laboratory data already available. Where the building investment is great, and wind conditions are as variable as in our local basin, very detailed wind instrumenting is needed.

WIND STORM RESEARCH INTERESTS AT SANDIA LABORATORIES

Jack W. Reed and Wesley L. Holley

Sandia Laboratories, an Atomic Energy Commission facility, is operated by Sandia Corporation, a subsidiary of Western Electric. Our interest in wind effects on structures has two primary facets. First, in predicting explosion airblast and seismic effects and hazards to structures and populations, at long range from AEC test sites, we need to know what natural background of structural deterioration is occurring. This is needed for comparison with nuisance levels of damage which are, or are alleged to be, test-related. Second, for the handling or transport of hazardous radioactive materials, AEC systems must be designed with consideration given to the possibility of encounter with destructive wind storms.

Some of our related work to date has involved:

a. Investigation of damage from accidental explosions.
b. Research on the statistical nature of glass structural failures.
c. Studies and measurements of atmospheric boundary layer turbulence and diffusion, with applications to wind gust spectra definitions.
d. Analyses of structural damages to certain buildings struck by tornadoes or hurricanes.

In addition, two Sandians are members of the NAS SST-Sonic Boom Subcommittee on Physical Effects. Sonic boom effects on structures are almost the same as explosion effects, and very similar to wind effects.

Some of our specific concerns at present are:

a. An apparent lack of wind power spectral analyses for real community environments. Most meteorological collections have been made over relatively uniform flat terrain.
b. Lack of wind gust factor data as a function of height and as a function of community parameters (size, roughness, orientation, etc.)
c. Lack of spectral correlation analyses relating wind records (taken close to the test structure) to wall and window pressure records.
d. Lack of adequate statistical treatments of designs for low probability of failure, particularly in window glass installations.
e. Inadequate descriptions of destructive wind storms (tornadoes, hurricanes, etc.) and their climatology.

ANCHORAGE OF LIGHT FRAME BUILDINGS IN STORM-RESISTANT CONSTRUCTION

E. George Stern
Virginia Polytechnic Institute
and State University

The destruction and damage caused by Hurricane "Camille", one of the most damaging storms in recent history, was an eye opener to many. Damage prevention became an important aspect in the light of experiences gained as a result of careful damage inspection and analysis. Lack of anchorage or insufficient anchorage of the structures and/or their components was found to have been the most common culprit of destroyed or damaged homes. Anchorage from the roof down to the foundation has become a major item of consideration in building construction. This has resulted in "balanced" construction to resist, uniformly throughout the whole structure, such forces as may happen to occur because of wind and wave action, blown and floating debris, and debris accumulation.

Present efforts at the Wood Research & Wood Construction Laboratory of Virginia Polytechnic Institute and State University in promoting storm-resistant construction range from improved anchorage by means of improved fastening methods to the introduction of improved foundation systems.

Unsatisfactory toe-nailing of rafters to plates - considered one of the main reasons for major building damage during the 80 to 100-mile/hour thunderstorm in Sudbury, Ontario, Canada, August 13, 1970 - should in the writer's opinion be outlawed by the requirement to provide satisfactory uplift resistance especially for roofs with overhangs. The proposed requirement to provide satisfactory washers under the heads of masonry nails and explosive-driven pins and studs for fastening lumber plates to concrete slabs should lead to improved anchorage of wood framing to its foundation and should eliminate the splitting of unsatisfactorily anchored plates, resulting from the application of high uplift forces to roofs during severe storms.

The introduction of an integral foundation-framing system (Ref. 3), fully eliminating the need of conventional concrete foundations and foundation walls, should result in improved building anchorage partly because of the continuity of the pressure-treated framing posts and studs through the framed walls down into the ground. The proposed mass-production of standardized prefabricated rigid foundation bents (Refs. 4 and 5) may result in the introduction of fully satisfactory engineered anchorage of residential and other light-weight structures under normal as well as adverse exposure conditions regardless whether the building is located on a flat or steep lot and in the path of storms, hurricanes, tornadoes, floods or waves.

These and other improved anchorage concepts, giving full consideration to experiences gained during recent damage surveys, may be considered forward steps in providing storm-resistant construction and, thus, in reducing, if not eliminating, excessive damage during natural as well as man-made disasters.

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WIND PROBLEMS ON SMALL STRUCTURES

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Many simple but very practical wind loading problems exist which have been largely neglected or ignored in the past. One such problem which has received little attention is wind loading effects on outdoor signs and lighting and their support structures. Government has considered this area as "too practical" for research support and industry has too often turned to over simplified text book answers. Recently, however, industry has gone to large lighting fixtures and signs mounted on extremely long or high supports and structural failures have become commonplace. Unfortunately, shapes such as the standard "stop-light" traffic signal or stadium lighting are seldom aerodynamically clean and easy to treat by text book methods. This is leading to an increased interest by industry in wind tunnel evaluation of wind loading on such structures. Considerable short term test work has been done in the Virginia Tech 6 x 6 foot wind tunnel in this area in the past two years.

Such tests as those performed on traffic signals have led to substantial interest in the redesign of the standard stop-light to minimize wind loads while maintaining its present desirable properties. However, lack of government or industry financial support has held this effort to a minimal level.

Another practical problem recently studied dealt with wind loads and flow in and around large open-top cylindrical tanks. Complex three dimensional flow patterns were observed inside such structures. A better understanding of the parameters affecting these flows must be obtained through wind tunnel tests and theoretical modeling. Floating tops in such tanks are subjected to substantial stresses which can easily lead to failure. Exposed liquid surfaces are also subjected to unusual air-liquid interface shears and interactions. Considerable research in several fields is needed for a solution to this problem.

The above problems, often considered too practical for basic research efforts are of just as much importance as many others currently receiving considerable attention. Everyone is interested in solutions to problems of vortex shedding and structural interaction and in wind tunnel scaling effects for non-aeronautical testing. It is important to continue a large effort on these large scale problems. However, this must not be used as an excuse to ignore the smaller, more immediate problems which are of importance to everyday society.

TORNADO FORCE CONSIDERATIONS FOR CONSTRUCTION DECISIONS

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Because of space allotment, the following comments are offered without the usual support information. I will be quite willing to discuss these statements more fully with interested parties.

From the construction viewpoint, tornado forces may be put into four broad categories: the direct, pushing force of the wind; the outward forces from the lee side pressure deficit; the outward forces because of the pressure differentials resulting from the atmospheric pressure drop in the tornado vortex; and forces transmitted through flying missiles. The primary meteorological parameters are the wind speed and the atmospheric pressure deficit. Insofar as a building within a tornado is concerned, it often will be simultaneously subjected to forces of all four categories. Therefore, it would not be realistic to ignore either the low atmospheric pressure in the vortex or flying missiles when considering the problem of wind loads during tornadoes.

Because of the extreme gradients of wind speed and atmospheric pressure, buildings, and especially large ones, are subjected to severe shearing stresses. Because of the vortical nature of the storm, the intensities and directions of these stresses change rapidly in time. In addition there are extreme, very short-duration gusts, and probably pressure drops, which may be very important from the viewpoint of construction decisions. The degree of periodicity is an unknown factor.

No one knows, and perhaps ever will know the magnitude of the absolute maximum tornado wind speed and pressure drop. Using certain simplifying assumptions, one can calculate a theoretical maximum for either, assuming the other (Abdullah, 1955; Brooks, 1957). It is generally agreed that tornado maximum wind speeds are somewhat above the ground level.

Most of us who have been actively interested in tornado wind speeds and pressures are inclined to believe that the absolute maximum speed is probably well under 400 mph and the maximum pressure drop probably less than 10 inches of mercury. Most tornado researchers have been more interested in tornado characteristics than in resistance to the forces, and have not felt the need to generalize with respect to maximum forces.

Consequently, at the University of Wisconsin Tornado Conference (Reynolds, 1970) the Group on Tornado Parameters recommended that an effort be made to summarize the stands taken by the various "experts" with respect to tornado force intensities and distributions, coupled with the evidence, assumptions, and reasoning behind each premise. Subsequently, a letter was submitted to the Atomic Energy Commission, proposing the development of such a summary. It was further proposed that this summary be supplied to a conference of experts, who would be paid to commit a proper amount of time to the understanding of the material, prior to the conference. Thus they would be genuinely prepared to discuss the validity of the various premises. A more complete and proper proposal is expected to be submitted soon to the National Academy of Engineering, the National Science Foundation, or perhaps some other agency.

Whatever the maximum wind speeds of the worst tornadoes, maximum speeds in less severe tornadoes are certainly much less,* and the maximum within a tornado only occurs over a small part of it. Therefore, feasible considerations may offer protection for all but the worst parts of the worst tornadoes. Evidence exists which suggests that the survival of a structure in the midst of rubble may very well indicate a difference in resistibility rather than a caprice of nature (Reynolds, 1958, 1970).

With respect to the atmospheric pressure drop in tornadoes, it is my impression that buildings exploding from tornado low atmospheric (as opposed to dynamic) pressures is grossly overstated. Such explosions apparently do occur, but the reported frequency is highly questionable. In all fairness, some informed persons may disagree with this statement. Again, the University of Wisconsin Discussion Group agreed that a tornado pressure measurement program is probably feasible, if we would be satisfied with fairly gross measurements of minimum pressures. Such information would be a giant stride, from the viewpoints of tornado forces and tornado dynamics. Tornado pressure estimates were included in the letter proposal to the AEC.

The frequency of tornadoes varies remarkably with season and region of the country. There are even significant local variations within an area. Knowledge of the intensities of tornadoes is less advanced, but it is possible that they are as variable as the frequencies. Certainly the intensities within an area vary remarkably from storm to storm. The widths of damage paths also fluctuate from storm to storm, and probably with season and location. From the viewpoint of avoiding over-design, the cost-benefit ratio from the further development of the knowledge concerning these three factors would be highly favorable.

From the viewpoint of absolute fail-safe construction, such as is needed for nuclear reactor housing, the stake-like action of flying debris

* A few of us feel that, in general, the maximum speed is in the vicinity of 200 mph or even less, and that the atmospheric pressure drop may be less than 5 inches.

must be considered. A great deal of knowledge in this respect can be gained by careful damage surveys.

The interdisciplinary team survey approach applied to the Lubbock tornado (or tornadoes) of May 11, 1970 has proved to be quite profitable. Any one of the several reports that have already been published has been worth more than the total cost of these surveys (Fujita, 1970; Thompson et al., 1970; McDonald, 1970; Somes, Dikkers, and Boone, 1970), and additional valuable reports are yet to come. This kind of approach should be repeated until we can become confident of tornado force estimates. A funded, authorized, quasi-permanent inspection team (or teams) should be established. This would provide a capability for collecting vital evidence before it is removed from the scene. Every day of delay results in the loss of information which may be critical to understanding the requirements for resistance to tornado forces as well as tornado dynamics.

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ESTIMATES OF MAXIMUM TORNADIC WIND SPEEDS FOR USE IN WIND LOADING

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Volunteering as a Guesstimator in estimating tornado wind speeds and pressure drops at a recent wind loading conference (University of Wisconsin, 1969), I was hesitant about committing myself with respect to the maximum magnitudes for these two parameters. I have since remained hesitant but have come to realize that by not making my estimates known to the engineering community, estimates could be made that may be inconsistent with present knowledge (both theoretical and empirical) of the elusive atmospheric phenomena.

The values I shall provide are consistent with theory and are tempered with the measurements in the unfortunately few tornadoes where some relation to basic principles of hydrodynamics can be checked. The value of wind speed is the magnitude of the vector sum of rotational speed of 100 meters per second, plus 20 meters per second for translation, thus totaling 120 meters per second (264 mph), plus 50 meters per second in 15-second gusts. This estimate is for 100 feet above the ground. This gives a total during maximum gusts of 170 meters per second (374 mph) which is greater than the 360 mph previously estimated for the maximum speed. I also commented that, contrary to previous theoretical treatments, the vertical component of air motion within the tornado is of the same order of magnitude as the tangential component. The height above the ground is important since the ground's roughness affects this maximum value. The same tornado would have less wind speed among city buildings than over a flat field.

Reynolds and Golden were on the opposite end of the spectrum of estimates, with maximum values of 200 mph plus gust factors of 60 mph and 40 mph respectively. Note that Golden's estimates are based on measurements of spray about water spouts and Reynolds' are based on damage to ground-based structures very near the ground; while mine are based on moving clouds, dust and debris throughout the depth of the tornado, and my values have their maximum located at an average height of about 100 ft. Obviously, further discussion is needed, but time was not available at that conference.

It is possible, and perhaps quite likely, that Reynolds' low estimates near ground level and my high estimates for the 100 ft. height are compatible. If there were linear shear in the maximum wind from zero at the ground to 374 mph at 100 ft., then the speed at 30 to 40 feet (where others made their 260 mph estimates) would be 125 mph. Thus, the combined estimates call for a boundary layer type profile with very high shear near the ground (i.e., $\frac{260}{33}$) and lower shear (i.e., $\frac{114}{66}$) from 30 to 100 ft. The pressure drop from storms of this magnitude is about 0.8 # mi.$^{-2}$ sec^{-1}.

Preliminary results of our study of data from this year's Lubbock storm verify the need to consider shear. From an examination of these estimates, it must be obvious that we do not know enough to provide confident estimates for design decisions. These estimates referred only to maximum values. Not enough consideration has been given to the wind speed vs. distance-from-the-center relationships. The same can be said about wind speed vs. duration at a point, relationship. These relationships probably vary with season and location, and certainly with tornado type.

In an effort to utilize the most plentiful measurements of the phenomena, Goldman developed a method for extracting tornado wind speeds from poor quality moving pictures taken by the public that show only the vertical components of motion. This method has been computerized so that outputs of radial and tangential components are provided from inputs of vertical components. Pressure distributions can obviously be extracted from the resulting three dimensional wind distribution.

If appropriate agencies urge the public to submit the motion pictures, an empirical model of wind could be developed. Perhaps, if the right agencies were to give rewards for usable tornado photographs, it might encourage more picture taking of tornadoes in action.

The forthcoming empirical data from photographs combined with estimates of wind loading determined from structural and material damage (such as from the Lubbock storm) will be a good base upon which to establish empirical models of this phenomena that tends to elude measurement in fixed networks.

TORNADO CLIMATOLOGY AND REPORTING

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Introduction

The problem of tornado climatology and reporting is one of long-standing. A true, accurate account of the number of tornado occurrences does not exist and probably never will. But there is a need for more accurate tornado statistics as cities expand into former rural areas and large developments rise in what may well be a "favored" storm track. The tabulation of the tornado event takes on a variety of forms, each important in its own right, and none should be neglected. The rise in the number of tornado reports over the past 15 years can be attributed to a better reporting system. Yet there is still some confusion and doubt as to what constitutes a tornado and what a windstorm. While the reasons for this confusion may seem to be legion, it most likely revolves about the "invisible funnel".

Tornado Climatology

Tornado statistics have been presented in a variety of forms. Tabulations by state and month, hour of the day, by one-degree squares, smoothing has been introduced in the form of two-degree squares or weighted averages. Selected regions and areas have been studied with respect to a severe convective storm pattern, if one exists. The path length and path width of tornadoes are recorded. Unfortunately only the more severe and intense storms receive the attention of this most important statistic. Some attempt is made at a monetary damage figure but this usually falls into a wide range of values that is quite cumbersome for anyone interested in this area of the tornado's impact on the economy.

While the foregoing are kept fairly well up-dated, some one of a kind investigations of the past need to be re-worked in light of additional years of data. These include tornado probabilities and tornadoes per unit area, say 10,000 square miles. Indeed, fresh views are needed in the presentation of tornado statistics so that maximum utility of these can be made not only by the meteorologist but by the engineer. But to attain the best possible climatology, an accurate count of the tornado event is required, the problem that plagues the researcher.

Tornado Reporting

Not all tornadoes are observed and reported. Some weather events have been erroneously listed as tornadoes. And many more weather events which at first were described as tornadoes have been downgraded to windstorms. Even official publications listing tornadoes are subject to error. Some may consider that the present sampling is sufficient for their purposes. However, a survey of tornado reports in the tier of counties surrounding Cook County, Illinois, shows that 22 tornadoes were reported in this area (roughly a 50 mile radius of downtown Chicago) in the period 1916-1954. For the period 1955-1967 over 90 tornado reports are listed. This is due in part to the National Weather Service establishing severe storm reporting networks beginning in the mid 1950's. But a large part is due to the migration from the city and growth of what was once called rural areas.

Thus, a more complete picture of weather occurrences is available from densely populated areas;still,errors creep into the climatology. There will always be a minority of irresponsible reports and the forever present "attention getter". However, valuable reports are being lost due to the definition of a tornado itself. The visible funnel cloud and the rotation of debris have been requirements in the past. And these still linger on although documentation over the past ten years indicates one or both may be absent. The late Dr. Fred Bates(1) has documented the invisible funnel quite well. Reports of the invisible funnel have appeared in Storm Data(2). The strongest evidence has been the photographs and movie film that have recorded this event. From my own personal study of the reports, photographs and films of the invisible funnel, it appears that the closer the observer is to the funnel the less apparent it is. Whether due to lighting, terrain conditions or some internal structure of the circulation, many tornadoes go unreported or are classified as windstorms. Perhaps when this is universally recognized and accepted, a more accurate tornado climatology will result and that it will become apparent the tornado is more commonplace a weather event than one of nature's oddities.

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SIMULATION OF TORNADO-LIKE VORTEX

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The research at The Catholic University of America is on dynamic simulation of tornado-like vortex with axially symmetrical fluid mechanical models. These models can simulate the turbulent tornado-like vortex near the ground boundary with reasonable accuracy and easy control. The velocity profile in the turbulent boundary layer and general mean flow pattern have been explored:

(a) with three-dimensional hot-film and anemometer developed in the tornado research laboratory in the University,

(b) with steady pressure probes,

(c) with soap bubbles, and

(d) with smoke.

The size of the model tornado funnel ranges from 20" to 40" in diameter. The circulation can vary from 0 - 500 square feet per second and the upper draft mass flow rate from 0 - 300 cubic feet per second. The maximum vacuum at the vortex core can reach 14" of water. The roughness on the ground's surface can be controlled.

This equipment can study building models of different sizes and orientations. It can also be used to study moving building models with different travelling velocities which are relative to the tornado core.

For public safety and welfare, we may need to build tornado-proof buildings such as nuclear reactors and storm shelters in public schools. The four types of tornado wind-loads on such structures can be identified:

(1) The sudden suction in the neighborhood of the travelling tornado core.

(2) The maximum velocity due to a combination of the rotation and travelling core of the tornado vortex.

(3) RMS (root mean square) gustiness of the maximum velocity.

(4) The missile driven by the maximum rotation of the wind.

The sudden suction of the tornado core may be in the range of 50 - 100 millibars. This upward lift on the building may result in many roof and window explosions and great damage. Automatic venting in the roof is absolutely necessary. The residue suction, if small, can be offset by the design of the roof structure to withstand upward lift.

The dynamic pressure created by maximum wind is on the order of one magnitude higher than the conventional allowable wind-loading in the present building code. Therefore, in general, the construction of tornado-resisting buildings up to a certain wind load is preferable to reduce the width of the damage of a tornado track. The RMS gustiness is of the order of 30%.

There is no recorded data available at the present time on the gustiness and maximum velocity of the tornado.

Last, wind-driven missiles from tornadoes can cause serious damage due to their impacts. The best method is to eliminate objects which can become missiles in the tornado track.

At the present time, a great deal of effort should be directed toward building models in a tornado-like vortex as mentioned previously. Currently, our laboratory is developing techniques and details on how to measure windloads of such building models.

THE STRUCTURE OF SEVERE STORMS

Tony Maxworthy
University of Southern California

This research is concerned with the modelling of the dynamics of tornadoes and hurricanes. A series of laboratory models have been constructed; starting with mechanically driven devices and continuing with models which are more realistically driven by thermal effects. A number of field studies of dust devils have been undertaken and more work is anticipated for the future on these milder, but still representative atmospheric vortices.

Many of the characteristics of intense atmospheric vortices can be reproduced in the laboratory and there studied in detail by well known experimental techniques. These include the boundary layer inflow, eye region and spiral rain bands for the hurricane and inflow, suction spot and downward core flow in the tornado. We are also investigating methods of modifying and, perhaps, destroying such vortical flows.

In the spirit of the present conference, it would also seem possible to place various objects (building models?) in such flow fields in order to determine the effects on bluff bodies of flows with a <u>three dimensional</u> mean velocity field.

WATERSPOUTS AND TORNADOES OVER SOUTH FLORIDA

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NOAA, National Hurricane Center

What is a waterspout? Is it just a tornado over a water surface (as defined in the Meteorological Glossary), or is there some fundamental difference in structure and energetics? We can't be sure, but the Director of the National Severe Storms Laboratory has noted in a recent survey article on tornadoes that waterspouts appear to embody tornadoes' essential properties (Kessler, 1970). My own research on the extensive data acquired during the Lower Florida Keys Waterspout Project, May - September, 1969, confirms his statement to a high degree. For purposes of discussion, a waterspout will be defined as an intense columnar vortex, usually containing a funnel cloud, of small horizontal extent which occurs over a body of water. We emphasize that, at least for waterspouts over South Florida, rarely does the visible funnel extend all the way down from parent cloud base to the sea surface. As in the case of the tornado, most of the waterspout funnel is thought to become visible by condensation of water vapor. The visible funnel's outer surface would then outline the surface of constant-isentropic condensation pressure.

While tornadoes are most often associated with thunderhead activity, waterspouts may originate from "trade cumuli, with tops not higher than 12,000 ft." (Riehl, 1965). Furthermore, waterspouts have been reliably reported pendant from shallow stratocumulus clouds. The classical tornado occurs in the right-rear flank of squall-lines or in an airmass with pronounced low-level instability and vertical wind-shear. Both of these last two conditions are typically absent from the environment of the South Florida waterspout; indeed, the airmass in this region during the summer is usually homogeneous in the horizontal and stable, with very weak vertical wind shear. The evidence is that the major observed differences between the average land tornado and the average large waterspout are intensity, duration, and translational speed. Other more fundamental differences may exist, and my own work suggests that the primary energy sources might be one, particularly the relative importance of latent heat of condensation in the funnel and parent cloud-system. Morton (1966) and others, in accounting for these differences, stress the different flow termination over ground and water. Brooks (1951) emphasized the importance of the lower boundary by noting that waterspouts often dissipate on reaching a shoreline. It was observed by the present author (Golden, 1968) that the first of two waterspouts which made landfall on the south shore of Lower Matecumbe Key on September 2, 1967, soon afterward resembled a large dust-devil. The circulation at low levels decreased rapidly after moving overland, and the visible funnel expanded, became very hollow and translucent, and gradually retracted into the parent cloud. However, this average-sized waterspout maintained its vortical identity while crossing some 1100 yards of flat land, and reformed after moving off the north shore of this Florida Key.

Of the many questions which invite attention to the waterspout, the following represent the interest toward which my recent work has been directed:

(a) Is this vortex mechanically forced or is it a thermally induced quasi-hydrostatic system?

(b) What is the environmental setting favorable for waterspout formation?

(c) Is the vertical flow in the vortex driven by buoyancy, friction or axial pressure gradients due to the development of a concentrated core? Specifically, is the vertical motion of the funnel's core upward or downward?

(d) Does the Florida waterspout have a life-cycle, and if so, does it result from the interaction of various scales of motion?

During a chance aerial encounter near Lower Matecumbe Key, Florida, a series of three waterspouts was documented at close range over a period of 35 minutes. Using a high resolution Super-8 movie camera with 5:1 zoom and bayonet-type slide camera, the approach, landfall, crossing and reformation of the first small waterspout over the Key was recorded. The aircraft flew in a tight clockwise circle and descended from 2000 to 800 ft to obtain detailed observations on the structure and kinematics of the second larger waterspout, especially the lower portion made visible by sea-spray. Cloud base and the aircraft's altitude were determined from the pressure altimeter setting, and the tops of the NNE-SSW line of cumulus congestus clouds which spawned the waterspouts were estimated at near 20,000 ft. The circumstances leading up to this aerial encounter and its documentation appear in a preliminary article (Woodley, Golden, et al., 1967) and later in more complete detail (Golden, 1968).

Soundings taken at Miami and Key West, 1½ hours later in time and each 60 n mi away from Lower Matecumbe Key, indicate that the airmass over the Keys was quite homogeneous at the time and place in question. The Key West sounding (Golden, 1968) shows an airmass typical of undisturbed trade-flow, with no pronounced subsidence inversions and weak vertical wind shear in the lowest 20,000 ft.

Photogrammetry using the slides revealed that the largest waterspout funnel varied in diameter from 125 ft near parent cloud base to 70 ft at its lower end. Using the dimensions of the surface spray vortex obtained with the slides and then tracking and timing the rotation of spray plumes and particles at various radii, we obtained a tangential velocity profile through the spray vortex. The resulting three-dimensional model synthesized from the data on the two major waterspouts is shown in the accompanying figure, which includes an inset showing the measured tangential speed profile across the spray vortex of the intense waterspout. Subsequent data gathered and analyzed by the author lend additional support to this model.

The derived tangential wind-speed profile through the waterspout's spray vortex closely approximates that of a Rankine-combined vortex. With the ordinate axis as tangential wind speed (V_T) in m/sec and abscissa as radius (R) in meters, we note that the maximum tangential wind speed is 65 m/sec or 130 knots at a radius of just 12 m from the center. This profile and maximum tangential wind-speed should be compared with Hoecker's (1960) analysis of the Dallas tornado films. In the latter, a composite distribution of tangential and upward components of the air flow around the Dallas tornado was determined by tracking debris particles, dust parcels and cloud tag movements in scaled movies. (Doubts may be raised here as to how well solid debris, such as sheet metal or lumber, responds to the air motion.) The greatest derived tangential speed using this method was 170 mph at a radius of 130 ft and an elevation of 225 ft. Looking at the figure again, we note that the profile derived from the Lower Matecumbe Key film is really the vertically-averaged tangential speed distribution across the uppermost layers of the spray vortex. The average depth of the spray vortex was about 50 ft.

In atmospheric dynamics, it is often assumed that the cyclostrophic wind is a valid approximation to the real wind in small-scale vortices with very great wind speeds and path curvature (e.g., Hoecker, 1961 and Long, 1958). Having derived a profile of tangential wind speeds through the spray vortex of a large waterspout, it should be possible to integrate the cyclostrophic wind relation from the outer edge of the spray vortex (R = 36.5 m) inward to its center, and thereby obtain the total pressure drop across the vortex. We may write the cyclostrophic wind relation as

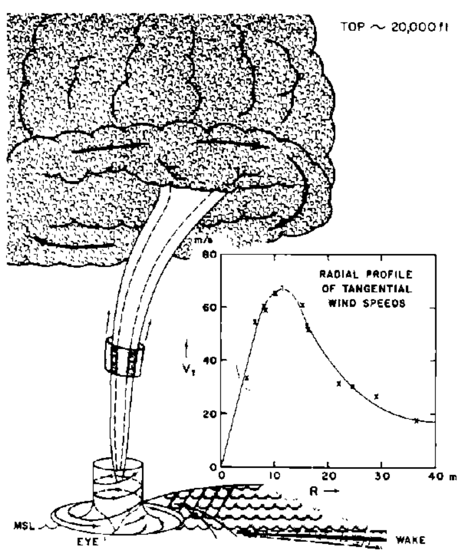
$$\frac{V_c^2}{2} = \frac{1}{\rho}\frac{\partial p}{\partial r}$$, where p is pressure and r radius.

Using the characteristics of the derived profile discussed earlier, the above relation was integrated with respect to radius in two steps: from R = 36.4 m inward to R = 12m (the speed max), and from R = 12m to the vortex center. The value of density used was that for saturated air with an adjusted virtual temperature, from synoptic data at Key West International Airport. The total pressure drop across the spray vortex was 44.3 mb

(1.3 inches) giving a central pressure of 971 mb. All but a few percent of the total pressure drop occurred from the outer edge of the spray vortex inward to the speed maximum. A total pressure drop at the ground of almost 60 mb was found for the Dallas tornado of 1957, by an integration of the cyclostrophic wind equation (Hoecker, 1961). Hoecker suspected that this figure is a conservative estimate of the actual surface pressure drop, since most of his wind speed values were derived during an immature stage of the tornado.

A "spray sheath", concentric with and outward from the visible funnel and rising from the sea surface has been documented from the Matecumbe data. For the larger Lower Matecumbe Key waterspout, the spray sheath had a diameter of 130 - 150 feet (see figure). The spray sheath is an important feature because it outlines an annulus of intense rising motions surrounding the visible funnel and extending upward (in this case) to 400 ft MSL. The upward extent of the spray sheath in any given waterspout would depend upon the terminal velocity of the size spectrum of spray droplets carried helically aloft and the balancing rising motion. The ring of maximum tangential winds occurs at a radius just outside the 'eye' region in the figure.

Returning to the questions we raised earlier - what are the dynamical implications of this wind profile for the circulation in the waterspout's spray vortex? Consistent with the Rankine-combined nature of this vortex, we note that inward from the speed maximum near 12 meters, the air-spray mixture is in solid-body rotation with a near linear decrease of speed inward to the vortex center. In this region, a parcel subject to displacements will conserve its angular momentum and tend to remain at the same radius (be dynamically neutral). Outward from the speed max, the air-spray circulation becomes irrotational and the derived profile fits the theoretical curve VR = constant very well.



TORNADO AND TROPICAL CYCLONE RESEARCH

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TRW Systems

Since 1965 the genesis, quasi-steady mature-stage structure, and decay of severe vortical storms have been examined by simple analytic modelling. The motivation for the research is (1) basic understanding so the phenomena may be included in large-scale numerical atmospheric simulation; (2) development of improved storm prediction and modification procedures; and (3) establishing guidelines for navigation and civil engineering in storm-prone areas. The latter goal has led to efforts at estimating tangential velocity components in severe storms (which turn out to be rarely much in excess of two hundred miles per hour in either tornadoes or tropical cyclones). A sketch of these and other project results achieved thus far is now given.

Prior to 1970 the following results were achieved:

1. A means of estimating the maximum swirling speeds in tornadoes from a knowledge of the ambient cloud deck and a photograph of the funnel cloud.
2. A means of estimating the maximum swirling speeds in hurricanes from knowledge of a tephigram for the ambient atmosphere in which the storm was generated.
3. Rudimentary parametric criteria for the onset of intense swirling from studying the competition between convectively induced advective concentration of local angular momentum and radial turbulent diffusion.
4. Proposal of a new structure for fully developed hurricanes denying that greatly augmented local heat and moisture transfer from ocean to the lower atmosphere as the driving mechanism (Riehl-Malkus theory) and asserting instead that the hurricane convects its own supply of warm moist air (captured at the time of formation) with it (Carrier theory).
5. Suggestion that hurricanes weaken in time because the "stored fuel supply" in time being used as through-put is typical of the higher autumnal tropical atmosphere and hence is relatively colder and drier than the warmer, moister, lower-level air used as through-put earlier (eventually hurricanes die even at sea because the stored "fuel supply" is exhausted).

In 1970 the following new results were achieved:

1. The dynamics and energetics of the surface frictional layer were

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examined to establish quantitatively:

a) the mass flux up the eyewall is not air flowing in from the outer edge, but rather is air slowly sinking downward from the bulk of the storm;

b) the total enthalpy profile (sum of dynamic, potential, static-enthalpy, and latent-heat contributions) is little modified from its ambient profile so enthalpy flux from ocean to atmosphere is about the same whether a hurricane is present or not, so this enthalpy flux is not deposited in the surface frictional layer but is transported across it with little diminution by plume and radiative mechanisms and is deposited in the atmosphere above the frictional layer;

c) the surface frictional layer is dominated by a balance of Coriolis and frictional forces (linear Ekman layer) in the outer half of the hurricane, but toward the eyewall it consists of a thin region near the wall in which friction matters and a thicker region away from the wall in which inertia, pressure, and centrifugal forces balance;

d) the realization that the formative stage of the hurricane cannot be correctly described without including the surface frictional layer because fluid moves radially inward more quickly through it than fluid moves inward above it (fluid erupting from the boundary layer flushes up and out the air originally situated at the center of the storm).

2. Recognition that the bringing of the surface frictional layer to dynamic equilibrium is the rate-controlling (slowest) step in the process of intensification from a tropical depression to a hurricane.

3. Description of the formation of the eye as the sinking of relatively dry air down the center of the storm owing a rarefaction created by an inertial oscillations of the eyewall at the terminal stages of formation.

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TORNADO WIND LOAD RESEARCH

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Major interests of the Air and Water Resources Program in our Department of Energy Engineering, center around applied meteorology, aerodynamic flow around structures, and atmospheric turbulence. Research efforts are presently being directed towards problems related to the urban environment, particularly the overall structure and dynamics of the atmospheric flow field in which building structures are situated. Present research is concentrated on two particular problems. The first problem involves a theoretical analysis on the dynamics of a tornado vortex and the transient forces imparted to a man-made structure by such a vortex. The second area of concentration is concerned with an analysis of the transition in the wind flow field as it passes from rural to urban surroundings. This is of particular importance since most major structures are located in urban centers, and hence are subjected to turbulence levels and other factors which can differ significantly from that of rural areas

Some specific research problems that I feel are of special importance are: (1) wind loading due to severe weather phenomena such as tornadoes and hurricanes; (2) the response of structures to lightning and hail associated with severe storms; (3) more refined methods for laboratory simulation of wind loading phenomena, in particular, additional programs such as that conducted by Professor Cermak and the Fluid Mechanics Group at Colorado State University should be encouraged; (4) laboratory simulation of transient loads due to severe storms; (5) investigations devoted to a better definition of the overall rural-urban wind flow field; (6) analytical studies concerning the aerodynamics and flow fields of irregularly shaped bodies; (7) determination of the response of structural materials to the trailing shock waves of supersonic aircraft; and (8) improved analytical models for the turbulent boundary layer over urban areas.

RESUME OF OBSERVATIONS DURING A VISIT TO CORPUS CHRISTI, TEXAS, TWO WEEKS AFTER HURRICANE CELIA

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Monday, August 3, 1970, the center of the eye of Hurricane Celia passed about ten miles north of downtown Corpus Christi, Texas. At Ingleside, Texas, almost directly in the center of the path of the storm, anemometer and wind direction recordings indicated a north wind buildup to some 30 minutes of sustained winds near 115 mph, with gusts as high as 138 mph, followed by a sharp (five minutes) reduction in average velocity to only 30 or 40 mph. The "calm" period lasted about 30 minutes and the wind direction shifted abruptly to the south as the wind velocity within ten minutes was built up again to sustained winds of 110 mph, with a peak gust recorded at 125 mph. The average wind velocity gradually decreased during the next two hours. Approximately three hours after the eye had passed, "normal" storm conditions existed, and personnel attempted to move about the streets, returning to homes. The wind data quoted here were recorded at the Reynolds Metal Corporation.

Wind velocities could have been somewhat higher or lower than those recorded, because the calibration of the recording equipment had not been checked for the very high velocity range. Both the Reynolds Metal recorder and that of the Corpus Christi Weather Bureau required a scale change at 100 mph velocity. The Weather Bureau staff was unable to switch the range during their recording experience, but three observers reported a wind gust observed to be 160 mph.

I visited Corpus Christi two weeks later, along with the following members of the Engineering Staff of Dow Chemical Company: Elmer Neill, Plant Engineer, Harry Youens, Civil Engineer, and Walt Henden of the Engineering Planning staff. We stopped frequently to inspect damaged structures and during two days attempted to confer with engineers from each of the main refinery or industrial installations along the Nueces Bay Ship Channel.

Engineering personnel were obviously busy with their own repair responsibilities, but those intereviewed were in all cases very sympathetic to our mission of seeking enough data to reduce future storm damage problems. Candid reports of damage would be very useful and should be available to responsible technical personnel. The constraints to candid reporting that industrial suppliers insist upon probably contribute to damage when less than adequate construction practices remain unpublicized.

In general, most industrial structures in the area were designed for 40 to 50 psf nominal ground-level wind pressures. Little, if any, structural damage was observed for structures actually designed for such wind loads. However, damage was observed for some structures designed in accordance with the Southern Building Code, which uses a ground-level wind pressure of 25 psf for coastal installations. In one case, an elevator tower and head house supporting a conveyor was destroyed when windward column anchors failed in tension. A water tank structure also failed when column anchors yielded and broke. One rather unique demonstration of design pressures took place at a warehouse, originally designed for a 40 psf wind load on the windward face. A later addition was proportioned for 25 psf wind pressure. The new addition was destroyed by the storm, but the original half appeared undamaged.

Power distribution and telephone service was interrupted everywhere as poles failed. Wood poles failed in flexure at the ground line. Aluminum poles failed at anchor fittings in the base.

Damage to windows was widespread. In many cases, the entire window frame pulled out of its connections. Even door frames failed to remain anchored in many cases. Window sash was reported to have failed moving both inward and outward. More attention must be given to window frame anchorage into supporting structures.

A common type of damage to masonry walls appeared to be due to a lack of anchorage between brick veneer and backup block in cavity walls. Whole sections of brick veneer appeared to have pulled away from walls that contained little or no ties to the veneer. Some concrete block walls failed. No vertical anchorage to foundations could be detected at the concrete block walls that failed, and there was little or no evidence of ties to supporting beams or columns.

In general, the more massive construction types fared best from the storm winds. One pretensioned concrete T-beam system failed when about 30% of the sections, approximately six feet wide by twenty-five feet long were lifted off supporting beams on an overhanding canopy. There was no evidence that the deck sections had been connected to the supporting beams. Gravity alone had held them in place.

Many wood roofs were lifted and broken apart. Construction practice in numerous cases should have required better anchorage of roof elements to supporting walls. Any overhanging elements were particularly susceptible to the uplift of high velocity winds. Some smaller wood structures were lifted completely off foundation slabs. In numerous cases, plywood decking was ripped off roof purlins, and only the bare structure remained.

Many metal clad steel structures showed extensive damage and evidence that column anchorage was inadequate. In many cases, anchor bolts showed evidence of necking down prior to tension failures, and in some instances, columns broke away from fillet welds at base plates. Apparently, very little weld material penetrated the wide flange material at such base plate fillet welds. Several lightly framed quonset-hut structures were badly distorted. Some corrugated siding was torn away from the majority of structures containing such siding. Transite siding similarly tore loose from many frames. One plant engineer reported that no transite came loose if it was connected with self-tapping screws. Transite came loose when it was attached with J shaped bolts. Projectiles blown by wind did penetrate transite rather easily. Another plant engineer intended to replace all aluminum siding of .032 gage with .040 gage material attached with 3/4 inch diameter washers under self-tapping screws.

Of course, a very large number of metal clad steel structures endured the storm virtually unscratched. The most prominent characteristic of metal buildings that were undamaged was a scarcity of openings for windows or doors.

Many large capacity open top storage tanks of steel suffered damage from excessive wind pressure. "Dimples" appeared on the southwest face of perhaps a third of the vessels in refinery tank farms. In a few cases, the sides of open top tanks were more than dimpled as the top stiffening ring also failed. The rectangular welded joint at the top of one covered tank was rounded by the storm as the vacuum created by winds tended to lift the top of the tank.

Roof damage was extensive even when roof decking remained intact. Tar and gravel roofing was frequently stripped, felt paper torn away, and deck structure exposed. Shingles, whether composition, wood, or tile, were stripped in many places. In a similar phenomenon, fiber insulation covered with corrugated aluminum sheeting was torn from the surface of many process towers. The aluminum sheeting appeared to remain intact in those installations that used sheet banding at two to three feet spacing or at least two bands per set of sheeting.

The storm was obviously capricious. There appeared to be streaks of severe damage adjacent to rather flimsy construction that was not damaged. Shielding of one structure by other, more stable structures also seemed evident. There were implications also that open areas in the direction of the severe winds tended to increase vulnerability. The most severe damage in regions always occurred adjacent to open areas that offered no barriers to wind gusts.

Some rather subtle forms of structural damage were missed by us, and the two day tour of the area did not permit detailed study of structures that displayed no damage. One plant engineer reported that some of the nuts on windward anchor bolts were lifted as much as 1/4 inch off the top of base plates on tall, cylindrical process towers. He attributed the phenomenon to yielding of the anchor bolts. The loose anchors were discovered when base cracks in insulation were being investigated.

Severe damage occurred to the dock facilities on both sides of the Nueces River ship channel, but we were unable to include dock inspections in our tour.

On the basis of this sketchy and superficial study of damage to buildings, it is difficult to state specific conclusions on which recommendations for better design might be based. It seems apparent that structures could be constructed to protect everything inside from even the most severe thrusts of extra-high-velocity winds and from projectiles pushed by extreme winds. Construction for such structures would be considerably more expensive than for ordinary or customary building practice. In order to balance economic resources and needed protection, an assignment of priorities to components of industrial or civil facilities appears to be needed.

Shelters for personnel and for vital components of an industrial establishment should be proportioned to resist winds in the order to 200 mph with corresponding design windward pressures near 100 psf, roof pressures of ± 80 psf, and leeward pressures of - 50 psf. All glazed areas would require protection. Arch and dome shaped profiles are superior to gable and rectangular shapes only if the smoothly curved shapes are supported by structures adequate for the unsymmetric, lateral loads of a storm. Resistance to the high winds and pressures should be considered as an ultimate load circumstance. The design limit state of structures could be based on perhaps a 1.10 load factor and the pressures suggested above.

Less than vital structures can be proportioned for the sustained velocity winds reported for coastal regions, perhaps 125 mph winds and limit load design pressures such as 40 psf on windward walls, ± 35 psf on roofs, and - 20 psf on leeward walls. Openings must be reinforced or shielded to resist debris blown by high winds. In the most severe storms, perhaps five to fifteen percent of the structures in this category could be destroyed. If shelter zones or regions are provided and designed as "vital" structures, the remaining parts of apartment house, public buildings, office and commerical structures, and most warehouses might fit this category. Private dwellings could be made a part of this category with only slight changes in present design concepts, but significant changes in construction practice.

The most significant modifications needed for construction practice in small buildings appear to include:

a) Tie down all exterior walls to foundation slabs with anchor bolts embedded at least six inches into grade beams. A crude estimate of design uplift forces equal to 100 plf of wall should be adequate for small buildings.

b) In addition to sheetrock acting as a diaphragm, brace major walls in two directions with diagonal 1 x 6 boards (or so) nailed to toe boards, studs and headers.

c) Tie down roof structures to supporting walls with positive anchorage adequate for a net uplift of 15 psf in the entire roof. Overhanging eaves should be braced to resist 40 psf pressure applied upward outside exterior walls.

d) Anchor brick veneers to cavity walls with ties adequate to hold negative pressures of 20 psf on the veneer. Anchor door and window frames to supporting walls to resist $\pm$ 40 psf pressure on the door or window.

e) Provide for protection of windows with shutters or removable, rigid screening.

f) Attach roof decking to joists with enough nails to resist an uplift force of at least 1000 lbs per 4 x 8 sheet. Shingles should be nailed adequately to resist an uplift of 15 psf.

These suggestions can be accomplished at minor extra cost for the construction of small buildings.

DRAG COEFFICIENT FOR A HURRICANE

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A formula is derived for computing the surface drag coefficient C_D from the local values of the divergence, vorticity, and gradient wind speed. Patterns of C_D are then computed for four days of Hurricane Abby, 1968, for which low cloud velocity data have been made available from ATS-111 satellite photograph sequences. An analysis of drag effects is of special interest for this storm, since its eye crossed over the Florida Peninsula.

Magnitudes of C_D were found to be only slightly larger for the hurricane than for the non-storm conditions in which numerous instrumental measurements have been made. The linear increase of C_D with wind speed reported by some investigators was not seen in this analysis, and in fact, the central (high wind) region of the storm was located in a region of relatively low drag coefficient. Values of C_D over land were larger than over the ocean, but as the storm approached, the vorticity and divergence patterns over land changed in a manner to lower the magnitude of C_D. Thus the storm effectively moves in a region of reduced drag, regardless of surface roughness. The value of C_D near the central region of the storm reached a low of 10^{-3}, and never exceeded 5×10^{-3}, whereas the average drag coefficient over Florida and Cuba was 9×10^{-3} during this period.

SOME COMMENTS ON ATMOSPHERIC BOUNDARY LAYER RESEARCH AT THE NASA MARSHALL SPACE FLIGHT CENTER AS RELATED TO WIND LOADS ON STRUCTURES

George H. Fichtl
NASA - George C. Marshall Space Flight Center

1. Introduction:

The Aerospace Environmental Division at the NASA, George C. Marshall Space Flight Center (MSFC) is responsible for the development of engineering models of the wind environment in the atmospheric boundary layer for the design and operation of space vehicles and associated supporting structures. An outstanding example of the type of space vehicle we are talking about is the Saturn V which is launched from Cape Kennedy, Florida (KSC). The atmospheric boundary layer research at MSFC can be divided into two broad areas, namely research on the structure of the boundary layer, and climatological research.

2. Meteorological Tower Facilities:

To conduct boundary layer research we have constructed two data acquisition facilities and a third one is now under construction.

a. NASA 150-Meter Tower Ground Wind Facility:

This facility located at the Kennedy Space Center consists of a 150-meter meteorological tower instrumented at the 3, 10, 18, 30, 60, 90, 120, and 150-meter levels with cup anemometers and wind direction vanes. Vertical wind speed anemometers and thermocouples are located at selected levels. This facility provides hourly observations of mean wind and temperature profiles for climatological studies and turbulent velocity fluctuation time histories digitized at 0.1 sec time intervals for periods up to 70-mintues for use in detailed studies of atmospheric turbulence. This facility has been operational since 1966 and the data are available upon request from: Mr. William W. Vaughan, S&E-AERO-Y, National Aeronautics and Space Administration, George C. Marshall Space Flight Center, Alabama, 35812.

b. NASA Boundary Layer Modification Facility:

This facility, located at Marshall Space Flight Center, consists of four 25-meter meteorological towers in a relatively smooth pasture on a line perpendicular to a surface roughness discontinuity. The terrain upstream of the site is comprised of shrubs and trees. The towers are logarithmically spaced in the horizontal over a distance of approximately 250 meters. Cup anemometers are located at the 2, 4, 7, 13, and 25-meter levels on each tower and vertical anemometers are located at selected levels. Bead thermistors will be installed at the locations of the vertical anemometers, so that vertical heat flux estimates can be made. This facility will provide turbulent velocity time histories for periods up to thirty minutes. The data will be used to determine how the boundary layer is modified as air passes from rough to smooth terrain.

c. NASA Horizontal Boundary Layer Structure Facility:

This facility is currently under construction. It will consist of eight 25-meter towers logarithmically spaced in the horizontal on a line approximately 0.8 km in length. The instrumentation and data acquisition levels will be like those of the NASA Boundary Layer Modification Facility.

3. Past Research:

Our past research on the structure of the boundary layer has been concerned with developing models of the mean and ten-minute and one-hour peak wind profiles, longitudinal and lateral velocity fluctuation spectra, co- and quad-spectra of like velocity components between levels in the vertical, gust factors for various averaging times and stability categories. In addition, discrete gust studies have been pursued concerning gust accelerations and gust duration times. The above studies were conducted with the KSC 150-meter tower data. The climatology research has been concerned with the calculation of the distribution functions of instantaneous peak wind speeds at the 10-meter level for a given period of exposure of a structure to the natural environment. The location of primary interest for these calculations has been Cape Kennedy, Florida. However, five other locations are being examined with regard to peak wind statistical climatology. The use of peak wind statistics facilitates the calculation of design peak wind speeds at the 10-meter level for a specified time of exposure of the structure to the environment for an acceptable value of risk which is specified by the engineer. To specify the mean wind speed profile and spectra for a given peak wind speed condition the following procedures are used at MSFC. Peak wind speed profiles are used to calculate the design peak wind speed at the various levels above and below the 10-meter level. The mean wind profile is obtained by dividing the peak wind profile by the gust factor profile associated with a one-hour averaging period for the given peak wind speed condition. The friction velocity is calculated with the 10-meter level mean wind speed, the surface roughness length of the site, and the logarithmic mean wind speed profile law. The mean wind profile, the surface friction velocity and the turbulence spectrum model are then used to calculate the design turbulence spectra.

Climatological studies have also been conducted to develop statistical thunderstorm, tornado, and hurricane hit models. These models can be used to calculate the probability of a structure being hit by a thunderstorm, etc. for a given period of exposure of the structure to the environment.

4. Some Current Research Topics on Atmospheric Turbulence at MSFC:

a. Statistical Study of Instantaneous Wind Shears (2nd, 3rd and 4th Moments, Distribution Functions).

b. Spectra Associated with Second-and-Higher-Order Products of Turbulent Velocity Fluctuations.

c. Boundary Layer Modification Studies (Wind Profile, Spectra, 4 Tower Array).

d. Horizontal Turbulence Structure Studies (8 Tower Array).

e. Gust Exceedance Statistics.

f. Turbulence Structure in Thunderstorms.

g. Interaction between Synoptic Scale Flow and the Boundary Layer.

h. Discrete Gust Studies (Gust Accelerations and Duration Time).

i. Turbulent Flow Visualization Studies.

PLANETARY BOUNDARY LAYER STUDIES

Hans Panofsky
Pennsylvania State University

1. Introduction

This is a brief report on planetary boundary work carried out at Penn State University, primarily by A. K. Blackadar and H. A. Panofsky and their students and associates. The report will cover completed work, projects in progress and important problems remaining.

2. Wind Profiles

A) Homogeneous terrain.

Studies of wind profiles can be conveniently divided into surface layer, tower layer, and planetary boundary layer. In the surface layer, about 100 ft. thick, the variation of stress can be neglected; in the tower layer, the wind direction can be assumed constant.

Work on profile theory in the surface layer at Penn State was completed several years ago, with emphasis on the effect of buoyancy on profiles. The results are still used in applications.

Profile work in the tower layer is quite active. An equation, potentially very useful in strong winds, good to at least 300 ft, is:

$$u = \frac{u_*}{k} \ln \frac{z}{z_o} + 144fz$$

Here, u_* is the friction velocity at the ground (proportional to the square root of the Reynolds stress), z_o is the roughness length, z the height and f the Coriolis parameter $2\omega \sin \phi$, where ω is the earth's angular velocity and ϕ the latitude. Much of the profile theory has been applied to the winds observed at Cape Kennedy. The effect of buoyancy on the wind distribution in the tower layer has been treated less rigorously. The main difficulty with tower profiles is not so much the theoretical structure over homogeneous terrain but the usually nonhomogeneous terrain; also the selection of the zero point for the height scale causes problems.

The theory of the wind profile in the planetary boundary layer is quite well understood due to work here and elsewhere in the last 15 years. A rather complex model is now being considered including both effects of buoyancy and baroclinity. It is also now being applied to the estimation of surface stress from free-air parameters at Cape Kennedy.

The principal problems remaining in profile theory are related to stable (night-time) conditions when radiation may be important. Also the problem of scaling in unstable air has not completely been resolved. Finally, little analysis of tropical profiles has been accomplished.

B) Heterogeneous terrain.

The change of wind profiles due to change in surface roughness in neutral air in the surface layer has been satisfactorily completed. An understanding of the results is essential in the analysis of observed wind profiles since ground changes usually produce kinks.

Extension to greater heights and convective turbulence is in progress here and elsewhere.

3. <u>Variances</u>

Velocity variances observed on planes and towers up to heights of 300 ft. have been related to wind speed, roughness, buoyancy and height by use of the Monin-Obukhov similarity theory. The aircraft data lead, incidentally, to the concept of an "effective" roughness length.

The estimates are quite reliable for variances of vertical velocity, less so for horizontal velocities. Particularly in hydrostatically stable air, such estimation procedures are quite unsatisfactory.

4. <u>Spectra</u>

Spectra of wind components have been studied at Penn State for 19 years. The properties of the spectrum of vertical velocity are well understood up to a height of 400 ft. or so, except in very stable air.

The spectra of the horizontal components at high frequencies obey the Kolmogorov law above 50 ft. over land, and higher up over water. At lower levels the -5/3 law is still valid, but istropy does not occur. These results have been tested through the turbulent energy budget.

There is now a huge number of spectra of wind speed which differ greatly from each other at low frequencies. A systematic treatment of these spectra is overdue.

One-point cospectra between vertical and horizontal wind components also are well understood.

5. Space-Time Relationships

Space-time relationships at many sites have been compared, and this work is continuing. The results seem to confirm Davenport's hypotheses, that coherence is an exponential function of ratio of separation to wave length.

The rate of decay varies with orientation of the line between measurements, and with buoyancy, and, perhaps, with ratio of separation to height. Some of these results are rather tentative.

The ratio of phase delay to separation in the vertical is twice as large for the lateral as for the longitudinal winds, at all heights.

Given coherence, phase delays and spectra, estimation of space-time correlations in all directions should become possible.

METEOROLOGICAL RESEARCH PROGRAM AT BROOKHAVEN*

I. A. Singer
Brookhaven National Laboratory

The research program is basically a study of atmospheric dispersion and field experimentation on a scale of 10 to 100 kilometers. This scale is extremely important in the understanding and control of various atmospheric pollution problems. Many areas of this research are related to wind loads such as the three-dimensional structure of turbulence, variation of the mean wind speed with height, and the effect of roughness.

Our major interest is to obtain good experimental data in our atmospheric laboratory to verify existing theoretical physical concepts. This has been done satisfactorily for smooth terrain at low elevations (< 150') and the research is to expand our knowledge to high elevations and rough terrain. To understand the atmospheric wind structure at high elevations we will be analyzing the following wind data:

1. Brookhaven - 400 foot tower, variable roughness, bi-directional vanes, anemometers and temperature equipment at three heights.
2. Argonne - 150 foot tower, smooth - inland, same instrumentation at three heights.
3. Savannah River - 1400 foot, smooth - inland site, same instrumentation at five heights.
4. Cape Kennedy - 500 foot, smooth - coastal, same instrumentation at four heights.

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*Research carried out under the auspices of the U.S.Atomic Energy Commission.

5. Drexel tower - 900 foot, rough. Six levels having only horizontal winds.

Attempts to find acceptable turbulence measurements, especially at high elevations, have revealed two important deficiencies that must be eliminated:

1. Bivanes of the conventional X-tail design are not suitable for continuous untended use. They are too flimsy and easily damaged, and progressive unbalance of the tail assembly raises the question of their ability to maintain accuracy. Two new designs have been built and are being tested; one features a modification of the annular fin tail of the early Brookhaven bivane, and the other has a pair of plastic spheres as the tail. In both instruments the emphasis is on a reliable vertical response, since that is the difficult element to measure effectively, rather than the horizontal fluctuations.

2. Complete lack of appropriate continuous meteorological data in an urban area at elevated heights.

After analyzing the existing rural data and completing our new bivane, we propose to equip two 900 foot towers within New York City. The analysis will be done cooperatively with meteorologists and structural engineers.

STUDY OF ENVIRONMENTAL WIND CONDITIONS AT MARS SITE, GOLDSTONE, CALIFORNIA

M. S. Katow, W. W. Van Keuren, and M. G. Newsted
Jet Propulsion Laboratory

The operational limits of large radio antennas with respect to the environmental wind conditions are a function of the long-term average of the magnitude and direction of the wind velocity, the ratio of the peak wind velocity to the average velocity, the magnitude of the change in direction of the wind with respect to the average velocity, and the frequency spectrum of the magnitude and the direction of the wind. In a limited effort to obtain experimental data with respect to the first three items of wind characteristics described above, a 300-ft tower was instrumented at three levels to measure the wind velocity and direction. A 5-min period was used for all three items. Data was collected from September 1966 through August 1967 and reduced.

At three levels of the 300-ft tower, located 564 yd from the 210-ft antenna in the southwest direction, propeller-type anemometers, direction vanes and a potentiometer connected to the center body were mounted. The levels were at 50 ft, 152 ft, and 286 ft above the ground level at the tower. For the purposes of the discussion, the levels will be referred to as 50, 150 and 300 ft.

The described sensing and recording system was limited in response frequency by the recorder characteristic. Its time period was 1/2s, with the recording mechanism critically damped. However, for the 5-min period used to compute the three characteristics of the wind as previously described, this time response was adequate.

For each sensor, three strip charts advancing at a rate of 6 in./h recorded the wind velocity, the wind direction measured in the horizontal plane, and the wind direction measured in the vertical plane.

IBM cards with the punched tabulated data were produced by contract with Meteorology Research, Inc. The cards were then input to the 7094 computer with a special data-processing program to produce the tabulated charts. The data was reduced to reflect the percentage frequency of occurrence of each item of the wind characteristics.

Environmental wind data for a period of one year starting at September 1, 1966 and ending at August 31, 1967 was recorded and reduced in the form of probability charts. The data will be available in a complete report at a later date with descriptions of the methods used to reduce the data with general comments on the environmental wind conditions by Meteorology Research, Inc.

APPLICATION OF STOCHASTIC PROCESSES TO WIND LOADS

Haresh C. Shah
Stanford University

Application of stochastic processes to wind loads and their interaction with structures is a prime research interest to us at Stanford University. In particular, we have been working on the following problems:

1. Stochastic models of wind gusts.
2. Study of extreme mean gradient wind speed for the state of California.
3. A stochastic model to study the occurrence of hurricanes in the Gulf of Mexico.
4. Hurricane induced wind-wave-structure interaction.
5. Study of statistical load factors for wind loads in design of structures.

Several reports on the results of the above studies have been published by the Civil Engineering Department at Stanford University.

We feel that the use of statistical decision theory in design of structures for wind loads should be of great value. Some very interesting work in earthquake related research has been conducted at Stanford, using decision statistics. Similar analytical tools can be used for wind loads. The analysis of risk in wind load design, the cost-optimization, proper utilization of past data and the subjective information can be incorporated by use of statistical decision theory. One of the problems faced by researchers in this area is the availability of sufficient and reliable data on wind loads. By using subjective information and the concept of maximization of utility, we can overcome this problem.

Another important aspect of wind load research is the code oriented design methods. What are the code wind loads for a given region? What is the reliability associated with the prediction of these loads? How some of the analytical tools utilized in research can be put into code oriented simple and practical methods? These are some of the problems we are currently investigating at Stanford University.

MONTE CARLO TECHNIQUES IN WIND-STRUCTURE INTERACTION

M. Shinozuka
Columbia University

In recent years, much effort has been made to analyze the dynamic response of structures to wind pressure, treating the wind velocity as a stochastic process. In particular, the fluctuating part of the wind velocity has been assumed as a multivariate or multidimensional stationary Gaussian process with mean zero and with a specified cross-spectral density. For example, three components of the wind velocity at a point in space or components in a particular direction of wind velocities at different points in space form a multivariate process, whereas the x-component of the wind velocity $U(t,x,y,z)$ in the three-dimensional space in general forms a four-dimensional stochastic process.

In this context, analytical studies are being carried out in the Department of Civil Engineering and Engineering Mechanics at Columbia University in which an extensive use of Monte Carlo technique is made to investigate, among other things, (1) nonlinear structural response to wind load; mean square responses of a nonlinear string to wind velocity fluctuations, of a nonlinear plate to boundary-layer turbulence and of coastal structures to wind-induced waves (producing nonlinear drag forces), (2) effect of wind fluctuations on unstable oscillations of flexible structures and (3) the first-excursion-failure problem in particular, as to the validity of the commonly used factor $(2 \log \nu T)^{1/2}$, under various realistic conditions on the duration and spectral content of wind velocity and on the threshold value. The Monte Carlo technique is based on a method of digital simulation recently developed by the author for multidimensional and multivariate homogeneous Gaussian processes.

IDENTIFICATION OF THE DYNAMICS OF RANDOMLY EXCITED STRUCTURAL SYSTEMS

W. Gersch and N. Nielson
University of Hawaii

The application of time series analysis and stochastic process analysis techniques to the identification of structural dynamics under random excitation has been primarily constrained to estimation of the fundamental period and first mode damping coefficient. Analyses have deen dominated by an "autocorrelation" method approach introduced in Japan in the late 1950's. The key assumption in that approach is that the random excitation, wind for example in the case of tall building vibration, is broad band relative to the principal structural mode so that a "white noise" excitation could be formally assumed. Much more structural information could be obtained, using that assumption, from say observation of top floor random vibration data alone. For example, a differential equation, representation of the structure, foundation to building to transfer function, and more reliable estimates of the damping coefficients of several modes of the structure could be obtained. The value of a more complete structural description is the enhanced ability to compute structural response and hence damage due to severe winds and earthquakes.

To date identification of structural dynamics under digital computer simulation conditions have been extremely promising. Our activities have been to develop and apply new techniques in fitting parametric models to observed time series data to infer the aforementioned structural dynamics. An important test of our techniques will be to fit differential equation models to the 150' steel tower structure instrumented and studied by Professor A. Chiu, Civil Engineering, University of Hawaii. We would also welcome additional random vibration data taken from the top floor of buildings, or simultaneous data taken from more than one point on a building, as well as random wind and random vehicle motion induced simultaneous multi-channel records of bridge vibration data.

STOCHASTIC METHODS RELATED TO WIND LOADS

William A. Nash
University of Massachusetts

Work is currently in progress in the Department of Civil Engineering on development of methods for digital simulation of non-white stationary Gaussian random processes. The objective is to present methods for simulation of stationary Gaussian random loads with prescribed power spectral density functions of interest in structural analysis. It has been found possible to produce certain power spectra (of restricted form) by passing a white noise through a linear filter characterized by the frequency response function $H(i\omega)$ if all coefficients of the linear filter can be determined such that $H(i\omega)^2$ fits $G_y(\omega)$ where $G_y(\omega)$ is the power spectral density function of the output. This technique has thus far made it possible to simulate quite satisfactorily random loads and their power spectra corresponding to (a) jet engine sound pressures, (b) boundary layer pressure fluctuations, (c) gust loadings in atmospheric turbulence, and (d) ocean wave pressures. It is anticipated that other phenomena can be simulated with modest amounts of additional effort.

WIND STORM RESEARCH ACTIVITIES AND INTERESTS

Ernst K. Kiesling, Joseph E. Minor and Kishor C. Mehta
Texas Tech University

The Lubbock Storm of May 11, 1970, and Hurricane Celia which struck the Gulf Coast on August 3, 1970, provided researchers at Texas Tech with direct exposures to effects of severe storms on metropolitan areas. These first-hand experiences and interactions with other researchers stimulated the development of a multidisciplinary storm research program. Research studies in engineering, economics, sociology, and mesometeorology are currently being conducted in a University-wide storm research effort. These studies show promise for a long range program to evaluate the effects of disasters on sociological, economic, and physical systems.

Since the Civil Engineering Department is coordinating this University-wide research plan, we are involved in all aspects of the storm research. Attention is focused, however, on the response of structures to wind forces.

CURRENT RESEARCH ACTIVITIES IN THE C.E. DEPARTMENT

Specific studies underway or having been completed at the present time are enumerated below.

1. Study of Response of Structures in the Lubbock Tornado

The Lubbock Storm affected about 10 square miles of the city. The area includes a downtown section, an industrial section, as well as medium and low density residential areas. All types of structures were affected including multistory office buildings, municipal facilities, mill type industrial buildings, warehouses, 2-story apartment complexes, and single family residences.

Evaluations include modes of collapse, anchorage and connection detail failures, extent of damage from wind or missiles. We participated in a preliminary report published by the National Academy of Science for the National Academy of Engieering. The National Science Foundation supplied funds for the investigation and the publication. Professor J. Neils Thompson was the lead author on the report.

2. Response of Structures in Hurricane Celia

Researchers at Texas Tech did a survey of structural damage. We have approximately 200 documented photographs which are being compared with photographs of wind damage resulting from the Lubbock Tornado.

Objectives of the study are documentation of the effects of hurricane winds on structures. This study is sponsored by Texas Tech University.

3. Response of a 20-Story Building to the Lubbock Tornado

The Great Plains Life Building is of considerable interest both to the general public and to the engineer. It is of interest to the general public because of the publicity given the building by the news media immediately after the storm: its imminent collapse was reported a number of times. It is of interest to the engineer because it was subjected to winds probably exceeding 200 miles per hour. The structural frame sustained 12-inches of permanent deformation in its 270-foot height. The building suffered extensive damage to window glass, face brick, interior partitions, and to its furnishings. Damage was caused by winds, by windborne debris, and by racking of the building.

A preliminary report has been published by Texas Tech University. The report will soon be available from the federal clearing house. The study was sponsored partially by the American Institute of Steel Construction.

We are interested in continuing studies on the response of the building in view of proposed straightening operations and reconstruction.

4. Response of Pre-Engineered Metal Buildings

The tornado in Lubbock affected over 60 pre-engineered metal buildings. Damage ranged from minor deformation to total destruction.

Objectives of the study included documenting the damage and determining the failure mechanisms. A preliminary report has been submitted to the Metal Building Manufacturers Association which provided partial sponsorship for the study. The report as submitted to the MBMA is considered proprietory.

RESEARCH AREAS OF PRIMARY INTEREST TO TEXAS TECH RESEARCHERS

We would classify research activities into two broad groupings: 1) Wind-Structure Interaction (Determine the forces on structures), and 2) The Effects of Wind Forces on Structures. In studying the wind-structure interaction, we would try to understand the phenomena involved. In determining the effects of these wind forces, we would apply these understandings to improve engineering systems. Our specific interests are given below following the committee structure used for this conference.

1. Public Safety and Protection

We desire to continue assessing wind damage and to perform post-storm inspections. Furthermore, we feel it important to study the adequacy of codes, to update them to reflect the most current and best knowledge available, and further, to study the protection of life from wind storms. We are interested in looking at the civil defense aspects of protection, to consider such items as restoration of utilities and services in municipal areas and to try to provide protection in the home from storm winds.

In regard to protection in the home, a course is being offered in the Spring Semester at Texas Tech involving students from Civil Engineering and Architecture to develop concepts to provide protection in one portion of a residence.

2. Wind-Structure Interaction

We desire to extend wind models including wind direction as a variable parameter, to study dynamic interaction of wind and structures, and then to study stochastic methods for predicting structural response.

3. Structural Analysis and Design

After developing wind models and developing methods for predicting structural response to these winds, it is necessary to apply these response prediction methods to engineering practice. (How does the practicing engineering use our results?) We are also interested in developing structural damping factors and to study further tolerable motions. The factors of safety against collapse are also in need of study, particularly in multistory buildings such as the Great Plains Life Building in Lubbock.

One of the areas of greatest concern and interest to Texas Tech researchers is the assessment of current design practices for window glass installations. In many cases, the value of contents may exceed the value of the structure itself. A considerable research effort is therefore warranted to develop glass window installation criteria to insure the protection of the contents. Contrary to what codes imply, we feel that the prevalent cause of window failures is windborne debris rather than wind forces. Design codes must consider this in order to be realistic.

STUDY OF DYNAMIC WIND RESPONSE OF GUYED MASTS

R. W. Clough
University of California, Berkeley

Work on the dynamic response of guyed masts to wind loadings has been carried out at U. C., Berkeley. Engineering interest in the analysis of guyed masts was stimulated by the introduction of radio transmission, and one of the earliest contributions, by Walmsley in 1924, was concerned with the static loads applied to stay-ropes used to support wireless masts. Problems associated with the dynamic behavior of cables have received much attention in classical texts for well over a century. The motion of inextensible loose chains and the small oscillations of tight elastic strings have been discussed extensively by Routh in 1860, and Rohrs in 1851. Probably the earliest detailed method for the static and dynamic analysis of guyed masts under the action of wind forces, however, was due to Kolousek in 1947. In more recent years, due largely to the increased heights and importance of telecommunications masts, there has been considerable interest in this field of study, with notable contributions by Cohen, Dean and Davenport.

In the past, the static analysis of guyed masts has usually been accomplished by treating the shaft as a continuous beam-column resting on nonlinear, elastic supports using solution techniques based on modified slope-deflection equations. Generally, the solution methods employed and the description of the system have been rather cumbersome and not entirely suited to the analysis of the fully integrated guyed mast system. For this reason, various approximations have been made in both the guy cable representation and in the manner of application of the steady wind forces, the result being the evolution of a number of similar methods of analysis differing only in the number, or degree of approximations to the real system.

The dynamic analysis of guyed masts has received very limited attention to date, and those methods proposed are often quite unsuitable for any detailed investigation of the dynamic responses to fluctuating wind excitations. An exception was the report by Hartmann and Davenport in 1966, which described the spectral response analysis of a tall, guyed mast utilizing a single degree of freedom, discrete parameter model to represent the cables. Even in this case, however, the effect of the wind on the cables was neglected in the analysis.

The purpose of this paper is to report on detailed computer studies made using a suitable discretized model to investigate the response characteristics of guyed masts under the action of turbulent wind influences. The model representing the system is fully integrated geometrically and structurally, and may be used to study both the static and dynamic behavior of the system. Estimates of the dynamic responses of a tall, guyed mast are evaluated deterministically using actual wind velocity data, and nondeterministically using the theory of random vibrations and incorporating available wind velocity spectra. A comparison between the deterministic and nondeterministic responses, and a discussion of the relative merits of the two procedures are also presented.

The real cable was represented by an assembly of one-dimensional cable elements (CE) interconnected at nodal points located on the initial cable profile, utilizing a lumped mass idealization for the dynamic analysis. In order to test the convergence properties of the finite element idealization as the number of elements is increased, the lowest natural frequencies of a single cable were computed and compared with the results obtained from a series solution for an assumed overall parabolic profile. The finite element idealization of the guyed mast structure was composed of beam-column elements. The complete structure was idealized as an assemblage of both cable and beam-column elements. Stress and deformation behavior was analyzed under both static (mean wind) and dynamic (gusts) loadings.

The finite element model was shown to provide a suitable representation of the guyed mast and allows detailed static and dynamic analyses to be performed on a fully integrated system. Several hitherto ignored factors, such as the wind effect on the cables and concentrated areas, and the use of the deflected static equilibrium position as the mean dynamic configuration, can be naturally included. The behavior of the actual structure can be arbitrarily approximated by a mesh refinement process limited only by the capacity of the computer program, and the incorporated static and kinematic assumptions.

The computer program has been used in the analysis of a number of complex guyed mast systems, but can also treat arbitrary two-dimensional structures, including suspension bridges. Moreover, the methods described in this paper can be extended to include any conceivable structural system by constructing the appropriate finite element models.

The deterministic responses due to a single wind record sample depend on the duration of the sample, as well as the atmospheric conditions at the time and place of measurement. These observations suggest that wind record samples are not a useful means of determining the probable maximum responses evaluated on a statistical basis. The procedure is tedious and uneconomic, and, due to the random nature of the wind gusts, the use of stochastic procedures is clearly the more rational approach. Deterministic methods, however, do have useful applications in providing time-histories of response, particularly if used in conjection with actual response measurements.

RESPONSE OF TALL CYLINDRICAL STRUCTURES TO WIND

Wadi S. Rumman
University of Michigan

Research efforts in this area in the Civil Engineering Department at the present time are mainly directed to the response of tall cylindrical structures to wind forces. A research project has been started to study the dynamic response of tall tapered reinforced concrete chimneys to fluctuating wind forces. Besides the important condition of lateral vibration due to vortex shedding, there is the problem of random vibrations due to the constantly varying wind in both velocity and direction.

Wind data for one hour duration have been obtained from the National Severe Storms Laboratory in Norman, Oklahoma. The furnished punched cards give the velocity and the yaw at 2 second intervals and at seven levels of height up to 1458' above ground.

The velocities and directions given at any level will be considered to be the mean values at that level. Each level will be taken as the reference plane for a strata bounded by horizontal planes passing midway between neighboring stations. Although the variation of the mean velocity within a strata will be assumed to vary with height according to a power law, no variation of yaw will be assumed.

Fluctuations of velocity and yaw about the mean will be computed randomly at short intervals of time. For example the velocity (V_{zt}) at any height z within the jth strata can be computed as the mean velocity ($\bar{V}_{zt}$) at that height plus the standard deviation of the reference velocity (σ_{jv}) within the strata multiplied by a random member (γ_{vt}):

$$V_{zt} = \bar{V}_{zt} + \sigma_{jv} \times \gamma_{vt}$$

Resolving the fluctuating velocity function about two orthogonal axes, the response of the chimney will be computed about two axes and combined by the square root of the sum of the squares procedure. Two or more modes of vibration will be considered.

It is apparent from the above that the manipulation of the data is extremely important in this type of investigation. Flexibility will therefore be built in the computer program to accommodate any changes in the handling of the data.

Another area of research that we believe is of the utmost importance is the compilation of measurements on actual structures. It is hoped that records on actual chimneys will be available in the near future. Certain chimneys are being instrumented at the present time. Measurements that will give wind velocity and direction as well as displacements will be extremely useful in correlating the actual conditions to the theoretical results of the investigation.

We also feel that further investigation of the resonance conditions of tall tapered structures (like chimneys) is needed for design purposes.

DYNAMIC PROPERTIES OF TALL BUILDINGS

Paul C. Jennings
California Institute of Technology

Both experimental and analytical studies of the dynamic properties of tall buildings have been carried out at Caltech during the past few years. Most of the studies have been motivated by an interest in the earthquake response of these structures, but the same dynamic properties also are relevant to the wind response of the tall buildings.

The most recent experimental work includes the forced vibration tests of the Millikan Library (9 stories), ambient or wind-excited tests on the Union Bank Building (42 stories) and, with UCLA, a combined forced vibration, ambient and analytical study of the San Diego Gas and Electric Company Building (22 stories). An example of the experimental results is given in Figure 1 which shows the second through sixth E-W modes of the San Diego Gas and Electric Company Building.

When the results of these tests are combined with those done by others, some trends in the dynamic properties of tall buildings become apparent, even though the experimental data are admittedly sparse. First, it is noticed that the frequency ratios and mode shapes of the tall framed building are similar to each other and resemble the properties for a simple cantilever beam deforming in shear. This similarity is most apparent in the higher mode shapes; the fundamental modes of the tall buildings show more variety. Second, it appears that the damping in the first several modes of the tall buildings tends to be roughly constant, in the range of 2 to 4 percent of critical.

There are some exceptions to these trends. In particular, the tests of the San Diego Gas and Electric Company Building showed that it is possible for translational and torsional components of mode shapes to be coupled strongly, even if the overall structural frame is symmetrical. Coupling of the mode types leads to torsional components of modes which can be significant for the dynamic response of the building. The tendency toward coupling is amplified by the nearness of the translational and torsional frequencies and, of course, by eccentricities in the mass and stiffness distributions in the building. Another exception to the trend is that some higher modes of some buildings show large displacements at the top of the structure. This "whipping", which is related to the increased flexibility of the upper stories, may have a detrimental effect if the mode is excited strongly.

The theoretical studies of tall buildings have been directed mainly toward the development of simple analytical models of tall buildings for the purpose of identifying trends in the earthquake response. Some of this work may be applicable to the wind problem. Studies are also in progress on the topics of the dynamics of soil-structure interaction, the dynamic properties of coupled shear-wall structures, and on the effects of eccentricities on the dynamic properties and earthquake response of tall buildings. These research studies are being performed by doctoral students in civil engineering and applied mechanics, with the support of the National Science Foundation

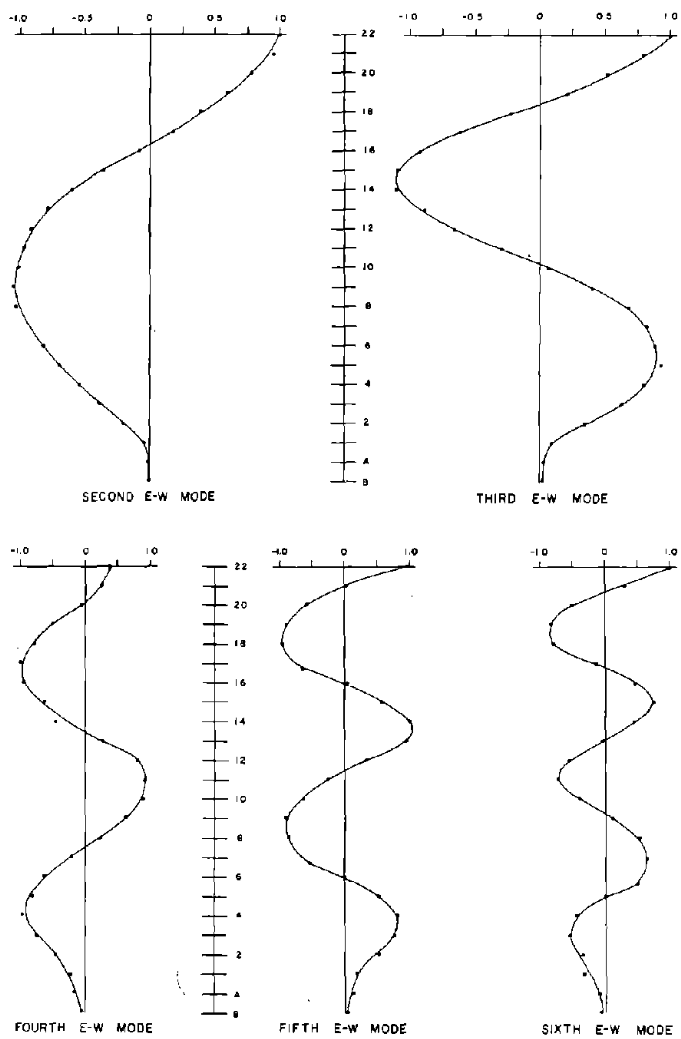

FIGURE 1. HIGHER E-W MODES OF THE SAN DIEGO GAS AND ELECTRIC COMPANY BUILDING

RESPONSE OF A MULTISTORY CONCRETE BUILDING TO EXTREME WIND LOADING

M. Agbabian
Agbabian-Jacobsen Associates

This study involving the analysis of a multistory concrete building subjected to extreme wind loading is currently in progress at AJA. The study is in continuation of another study, "Three-Dimensional Finite Element Dynamic Analysis of a Multistory Office Building Subjected to Earthquake Loading." The previous study was undertaken to demonstrate the feasibility of high-rise reinforced concrete building construction in highly seismic regions.

The objective of the present study is to demonstrate the feasibility of high-rise reinforced concrete building construction and the advantages of a framed tube design in regions with high probability of tornado occurrence.

The same example building that was used in the previous study is also being used in the current study. The building frame considered in the analysis is a forty-three story reinforced concrete building. The building has a total height of 539 ft. The plan of the building is a square of 150 by 150 ft. An interesting feature of the building is its framed tube design that uses closely spaced exterior columns.

The analysis of the building is being performed using an existing general three-dimensional finite element computer program. To conserve computer cost, the three-dimensional finite element model of the building is constructed with only eleven levels. An auxiliary analysis is made to insure that the overall stiffness of the model is approximately the same as the full forty-three story model.

The response of the building will be compared with the corresponding results from an analysis of the building subjected to pressure loads computed according to standard building code requirements.

WIND LOADING DATA ACQUISITION AND ANALYSIS

A. J. Schiff
Purdue University

There has been a long standing effort in earthquake engineering involving several people at Purdue. These include Professors John L. Bogdanoff in the School of Aeronautics, Astronautics and Engineering Sciences and John E. Goldberg in the School of Civil Engineering. Recently two phases of this effort have been expanded to include certain aspects of wind loading on structures. While some work is in progress, the majority of this report will describe proposed research. This effort is to be directed at developing techniques of data analysis and supporting data acquisition systems to enable the dynamic response of structures to be better understood. These two parts of the research effort are being carried out so as to complement each other in determining the dynamic response of structures. The first part is to develop methods of data analysis and the selection of type, specification and deployment of instrumentation to maximize the information content of the data. The second part is to develop hardware, that is, transducers and associated instrumentation systems to sense, collect and store the pertinent structural response variables and the excitations causing the response. Two instrumentation systems which are particularly relevant to wind loading are a system to measure the pressure distribution over a structure and a system to remotely sense wind velocity.

The pressure sensing system is being designed for ease in installation. The system will be installed to the outside of the structure so as to eliminate the need to penetrate the structure's cladding. Frequency multiplexing techniques will be utilized to simplify the transmission and storage of pressure information. The feasibility of extending and specializing techniques of acoustical radar for remote sensing of wind velocity will also be examined.

WIND-EXCITED STRUCTURAL DYNAMIC TESTS

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A widely-used method for experimentally determining the dynamic properties of full-scale structures is to measure their response to wind excitation. A sensitive vibration transducer-recorder system in an upper-story position will record low-level transient responses from which structural properties can be determined. Compact portable instrumentation for temporary installation is readily available, and such tests can be carried out in a matter of an hour or so without disturbing the structure or its occupants in any way.

One procedure involves waiting for a suitable gust of wind to initiate free vibrations of a sufficient amplitude to override background noise. From such a free vibration record, the fundamental period of vibration can be determined, and an estimate of damping can sometimes be made. For most structures in most locations, suitable wind excitations for this purpose will occur within an hour or so. Although it is usually only the fundamental frequency that is appreciably excited, there are some cases in which higher modes have been clearly recorded. By this method the Seismological Field Survey of the National Ocean Survey (NOAA) have determined the fundamental natural period of about 100 buildings in Los Angeles, San Francisco, Seattle, Long Beach, etc. These determinations assist in the evaluation of the appropriateness of the structural models assumed in the design process, and for the improvement of the earthquake-resistant design provisions in building codes. This "pre-earthquake" data is also valuable as a check point for "post-earthquake" determinations to study possible relationships between earthquake damage and natural period change. Several specific cases have now been documented in which strong earthquake ground motion has apparently permanently altered building periods by easily measurable amounts. Such investigations may ultimately result in a means for ascertaining the presence or absence of "hidden" earthquake damage.

A second method of making wind-excited tests uses lower-level wind contributions to the general background noise level of building motion. Such background levels are the result of microtremors, traffic inside and outside the building, operation of elevators, air conditioning equipment, and other machinery, etc., in addition to the wind. By making the test in the absence of prominent wind gusts, the overall excitation can often be approximated as a stationary random function, and the building properties can be derived from a spectrum analysis of the recorded response. In one method of analysis, the calculated Fourier Spectrum curves show directly the location of natural frequencies, and the shapes of the peaks give an estimate of damping. In another method of analysis, auto-correlation curves of the response are prepared. These auto-correlation curves should theoretically have the appearance of damped sine waves, from which the structural frequencies and damping can be determined. By either of these techniques a number of natural frequencies corresponding to various modes of vibration can be obtained.

For several buildings it has been possible to compare the dynamic properties as obtained from tests of the above type with those obtained from forced vibration resonance tests using vibration generator tests. Although the vibration generator tests usually involve amplitudes an order of magnitude or more greater than the wind tests, excellent agreement has been obtained. It appears that even at the very low levels of building vibrations associated with microtremors and low-level wind tests, the linear dynamic properties of the structure are accurately portrayed.

DYNAMIC RESPONSE OF STRUCTURES TO HIGH-VELOCITY WINDS

Arthur N. L. Chiu
University of Hawaii

A research project to investigate the dynamic responses of full-scale free-standing towers to high-velocity winds has been initiated at the University of Hawaii. The study will include measurements of horizontal wind velocities and horizontal accelerations in two orthogonal directions at five levels of a 150-ft free-standing triangular latticed tower.

Computed responses, due to time-varying wind forces derived from wind velocities measured at these five levels, will be compared with the field results. Additionally, responses will also be computed for simulated wind data generated by a random procedure on a digital computer.

Strong winds are frequently encountered during December-January in Hawaii, and it is expected that data will be gathered during the forthcoming windy period.

INTERACTION OF FLEXIBLE STRUCTURES WITH WIND

Norman A. Evans
University of Pennsylvania

The Towne School of Civil and Mechanical Engineering has, for several years, been involved in the study of the dynamic response of flexible structural systems, especially those supported by cables, with sponsorship mainly from the American Iron and Steel Institute. The accomplishments to date include:

a bibliograph on the subject;

the writing of computer programs to determine the dynamic response of single taut or sagged cables vibrating in a single plane when subjected to time dependent transverse forces, and to design an orthogonal net cable system of arbitrary form with the lowest natural vibration period falling within specified limits;

a comprehensive study of a pretensioned, single layer orthogonal cable network with respect to frequencies and mode shapes for a flat roof with different boundary shapes, together with errors incurred through treating the network as an equivalent membrane;

analysis of the vibrational characteristics of a cable network by Galerkin's method allowing treatment of arbitrary fixed boundaries, while another analysis has shown the effect of initial sag in a single cable on the lower resonant frequencies.

In addition, an examination of the statistical character of wind loads on structures has been carried out, and a preliminary wind tunnel study performed on a single cable.

In view of the extreme importance of the wind role, an effort is presently under way to establish a comprehensive program of wind tunnel testing on cables, membranes and combinations of each to determine the appropriate excitation distributions, thereby providing inputs for the theoretical analysis of the dynamic response. Another wind tunnel program will be concerned with vortex shedding in a laminar shear flow (representative of the atmospheric velocity profile) from relatively stiff slender bodies of circular cross section and straight taper. The aim will be to improve the basic understanding of the phenomenon, to provide a basis of comparison with the rather large amount of work already available using laminar uniform flows, and to obtain information in the somewhat neglected area of time-dependent pressure distributions and loads. Subsequent phases will involve the interaction of multiple bodies (for example, one in the downstream wake of another), unsteady body motion with secondary vortex generation, and the effect on the results of adding turbulence to the shear flow so that the wind representation is complete.

The work will be performed in a wind tunnel with a choice of either a closed or open circuit. The shear flow will be produced by a system of horizontal boundary layer plates and an appropriate amount of flow removal from the tunnel floor through a suction slot. When required, controlled levels of turbulence will be obtained from step barriers inserted between the boundary layer plates. Instrumentation will include multi-channel hot wire anemometry, fast response pressure and strain gage transducers, and means for flow visualization.

AN EXPERIMENTAL AND ANALYTICAL INVESTIGATION OF UNIFORM AND NON-UNIFORM TORSION OF PERFORATED HOLLOW SHEAR WALLS

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West Virginia University

In high rise buildings, concrete shafts are often used as an economic means of providing lateral stability. Structurally a shaft provides an optimum efficiency for resisting bending and torsion. Usually these shafts are perforated by vertical bands of openings to provide horizontal circulation in the building. Lateral wind and/or earthquake loads subject such shafts to torsion as well as bending. Even in the case of buildings whose axis of symmetry coincides with the centroid of the shaft, torsional loads develop as a result of wind loads. In recognition of this fact the SEACC earthquake code requires that the vertical shear wall be capable of resisting a minimum torsional load assumed to be equal to the lateral load multipled by 5% of the maximum building dimension.

The study has as its objective the investigation of the elastic behavior of perforated hollow rectangular shear walls subjected to uniform and non-uniform torsion. The major emphasis is to obtain a better understanding of the role of perforations on the warping torsional rigidity, Saint Venant's stresses and stress concentrations around the openings. Specifically, the effect of sudden changes in torsional stiffness on shear flow will be studied in detail. The investigation will be limited to rectangular prismatic hollow sections with symmetrical perforations. The three major aspects of the study are:

1. An analytical investigation of perforated hollow shafts subjected to both uniform and non-uniform torsion. The bending and torsional stiffnesses change suddenly at the openings; as a result a closed form solution of the governing differential equation is not possible unless these step functions are transformed into a continuous function.

In this study the differential equation is solved numerically in an effort to determine the stresses at points where the stiffnesses change abruptly.

2. An experimental program utilizing prototype steel models to confirm the numerical solution.

3. The establishment of design criteria for torsional analysis of building cores in high rise construction.

WIND LOAD STUDIES IN THE FLUID MECHANICS PROGRAM

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Colorado State University

Introduction

Since 1955 the staff of the Fluid Mechanics Program at Colorado State University has engaged in research having the development of a rational basis for the determination of wind loading on structures as its objective. Recognizing that laboratory simulation of wind loading must be a central element in such a development, initial efforts were focused on the design of laboratory flow facilities which would have the capability of simulating natural winds.[1,2] Fortunately, mean and turbulent flow characteristics generated in the boundary layer of a special meteorological wind tunnel have been found to be similar to essential features of the atmospheric boundary layer when comparisons with natural wind data were made.[3]

Upon having established the basis and the facilities to simulate wind forces on model structures, the Fluid Mechanics Program staff has investigated basic wind-force problems and wind forces on particular structures. Currently, a program to compare wind forces on a model structure and its prototype is underway.

A brief elaboration of activity in each of the areas mentioned is presented in the following paragraphs.

Wind-Tunnel Facilities and Studies of Flow Similarity

Figure 1 is a floor plan of the Fluid Mechanics Program laboratory, the Fluid Dynamics and Diffusion Laboratory, which shows a plan view of the wind-tunnel facilities. The meteorological and environmental wind tunnels are of primary interest for studies of wind loading on structures since the long test sections permit development of thick turbulent boundary layers up to 3 ft thick. Within this region wind forces on scale models of structures at scales of 1:200 to 1:500 can be studied in the simulated natural winds. The meteorological wind tunnel has the added capability of developing thermally stratified flows which can be employed to investigate environmental factors associated with air pollution and human comfort in the complex of structures near a new building development. On the other hand the environmental wind tunnel with a width of 12 ft can accommodate models of an entire city for studies of near meso-scale flow characteristics. A study of the heat island effect over the city of Fort Wayne, Indiana modeled to a scale of 1:4000 is currently in progress.

Much has been written on the similarity between shear flows generated in these wind tunnels and natural winds of various scales in the atmospheric boundary layer. A summary of most of the important findings may be found in References 4 and 5. It must be emphasized that winds simulated by these wind tunnels do not include features inherent in strong frontal action, intense thunderstorms or tornados.

Basic Research

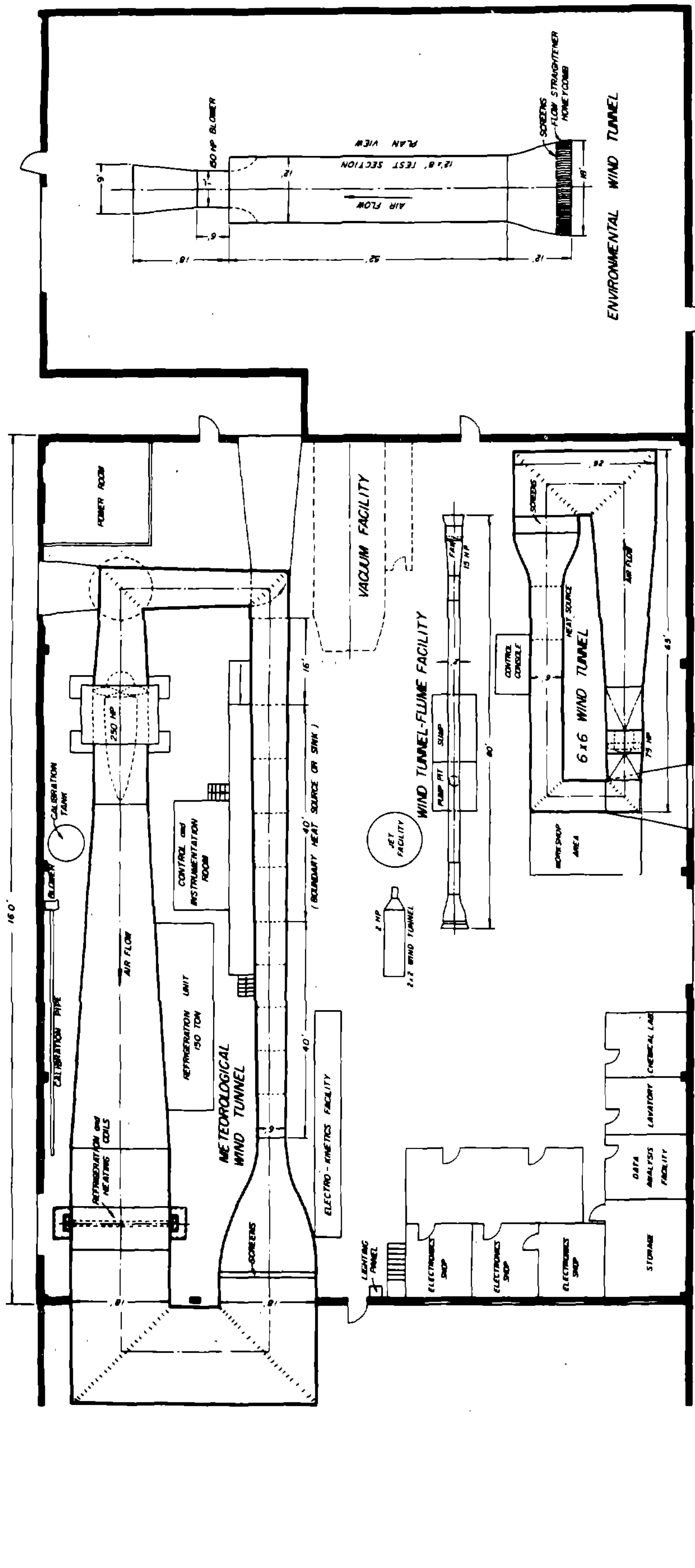
Two fundamental areas of fluid mechanics research related to wind forces on structure continue to be of interest in the Fluid Mechanics Program. One problem is the description of pressure fluctuations on a bluff body in terms of turbulence structure of the approaching flow. The other area is separation on a cylinder in a turbulent shear flow in which turbulence intensity, turbulence scale, mean shear intensity, cylinder surface roughness and Reynolds number are important variables. Dissertations by Marshall [6] and Roper [7] are contributions to the former and later problem areas respectively.

Applied Studies

Numerous wind-loading studies of particular structures have been accomplished in wind tunnels of the Fluid Dynamics and Diffusion Laboratory.[8] The meteorological wind tunnel was utilized for the first thorough study ever made of wind loading on a structure. The simulated natural winds made possible a quantitative determination of mean pressures, fluctuating pressures, dynamic response of the structure, and the effect of the structure on street level environment. This study was made on a 1:500 scale model of the World Trade Center Towers in a cooperative study with Dr. A. G. Davenport; the engineering firm of Skilling, Helle, Christiansen, Robertson and the Fluid Mechanics Program staff. Wind-force measurements have been made on scale models of the Bank of America World Headquarters Building,[9,10] the Atlantic Richfield Plaza Buildings,[11,12] the Kaiser Center Office Building,[13] and the Standard Oil Company (Indiana) Building.[14,15] Currently, a study of wind forces and diffusion of contaminants around the proposed Childrens Hospital, National Medical Center is in progress.

Model-Prototype Wind-Loading Comparisons

The inability to obtain "exact" similitude in both the flow dynamics (inequality of Reynolds numbers) and elastic properties of the modeled system opens the question of how accurately do the model-determined wind loadings and structural response represent prototype quantities. A resolution of this question must be sought through critical comparisons of data obtained from measurements on a full-scale structure and a scale model or models of the structure. A cooperative effort of this nature between the Building Research Division, National Bureau of Standards and the Fluid Mechanics Program staff is currently in progress. The NBS has instrumented a 3-story building of the NBS Gaithersburg complex with pressure transducers



FLUID DYNAMICS AND DIFFUSION LABORATORY

and has installed towers upwind of the structure for use in measuring meteorological variables. Corresponding measurements are being made on a 1:200 scale model in the meteorological wind tunnel. Plans for future study in this cooperative effort include model-prototype comparisons on dynamic response of a tall flexible structure.

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RECENT ACTIVITIES OF THE BOUNDARY LAYER WIND TUNNEL LABORATORY

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The activities of the Boundary Layer Wind Tunnel Laboratory are also described in companion reports by M. Novak and B. J. Vickery.

I would like to comment briefly on four areas of work in which we have been engaged (1) design methodology; (2) meteorology; (3) the aeroelastic response of structures; and (4) investigation of full-scale structures.

DESIGN METHODOLOGY

A primary objective in the study of wind loading is to predict performance of structures realistically and then to demonstrate the sensitivity of performance to various design choices. This prediction process must of course link together in a balanced order meteorology, aerodynamics, structural response and design criteria.

There have so far been two outcomes of this work: First the gradual development of procedures for synthesizing predictions of performance from meteorological, aerodynamic and structural information. These methods are inevitably fairly complex and only suited to fairly significant structures. Second we have worked on the formulation of various design wind load code requirements (e.g., the Danish Code, 1970 National Building Code of Canada and several others which appear to be following suit).

METEOROLOGY

There are two main problems here - climate and wind structure. In the former the aim is to find statistical models for describing the wind climate and specifying the dependency of the parameters on latitude, season, etc. Various models have been developed and are in use on a local basis in design studies; we are also seeking to describe wind climate on a much larger geographic scale. This mapping has already been carried out for various extreme winds (e.g., Thom's work) and are useful for many purposes, however, much more information and understanding is needed.

In investigations of wind structure, we have included both the mean wind and the turbulence properties and in particular their variations with height. This is important not only for direct application in design situation but furthermore for verification of wind tunnel modelling procedures. Work in all these areas is in hand.

AEROELASTIC RESPONSE OF STRUCTURES

We have undertaken studies of the response of various structural forms to wind. Because of the importance of dynamic response these have generally speaking been scaled aeroelastic models. The studies have been undertaken both for specific design investigations as well as for the determination for general behaviour characteristics. Included are tall buildings, guyed towers, chimneys, bridges.

INVESTIGATION OF FULL-SCALED STRUCTURES

We have collaborated on a number of full-scale investigations. Primary purpose of these has been to develop comparisons between theoretical predictions and/or experimental predictions carried out in the Boundary Layer Wind Tunnel. Included are such structures as the Golden Gate Bridge, John Hancock Building, the work carried out by NRC Canada on the C.I.L Building Montreal, and one or two others. Most of these have not been expensive elaborate experiments - rather to the contrary. The philosophy is that by appropriate statistical analyses of records made during moderately strong wind one can obtain a surprising amount of information concerning the structure and its response to wind which can be used for evaluating theoretical and experimental predictions.

THE EFFECTS OF SURFACE ROUGHNESS ON THE MEAN AND FLUCTUATING PRESSURES ON LARGE ROUNDED STRUCTURES

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There presently seems to be considerable uncertainty about the effects of surface roughness on both mean and fluctuating pressures exerted on large, rounded structures by turbulent flows at large Reynolds numbers. The roughness under consideration may consist of uniformly distributed random shaped elements or of geometrically regular configurations; in the latter category longitudinal strakes or ribs coplanar with the axis of the structure have been used in both model studies and prototype installations. Model tests, cited below, have demonstrated conclusively that at Reynolds numbers of the order of 10^5 surface roughness significantly reduces the suction lobes of the mean-pressure distribution as well as the pressure fluctuations. However, the underlying mechanisms responsible for the reductions have not been satisfactorily elucidated, and it is not certain that scaled-up roughness would produce corresponding reductions on prototype structures, such as large natural draft cooling towers, for which the Reynolds numbers are generally two to three orders of magnitude greater than the model Reynolds numbers. If the pressure reductions can in fact be produced for prototype towers significant saving could be realized in the quantity of reinforcing steel used in the shells since the circumferential stresses are quite sensitive to the negative pressures on the sides of the structures. The net result of the foregoing considerations is considerable divergence in practice regarding use of surface strakes to reduce the pressure loadings on natural draft cooling towers. Cooling towers constructed in Europe, especially those in Germany, generally are fitted with small external strakes (typically 2 cm high, 8 cm wide, spaced at 3° to 5° intervals around the tower) (Rothert, 1968; Niemann, 1968), which incidentally, are also used to support slip forms during construction. Some American designers (Rogers and Cohen, 1970) favor the use of ribs while others have not adopted them.

It is well known that the pressure distributions around model cooling towers exhibit a strong dependence on Reynolds number, surface roughness, and, to a lesser extent, on free-stream turbulence. These factors significantly affect not only the critical Reynolds number at which the flow changes from subcritical to supercritical (i.e., at which the boundary layer becomes turbulent before separation occurs), but also the mean and fluctuating pressure distributions in supercritical flow, as will be presently discussed (Pris, 1959; Davenport and Isyumov, 1966; Armitt, 1968; Rothert, 1968). The available experimental results demonstrate that these effects are, in general, similar to those on infinitely long circular cylinders. In particular, Armitt (1968) has observed that the pressure distribution at levels just below the throat of a tower is only slightly affected by the flows around the open ends of the tower, and is nearly the same as the pressure distribution obtained on circular cylinders.

For smooth circular cylinders the pressure coefficient c_p as a function of θ, the angular distance from the front stagnation point, is given by Goldstein (1938) as a function of θ for several values of the Reynolds number Re. In subcritical conditions c_p falls from a maximum value 1.0 at $\theta = 0^o$ to a minimum value at about $\theta = 70^o$; this minimum is a function of Re, varying from about -1.0 for Re = 2,800 to about -1.40 for Re = 1.06×10^5. Beyond its minimum point c_p rises slightly, and from about 80^o to 180^o remains fairly constant. In supercritical conditions the minimum value of c_p is much lower and falls steadily with increasing Re as the point at which it occurs moves farther around the cylinder (as does the point at which the transition from laminar to turbulent flow takes place). At Re = 1.66×10^5, min. $c_p \sim -1.90$ at $\theta \sim 76^o$; at Re = 2.12×10^5, min. $c_p \sim -2.20$ at $\theta \sim 80^o$; potential flow theory predicts a value of min. $c_p = -3.0$ at $\theta = 90^o$. The pressure coefficient at the back of the cylinder rises with increasing Re in supercritical conditions.

Roshko (1960) measured pressure distributions and evaluated the drag coefficient, C_D, for smooth cylinders at very high Reynolds numbers from 10^6 to 10^7. Frequency spectra and vortex shedding frequencies were also obtained. The drag coefficient appears to increase with increasing Re, from its low supercritical value of about 0.3 to approximately 0.7 at Re = 3.5×10^6, and then to level off at the latter value. The pressure distribution corresponding to Re = 8.4×10^6 shows that the trends outlined in the preceding paragraph are reversed for sufficiently high Re; min. c_p for Re = 8.4×10^6 is larger than the minimum for Re = 6.7×10^7 reported by Flachsbart (see e.g., Goldstein, 1938), whereas the base pressure is smaller. It should be noted, however, that the drag coefficient of Roshko's sandblasted pipe cylinder (surface roughness about 0.2×10^{-3} in.) is considerably greater than the drag coefficient measured by Jones (1968), also at Reynolds numbers between 10^6 and 10^7, on a much smoother circular cylinder. If the difference in the drag coefficients is due indeed to the difference in roughness of the two cylinders, as Jones has suggested, a significant influence of surface roughness on the flow characteristics (in particular, on boundary layer growth and separation) is to be expected, in view of the rather small roughness of Roshko's cylinder, and the reversals in trend of min. c_p with Re could be, at least partially, roughness effects. Wootton's (1968) measurements on circular cylinders at Reynolds numbers greater than 10^6, show that there is a significant difference between the behavior of highly polished models and models with a surface roughness of about 10^{-3} in.

A systematic study of the effect of distributed roughness or of concentrated roughness elements on the mean and fluctuating pressure distributions on circular cylinders is not available in the literature to the writers' knowledge. Available data on the effect of the drag coefficient C_D (Goldstein, 1938) show that with increasing roughness the drop in C_D at transition becomes smaller and occurs at a lower critical Reynolds number Re_c; no appreciable fall in C_D would probably take place for large enough distributed roughnesses.The summary of available results presented by Rothert (1968) serves to emphasize both the importance of surface roughness effects and the lack of a systematic study of these effects. Rothert suggests using as significant parameter the ratio k/δ_{60}, where k is a measure of the roughness size and δ_{60} is the laminar boundary layer thickness 60 degrees downstream from the forward stagnation point.

Information on the effect of concentrated roughness elements is even scarcer. Goldstein (1938) shows that even small wires placed along generators at $\theta = \pm 65^{o}$ and projecting into the fluid a distance of only 3 percent of the boundary layer thickness have a large effect on the total drag. The disturbance created by generator wires becomes less severe when they are moved forward and away from the transition region; wires at $\theta = \pm 25^{o}$ were found to have practically no effect except locally.

Some work on roughness effects on mean pressure distributions on models of hyperbolic towers has been reported in the literature (Golubovic, 1957; Pris, 1959; Davenport and Isyumov, 1966; Armitt, 1968; Rothert,1968). The observed trends, however, have not been satisfactorily explained. Golubovic measured pressure distributions on a model of a hyperbolic cooling tower with different rib arrangements; his results show a strong dependence of the pressure distribution, especially of the magnitude of the maximum suction and also of its position, on the height and pattern of the ribs. The minimum value of the pressure coefficient is shown to vary from about -2.1 at $\theta \sim 83^{o}$ for a smooth surface to about -0.95 at $\theta \sim 73^{o}$ for a crossed-rib arrangement with the ribs disposed along the generators of the hyperboloid, with distance between ribs at the throat equal to 0.30 of the throat radius, and rib height equal to 0.3 mm. A slightly larger reduction is obtained with vertical ribs 1.0 mm. high, spaced also at 0.30 of the throat radius at the throat. (No Reynolds number is given in the paper for these data; see below). No attempt was made by him to explain the physical origin of the trend, and the question of what would be the optimum rib arrangement to accomplish the reductions in suction, which is of interest for design purposes, cannot be answered from these results. Moreover, the pressure distribution is taken to be independent of Re for Re > Re_c, with $10^3 < Re_c < 10^5$, a result contradicted by all other available experimental data. It is to be expected that if the ribs are high enough to fix the point of separation, then the tower would behave like an angular building, in which case only the possible effect of changes in Re on the wake mechanism is present and this effect is normally ignored (Rouse, 1947; Chien, et al., 1951). The elucidation of this point is also of interest with regard to model-to-prototype conversions.

Armitt (1968) has studied the effect of varying roughness, free-stream trubulence, and Reynolds number, on the mean pressure distributions on model hyperbolic cooling towers. The results for a tapping level just below the throat of the tower, less affected by the flows over the open ends of the tower and therefore more nearly resembling the results for long circular cylinders, were selected for discussion. For the smooth model, the maximum suction increases significantly with increasing Re. Wind tunnel test results obtained at the National Physical Laboratory (Cowdrey and O'Neill, 1956) at Re = 7.4×10^6 using a model hyperbolic tower show that this trend is reversed for high enough Re, as in the case of the circular cylinders discussed above. (The surface roughness of the NPL model, however, was not measured.) Armitt's (1968) tests revealed several things, as follows. The base pressure is strongly influenced by the sharp-edge separation at the upper lip of the tower and is relatively insensitive to changes in Reynolds number. Peak suctions are generally lower for a circular cylinder. Roughness effects are rather large. For rough surfaces the transition to supercritical regime occurs for smaller Re, and, in supercritical conditions, increasing the roughness steadily decreases the maximum suction. The base pressure is always relatively insensitive to changes in roughness, free-stream turbulence, or Reynolds number. Armitt suggests that the Reynolds number based on the size of the roughness, which he calls the roughness Reynolds number, is a significant parameter. It is interesting to compare this parameter with Rothert's k/δ_{60}, mentioned earlier.

These trends are generally confirmed by the work of Paduart (1968), Davenport and Isyumov (1966), and Pris (1959), also with distributed roughness. No satisfactory explanation for them has been provided, and application of these data to full scale may introduce significant errors unless adequate modeling criteria are developed. Moreover, appreciable differences in the magnitude of the side suctions, and also in base pressure, appear to exist between the various reported studies on hyperbolic cooling towers and require additional work (see e.g., Davenport and Isyumov, 1967).

It is these uncertainties that have resulted in the divergence of practice regarding the use of ribs on prototype towers.

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NON-STEADY SEPARATED FLOWS BY POTENTIAL THEORY

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Potential theory, augmented by the Kutta-Joukowski condition satisfactorily predicts airfoil lift as long as the flow is not separated. The method falls short in the case of separated flows. This short-coming is due, not so much to limitations of potential theory, as to inapplicability of the Kutta condition.

Its generalization to include nonsteady separated flows about a bluff body is expressed by the following two statements:

1. Shear layer detachment (not to be confused with separation point) occurs at points of velocity maxima.
2. The time rate of vorticity transport into the free stream at these points is $\frac{1}{2}U_s^2$ where U_s is the local potential surface velocity.

Implementation of this generalized Kutta condition (GKC) is accomplished in computer solutions of the nonsteady flow, using finite difference methods. The released vorticity is represented by discrete vortices periodically introduced at the instantaneous shear layer detachment point. The product of individual vortex strength and frequency of introduction satisfies the second criterion above. Finally it has been found that the spacing of vortices near the detachment point found in this manner can be related to flow Reynolds number through an equivalent shear layer thickness. Studies have shown this relationship to be of the form: $Re=25\left(\frac{a}{U_o t_f}\right)^2$ where Re = Reynolds number based on diameter, U_o = free stream velocity, a = radius of cylinder and t_f = period of new vortex introduction.

Validity of the GKC stated above remains to be fully proved, and perhaps further modified. Results so far obtained include forces and pressure distributions on a circular cylinder, both stationary and flexibly supported, at Re less than 1,000. These compare favorably with experimental data, and are reported in the following references listed by study contract number.

NASA/MSFC	Contract	NAS8-20140
NASA/MSFC	Contract	NAS8-21138 (Available as NASA CR 61198)
NASA/ARC	Contract	NAS2-3675
NASA/ARC	Contract	NAS2-4327
NAVY/NSR& DC	Contract	N00014 C-68-0223, Phase II (Available from Defense Documentation Center)

THEORETICAL INVESTIGATIONS

H. Serbin

California State College at Los Angeles

1. Flow around Blunt Bodies

The classical flow problem about a two dimensional flat plate normal to a freestream has been solved by modifying the Helmholtz solution to include viscosity. The drag coefficient so obtained is 2.3 compared to the accepted experimental value 2.0. The minimum pressure behind the plate agrees with the measurement of Roshko. The theory predicts that the length of wake varies as $R^{1/2}$. The analysis is based on steady flow and may be regarded as the time-averaged part of the real unsteady flow.

The results obtained so far are considered as a precursor to a more complete analysis leading to a description of the details on the lee side of the plate. More experimental data should be obtained to verify the resulting predictions.

The next step in the theory is to develop the fully turbulent flow in the far wake. A plan for doing this is being formulated.

2. Response of Structures to Turbulent Pressure Environment

Research on this subject has been carried out similar to a number of other investigations. However, the emphasis here has been to infer from the structural response information on the ambient pressure field. Research plans have been formulated for correlating experimental random pressure levels in a cavity with the drag of grids mounted in the cavity.

HIGHLY TURBULENT AND SEPARATED FLOWS

D. E. Coles and A. Roshko
California Institute of Technology

There has been a long-time interest in our laboratory in turbulent boundary layers, flow separation, aerodynamics of bluff bodies, methods of measurement, etc.

Current interest is centered around the problem of obtaining measurements in regions of low mean velocity and high fluctuation level such as occur in separated flow. Measuring techniques being developed make use of modern digital methods of data acquisition and analysis. The goal is to measure in complete detail the flow fields about bluff structures in highly turbulent flow, in particular, the difficult region on the lee side.

Recent work includes the problem of effects of surface roughness on flow separation. It has been noted that the drag coefficient of a circular cylinder at Reynolds numbers as high as 10^7 can vary by a factor of 2, depending on surface roughness. This is clearly an effect of the sensitivity of the boundary layer separation point, since bodies with fixed separation, e.g., at an edge, are not roughness sensitive.

Another area of work is concerned with the experimental correlation and semi-theoretical understanding of bluff body aerodynamic coefficients, their dependence on cross-sectional shape, wind-tunnel wall effects, etc.

AERODYNAMIC INTERFERENCE OF BUILDINGS

William J. Kelnhofer
The Catholic University of America

An experimental study in uniform flow of the effect of a neighboring building model on the steady-state wind loading of a primary model was recently completed. The models were rectangular in cross-section and parallel to each other. The relative model heights, wind direction and distance between models were varied. Depending on the model combination, the neighboring model had a favorable or adverse effect

These tests should be extended to include shear flows over the models. Detailed measurements in the flow field around and between the models should be taken. Also, investigations with models of other geometric configurations representative of actual buildings should be carried out.

Results of experiments such as these will add to the understanding of certain localized air pollution problems and hazardous wind flows around and between buildings. They should lead to improved standards, economies, safety and occupant comfort.

An attempt on an analytical approach to the problem of wind loading of buildings and the flow around buildings should be made. A semi-empirical approach using known concepts of flows around blunt bodies along with detailed results of a parametric study using models in a wind tunnel would probably give some interesting results.

FLUCTUATING LOADING ON STRUCTURES

W. Z. Sadeh
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Wind loading on structures is an integral element of functional, safe and economic design. The study of aerodynamic forces and moments acting on high-rise structures can now be accomplished through the use of scaled models in suitable large scale wind tunnels. The wind tunnel flow should be capable of simulating the atmospheric surface layer. Particularly, the surrounding and upwind roughness, both natural and man-made, must be also modeled to account for their effect on the oncoming flow. Basically, geometrical, kinematic, dynamic and elastic similitude of the prototype and modeled structure is to be attained. The various limitations in achieving exact overall similarity do not lessen the intrinsic value of wind tunnel investigations.

In addition to mean forces and moments, the fluctuating and instantaneous forces and moments are of prime importance in determining the overall effect of random gust loading, structure fatigue and maximum acting stresses. In particular, these effects are important for outer paneling and exterior skin design. The mean forces and moments can be deduced from mean pressure distribution acting on the structure. On the other hand, measurement of fluctuating and instantaneous pressure distribution and resulting forces and moments is most difficult and complex. The overall instantaneous overturning moments can be measured directly by means of an aerodynamic balance. The fluctuating pressure can be measured by using sensitive and relatively high frequency response (200 Hz or more) pressure transducers.

The problem of interest is to find out the mechanism through which the fluctuating loads are generated. This information is now becoming available due to advances in wind tunnel modeling technique. Recently, it was clearly shown that the fluctuating loads depend strongly on the oncoming turbulence (1, 2). A successful attempt of measuring the instantaneous overturning moment about the weak axis of a modeled tower by means of a single degree of freedom dynamometer was recently carried out (2). The dependence of the fluctuating moment upon the oncoming turbulence was clearly discerned. In the case of the upwind rough surface the instantaneous fluctuating moment reached up to 34% of the mean moment. Furthermore, the rms value of the fluctuating moment was about 20% of its mean value. It is important to notice that the turbulence intensity averaged over the tower height was roughly of the same order of magnitude. On the other hand, under exactly similar flow conditions but with smooth upstream surface, the fluctuating moment was only about 8% of the mean moment.

In order to assess the eventual correlation of the turbulence and fluctuating pressure, detailed turbulent energy and surface pressure fluctuation spectrum surveys were conducted (1). Generally, it was found that the spectra of both turbulence and surface pressure fluctuation exhibit a similar behavior. Most of the energy is concentrated within the same frequency range, i.e., up to about 20 Hz depending upon the particular spatial position. Moreover, within the inertial subrange, the -5/3 power decay was approximately satisfied by both spectra.

The general congruence between the turbulent intensity and the fluctuating moment, and between the turbulent-energy and surface pressure fluctuation spectra is significant. It can be inferred that both the fluctuating moment and pressure are generated primarily by the oncoming turbulence. Furthermore, it is suspected that they do correlate directly in a manner that is actually being investigated. Undoubtedly, the understanding of this mechanism is important for predicting the fluctuating and instantaneous loading on structures.

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UNSTEADY AERODYNAMICS OF BLUFF BODIES

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University of Michigan

For the past eight years we have been studying the unsteady aerodynamic forces and moments produced by the steady flow of fluid past three-dimensional bluff bodies. Our work began with observations of the unsteady motions of freely falling disks. The unsteady motions are caused by the instability of the near wake which at low Reynolds numbers causes periodic vortex shedding that is accompanied by a rocking motion of the disk. At higher Reynolds numbers the rocking motion becomes more violent, and the near wake is turbulent. If the moment of inertia of the disk is large, the rocking motion becomes a random tumbling motion.

The unsteady moments on a large disk were studied in a wind tunnel. With the aid of linearized aerodynamic theory the random buffeting motion and behavior of the disk can be understood for amplitudes of oscillation below 45 degrees. A right circular cylinder was also studied. It was found that in this case the damping coefficient is negative, owing to the motion of the separation line, and divergent oscillations occur followed by autorotation.

Measurements of autorotation phenomena of a two-dimensional wing section have also been made. The measurements include the mean and fluctuating lift, drag, angular velocity, pitching moment, and power extracted from the flow. In general the unsteady flow fluctuations produced by autorotation are extremely violent with large lift coefficients fluctuations, $\Delta C_{\ell} \simeq 5$.

Further studies involving more subtle motions of the separation line have been made for the flow over stationary spheres. In wind tunnel tests at Reynolds numbers above the critical Reynolds number the random lift (side force) fluctuations are of appreciable magnitude ($\Delta C_{\ell} \simeq 0.2$). The lift fluctuations are correlated with random vortex shedding, separation line motion, and fluctuating bound vorticity about meridian planes of the sphere. Additional work on spheres is now in progress using a unique towing tank filled with glycerine and fitted with an air bearing supported three component balance on a carriage. Flow visualization of coherent vortex shedding at low Reynolds numbers accompanied by measurements of force fluctuations are planned.

WIND-STRUCTURE INTERACTIONS

B. J. Vickery
The University of Western Ontario

1. Vortex Shedding from Non-Prismatic Structures in Turbulent Shear Flow

Measurements have been made of the spectra and cross-spectra of the fluctuating lift force on a tapered structure of circular cross-section. Results indicate that at a given section the forces are narrow-banded with the bandwidth increasing with increasing turbulence level and a centre frequency which corresponds approximately to a constant local Strouhal number. Cross-spectral measurements showed that the coherence dropped rapidly and was near zero for separations greater than about one or two diameters.

2. Significance of Torsional Vibrations for a Building of Square Cross-section

The dynamic response of a seven element model of a tall building of square cross-section has been investigated for a range of torsional/ lateral frequency ratios. Preliminary results indicate that significant torsional vibrations develop only for a frequency ratio near unity. The lateral vibrations are not markedly influenced by the presence of the torsional vibrations. There is strong aerodynamic coupling between the two modes at a frequency ratio near unity.

3. Pressure-Velocity Correlations for a Bluff Body in Turbulent Flow

Measurements have been made of the cross-spectra of the velocity fluctuations just upstream of a two-dimensional bluff body in turbulent flow and the pressure fluctuations at various points around the body. The coherence for pressures in the unseparated region is near unity for frequencies up to, approximately, the Strouhal frequency and then decreases rapidly and is effectively zero at about twice the Strouhal frequency. Within the wake region the coherence is well below unity at all frequencies although it would appear that velocity fluctuations at frequencies less than the Strouhal frequency are effective in producing pressure changes in the wake region. The low coherence is apparently due to substantial pressure fluctuations due to the body itself rather than the velocity fluctuations.

4. Wind Action on Yielding Structures

Theoretical studies have been made of the response of simple yielding structures to wind loads. To date, attention has been restricted to the development of permanent set in an idealized yielding structure under the action of mean and fluctuating drag loads.

WIND-INDUCED OSCILLATIONS OF STRUCTURES

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Since the completion of a low speed wind tunnel in 1957 the Mechanical Engineering Department at U.B.C. has pursued research on wind-induced oscillation of structures. The main emphasis has been on coherent mechanisms of aerodynamic excitation leading to oscillatory response, in one degree of freedom, of long cylinders of aerodynamically bluff cross section.

The first investigations concentrated on galloping oscillations in smooth uniform flow under nearly two-dimensional conditions. Galloping results from an aerodynamic instability to transverse or torsional disturbance velocity of the body, and the research has demonstrated that a quasi-steady theory, using static wind tunnel measurements of aerodynamic loading, accurately predicts galloping behaviour under the above conditions.

More recently, phenomena of wake-vortex-induced transverse oscillation of bluff cylinders, under nearly two-dimensional conditions in smooth flow, have been investigated. Details of the frequency lock-in phenomenon, and of cylinder amplitudes as functions of wind speed and their dependence on structural damping have been measured, as well as instantaneous pressure loadings, phase relations, and spanwise correlations, and their dependence on cylinder amplitude. Comparisons have been made between these phenomena for the circular cylinder and the D-section cylinder, showing the more vigorous oscillations of the latter caused by the correlating effect of its fixed separation lines.

Currently an investigation of galloping behaviour in turbulent winds produced by grids is in progress. The cylinders and elastic mountings used for the studies of smooth flow are being used again, and both static loadings and galloping behaviour are being measured, with a view to determining the applicability of the quasi-steady theory under the turbulent wind conditions.

In 1971, a new aerodynamics laboratory building will be completed, and a new 3-purpose wind tunnel is planned for it. One of the 3 planned configurations is a boundary layer tunnel, and it is intended to make comparisons of its performance in producing equivalent natural wind boundary layers with that of a configuration using a short section of special floor-mounted turbulence-generating elements, such as have been developed recently in laboratories in England and Canada.

GALLOPING INSTABILITY OF STRUCTURES

Milos Novak
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Aeroelastic (galloping) instability of structures is an important phenomenon for two reasons: First, strong lateral self-excited oscillations can develop above a certain wind velocity (onset velocity) as a result of the lateral aerodynamic force component. Second, the tendency to these vibrations affects the behaviour of the structure below the onset velocity since it produces a negative aerodynamic damping which can considerably reduce the total damping available to the structure. Both of these implications of aeroelastic instability come into consideration with structural shapes that are often in civil engineering such as prisms with square and rectangular cross sections. The ever decreasing specific weight, damping and rigidity of tall buildings bring the onset velocity closer to design wind speed. With smaller elements such as transmission lines, galloping phenomena have been observed for decades. The reduction of the total damping affects every structure with the mentioned cross sections since it increases the lateral response to wind gusts.

The quasi-steady theory allows the prediction of the galloping oscillations and the negative aerodynamic damping of structures and structural members. The main results of the theoretical analysis can be summarized as follows.

Galloping oscillations can arise above a certain onset wind velocity with lateral force coefficient $A_1 > 0$ (Den Hartog's criterion) and also at $A_1 \leq 0$. In the latter case, an initial disturbance (amplitude) is also necessary to trigger the vibrations. This triggering disturbance can be considerably smaller than the stable amplitude, must be larger than the unstable amplitude and it decreases with increasing wind velocity. The onset velocities are higher with $A_1 \leq 0$ than with $A_1 > 0$ and are directly proportional to structural damping in all cases.

The steady amplitudes are described by an algebraic equation, which can be written down directly with any lateral force coefficient, mode of vibration and even with a shear flow.

The validity of quasi-steady theory is restricted to wind velocities well above the vortex resonance and proved in general best with square cross-sections. With rectangular prisms the theory applies with higher reduced velocities than with square prisms. With prisms 2:1, it does not seem possible to predict either galloping instability or negative aerodynamic damping at reduced velocities lower than $U_f \simeq 12$ on the basis of quasi-steady theory.

Rectangular prisms feature the tendency to establish a strong control of the motion of the body over vortex shedding. This link is clearly manifested at low reduced wind velocities and low damping when strong vortex-excited oscillations of rectangular prisms can develop covering a very broad velocity range. A typical feature of these oscillations is that the dominant frequency of vortex shedding can become independent of wind velocity and consequently the frequency of the motion is constant and equal to the natural frequency of the body. With square prisms, the frequency of vortices is much more independent of the motion.

The lateral response of structures is affected by turbulence of the flow to various degrees. Turbulence corresponding to suburban environment need not entirely change the pattern of lateral response. However, turbulent conditions pertinent to downtown areas of large cities can entirely change the character of lateral response for both galloping instability and vortex shedding. Regions of strong response observed in smooth flow can completely vanish in turbulent flow and new vibration phenomena can appear. Therefore, thorough wind tunnel investigations in the turbulent flow simulating the natural environment seem to be the only reliable way of verifying the aeroelastic stability of structures surrounded by rough terrain and city environment.

AEROELASTIC STABILITY OF SUSPENSION BRIDGES

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Princeton University

The primary problem treated to date has been that of flutter of suspension bridges under steady laminar flow. While considerable concern was first shown for the basic problem of bridge deck cross-sectional geometric form, an attendant problem has been given much attention: that of experimentally obtaining aerodynamic coefficients capable of expressing quantitatively the inherent aerodynamic stability characteristics of any given bridge deck form.

To this end a method has been devised and used rather extensively to extract "flutter derivatives" from models tested in essentially two-dimensional flow.

A number of deck cross-sectional forms - notably streamlined, open-truss, and H-sections, including also the symmetrical airfoil as well as the original Tacoma Narrows deck, have been tested as two-dimensional models between end plates in an open-jet tunnel. Contributions to this technique, both experimental and analytical, have been made by Professor J. J. Tomko of Cleveland State University. For each model, flutter derivatives have been gathered by "back-calculation" from observed model motion. The amount of "noise" present in such back-calculation has been surprisingly low.

The model motion is, typically, sinusoidal motion with exponentially varying amplitude, and the theoretical validity of employing such motion to obtain flutter coefficients has been examined for the case of the airfoil, which has served throughout as a kind of prototype for the work. Results for many bridge deck forms, however, reveal clearly that theoretical airfoil flutter coefficients are inapplicable to bridge decks, simply because the flutter derivatives of the latter differ greatly from those of the former. The most notable difference lies in the possibility, for many bridge decks, of single-degree-of-freedom instability in torsion, an impossibility for unstalled airfoils.

A semi-quantitative theory for the torsional instability of both bridge decks and stalled airfoils has been developed under this study by Jon D. Raggett. The effect of the Reynolds number of the test flows, of necessity orders of magnitude below those of full scale flows, has also been examined by him. While not predominant, influence of Reynolds number is found appreciable in some cases and suggests precautions to be taken in scale model testing.

The entire problem of the buffeting of a suspension bridge, in the presence of the self-excitation terms required for aeroelastic stability considerations, has been taken up. (Notable contributions to it have already been made in the literature by A. G. Davenport.) The influence of turbulence in the oncoming wind has of course been a prime consideration in the later work of this study. The presence of turbulence in the oncoming flow appears in general to delay the onset of flutter, i.e., raise the flutter velocity over that developed under laminar flow. The aeroelastic problem in the presence of turbulence requires the repetition of the earlier search for flutter coefficients, but now in the presence of random excitation and response; it further requires the design of experiments permitting definition of the aerodynamic admittances of typical deck section models. Work of this type has been outlined and carried to an intermediate stage of advancement by E. Simiu at Princeton.

At present, representative results for laminar flow flutter coefficients for the incipient flutter motion of a wide variety of deck sections are available, and an ASCE publication is being prepared on this subject. They serve to indicate that certain streamlined sections are likely to be quite stable, that certain (but not all) open-truss decks can be made so also, but that H-sections are outstandingly unstable in the wind. The aerodynamic mechanisms of this are traceable through the available flutter coefficients.

The research outlined has been carried out under Grant No. K-010552 to Princeton University from the National Science Foundation.

WIND LOAD RESEARCH
SOME UNANSWERED QUESTIONS AND ANTICIPATED PROBLEMS

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The most needed research in the field of wind loads is a better characterization of the wind structure itself, particularly in storm conditions. Although some basic work has been done in measuring wind structures in relatively clear locations, very little appears to have been done in complex situations such as in a region with numerous structures.

Spatial measurements need to be made with late generation instrumentation in both open and complex regions. It would be useful, for instance, to know more of the aerodynamics of gusts, that is, the kinds of flow curvatures and pressure differentials that could be reasonably expected in storms. The gust is probably the cause of much of the nonstructural damage to otherwise well designed buildings. Line type structures and probably suspension bridges should be affected only by the short time increase in dynamic pressure, unless the disturbance is produced with some regular period corresponding to a resonant frequency of the structure. Research is needed on the effect of a short period gust or vortex on a structure in its path. Certainly, one would not expect the pressure distributions to be the same as that due to the steady wind of a standard wind tunnel. The transient character of the pressure distributions naturally raises questions concerning oscillation and fatigue of the structure and its elements.

Every obstruction to a moving stream of fluid leaves it distinctive imprint on the flow for some distance in the wake. When a second structure is, so to speak, flying in the wake, it is shielded to some extent because of a general velocity deficiency. However, the wake produced by the upstream object (buildings, towers, bridges) may contain large-scale turbulence possibly producing significant buffeting of the downstream object. This effect can be particularly troublesome for bridges, especially if one is a suspension type. The general problem is one of interference or interaction of adjacent structures. Guidance is needed for the designer faced with a location problem with a potential interference effect.

The testing of important structures such as extremely tall buildings has in recent years been carried out under conditions simulating in scale the local terrain including models of adjacent structures. This is a distinct improvement over the simple wind tunnel test. It is recommended that for such tests, some thought be given to the probability that the terrain may change markedly during the life of the structure. For example, what is to prevent the later construction of a similar structure a short distance away (upstream for prevailing winds)? What legal recourse (if any) exists to prevent construction if a serious buffeting condition can be predicted for the existing structure?

With respect to the tall buildings being constructed, it may strike an observer that these are poor cantilever wings in a sense. For such shapes, the center of pressure (at varying angles relative to the wind) does not coincide with the elastic center. Consequently, twisting moments are generated, with a resulting rotation of the structure. Present testing techniques need to consider the possibility of torsional motions particularly for structures with poor torsional stiffness characteristics. The possibility of coupled motions should also be considered.

Of extreme importance to the total picture of structural response to wind loads is the question of structural damping. The expanding use of light-weight building cladding and the greater use of welding (rather than riveting) has caused a reduction in the ability of all types of structures to limit vibratory motion. The ability to predict structural damping with its variation with amplitude and the development of methods of increasing damping without sacrificing structural integrity are of extreme importance to structural designers.

To summarize, research is needed in all aspects of the problem of wind loads and structural response. The research must be basic in nature, rather than just testing for specific cases. The time is past for reliance on the "judgment of the building official". The time is past as well for learning from failure by extrapolation.

RESEARCH ON WIND LOADS ON FULL-SCALE STRUCTURES

W. A. Dalgliesh
National Research Council of Canada

Wind load research by the Division of Building Research, National Research Council of Canada, was started over 10 years ago by the Division's Building Structures Section. Literature searches then revealed a great need for field investigations to provide data for checking wind tunnel and analytical methods by which design quantities can be estimated. To meet that need, which still exists today, three buildings, 9, 34, and 45 stories in height, have been instrumented in turn and preparations are now well advanced for the instrumentation of a fourth, taller building (an office tower).

One particularly important area of field measurements is the gathering of wind speed and direction information in a city environment. The instrument used by DBR/NRC consists of a separate vane and three-cup generator anemometer in use by the Canadian Meteorological Service. It is rugged and accurate up to at least 100 mph, but its frequency response is perhaps not quite adequate, possibly resulting in a loss of information at the high end of the spectrum. FM radio masts are used to site the anemometers, with a mimimum of two levels considered adequate (unfortunately, in past experiments only one level has been available). Not only are such records essential for correlating wind inputs with building response for the particular building under study, they are also needed for relating winds over the city to winds measured at the regular meteorological stations usually found at airports.

A second challenging field measurement problem is the recording of building displacements, both resonant vibrations at the fundamental frequency of the building, and the slow, a-periodic drift motions under the action of large gusts. A prototype of a measurement system suitable for the office tower now being instrumented has performed quite well in preliminary outdoor trials, for example, in measuring bridge deflections during the passage of a train. Analog signals representing X- and Y-displacements of a target on a moving part (of a bridge or building) are provided by a servo-controlled tracking system which locks onto a laser beam directed from a fixed reference location. Motions from d.c. to about 0.5 Hz with amplitudes up to 12 in. can be tracked to within 0.02 in.

Strain gauges have been installed on several of the main girders and on two typical columns to provide additional information on the response of the structural frame to wind gusts. The two main objectives are to investigate the nature of the wind loading and to compare the response of the structure with that predicted by design calculations. As in two earlier field studies, wind tunnel investigations are an invaluable, if not an essential, part of the project. In the present project, detailed model studies were carried out to provide the wind loading information used in design.

Confidence in the modelling of turbulent shear flows to represent wind realistically is steadily growing, and although confirmation of building response by field studies is still sorely needed, clearly the problem of cladding design (as opposed to design of the frame) is coming to the fore. Again, careful model studies seem to be the best hope but there are new uncertainties, such as possible scaling effects in the separation and reattachment of flow lines representing wake boundaries. These have been found to define regions of intense pressure fluctuations that are particularly significant for cladding design.

Surface pressures will be sampled at four levels of the office tower under study, with about twenty locations chosen for simultaneous recording at any one time. There will be a total of forty-eight locations to choose from. External pressures (measured with respect to some convenient internal pressure) must be modified by a consideration of the pressure within the wall cavity in order to find the net loading on the thin outer skin of the wall. In this respect, the ratio of cavity volume to venting area may be an important parameter.

Up to 32 parameters (surface pressures, strains, wind speed, etc.) will be sampled at intervals of ½ or ¼ second for periods of about 5 minutes initiated by a clock every six hours. This will provide a regular sampling of meteorological and building response parameters throughout the two or three years that the experiment will run. It is hoped that this collection of data will provide a useful statistical sample to check predictions of wind conditions made for longer periods. In the event of high winds, a second mode of recording is triggered, to produce longer recording periods of up to one hour. At the end of one period another record will be started almost immediately if the wind is still strong. By using preceding and succeeding 5-minute records taken during calm periods to establish zero positions, it should be possible to relate wind-induced pressure differences, strains and displacements, to the wind speed and direction.

WIND LOADS ON OCEAN STRUCTURES

John H. Nath
Oregon State University

This research is concerned with the wind drag forces on ocean structures. Preliminary experimental work has been performed on offshort platform-type structures in a wind tunnel at Colorado State University.

Early experimentation was conducted in a smooth wind tunnel of about 6 ft. x 6 ft. test section with wind velocities up to 50 fps. Model structures were subjected to uniform flow and flow where the structure was submerged in the boundary layer. It was determined that for structures supported on elevating legs that the drag coefficients were considerably lower than for the same structures supported flush on the wind tunnel floor. This was due to the jet of air under the structure which modified the pressure distribution on the upstream face and reduced the size of the wake. For example, the total drag coefficient for an elevated cube was about 0.94 whereas for a cube mounted flush on the floor it was about 1.32.

In order to gain possible insight to the behavior of the drag force on structures subjected to waves, a wavy surface of five sinusoidal waves was built into the floot of the wind tunnel. The waves were six feet long with a double amplitude of 0.45 ft. There were no separation zones in the lee of the crests. Velocity distributions in the boundary layer were nearly logarithmic. Four elevated structural types, a cube, a sphere, a platform and a platform tower, were tested at various positions on the fourth wave. Unfortunately, the boundary layer thickness was less than the structural heights so that the results were mostly applicable to conditions of nearly uniform flow.

Corrections were made to the measured forces to account for the longitudinal ambient pressure variation from the sinusoidally changing cross-section, for blockage effects and for added mass effects from the convective acceleration. From the resulting forces the experimental drag coefficients were derived and it was seen that at the position one fourth a wave length upstream from the crest of the fourth wave the coefficient increased from 20% to 60%. Thus, not only the turbulent variations in the wind act on the structure but the drag coefficients themselves may vary as a wave passes the structure. This may be due to the modification of the wake downstream of the structure due to the presence of the wave crest downstream. This work has not been verified and should be considered as very preliminary.

What is needed is a more complete knowledge of the combined wind and wave forces on offshore structures including directional qualities. The wave forces are functions of wave energy and frequency. If the structure is sensitive to wave frequency it will likely be sensitive to the frequency of fluctuating wind forces depending to some degree on the geometry of the structure.

GROUND WIND LOADS ON LAUNCH VEHICLES

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Ground winds blowing over erected launch vehicles can create problems in structural strength, guidance alignment, and clearance with adjacent structures. Usually ground-wind-loads data are needed before completion of the full-scale vehicle. Wind-tunnel studies using aeroelastic models are believed to provide the most direct and reliable means of predicting the response of launch vehicles to a steady wind. The two major ground wind loads are the vortex-shedding loads (which cannot be calculated at present) and the steady drag loads. Both types of loads are simulated by the wind tunnel.

Wind-tunnel studies of the effects of ground wind loads on a number of specific launch vehicles have been made in the NASA Langley transonic dynamics wind tunnel. Much of this work is reported in the following references.

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WIND TUNNEL WORK ON GROUND WIND EFFECTS ON STRUCTURES

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There are two major aspects of the problem of ground winds which presently concerns us at M.I.T. - the wind load and the velocity at ground level in the vicinity of structures. The former relates to the safety and the latter to some particular requirements of the structures. We shall elaborate these two points later. The investigation of these problems usually requires a wind tunnel test. In order to obtain realistic data, the specific structure must be tested in the presence of its surroundings and in a velocity profile appropriate to the terrain near the structure.

To create an appropriate velocity profile one may build special tunnels, such as those at the University of Colorado, or University of Western Ontario, with long test sections to enable the development of thick boundary layers to simulate the earth's natural boundary layer. Different terrains are simulated by using different degrees of roughness in the upstream part of the floor. Another approach which is the one used at M.I.T., is to utilize the existing subsonic wind tunnel with upstream being appropriately blocked by pipe grid to generate the necessary velocity gradient.

<u>The M.I.T. Wright Brothers Wind Tunnel</u>

The tunnel has a 7.3 x 10 ft. elliptical test section 15 ft. long and a current speed range from 0 to 140 mph at atmospheric pressure, the balance center being about 7 ft. from the end of the contraction section. A ground plane for performing experiments was installed 17 inches from the bottom of the ellipse and 13 inches from the usual floor. It extended over the entire test section. The pipe grid is installed at the leading edge of the ground plane. The detailed description of the design of the pipe grid to create a specific velocity profile is documented in Ref. 1.

Wind Load

Structures erected on the ground must be designed to withstand the dynamic and static load exerted by the expected strongest wind in its life span. Information on the load distribution is required for the structural engineer to carry out the design. Accurate load information usually can only be obtained by wind tunnel tests. The measurement of the wind load on a radome at different stages of construction has been carried out at M.I.T. (Ref. 2). It was found that the potentially most dangerous time for the radome is just before the top is closed in, because then the pressures on the outside will be nearly the same as on the complete radome, whereas the inside pressure will be essentially the lowest negative pressure, i.e., that at the top of the dome. Also, all during construction the pressure differences across the windward side of the radome are greater than those finally expected - assuming that static pressure is maintained inside the completed radome. On the side and in the back, with respect to the wind, the loading is smaller than finally expected and of the opposite sign.

In recent years, tall buildings have been built by steel beams bolted, riveted or welded together. This kind of construction tends to have very low structural damping (much lower than reinforced concrete). Thus aeroelastic instabilities such as flutter, stall flutter, etc., can occur if the structure is not carefully designed. The group at M.I.T. is devoting considerable amounts of effort to the study of dynamic wind effects on structures along this line.

Velocity in the Vicinity of the Structure

We are concerned about two problems.

(a) Minimum magnification of wind velocity at ground level in the area surrounding a building or complex. This is the so-called people problem (Ref. 3). In the area surrounding a building a wind of magnitude which may be of no concern to the safety of the structure can cause extreme discomfort to the people who happen to be there. The layout of the complex and the exterior configuration of the building must be designed to have the induced wind at the area frequently used by people as small as possible. A proposed new high-rise dormitory for the married students of M.I.T. (Ref. 4) and its surroundings has been tested in the wind tunnel. A 1/4 power wind velocity profile was used. At $V = 4$ at the top of the tallest building with the wind from the SSW vortices are shed. According to the scaling law proposed by Nemoto (Ref. 5) this will correspond to 30 mph full scale. Contours of constant wind magnification factor were obtained. The magnifica-factor is defined as the ratio of the wind with the building present to that where no buildings are present.

(b) Maximum magnification of the wind. For building structures in the arctic (Ref. 6) or desert, the appearance of people in its surrounding is rare. However, the blowing of snow or sand may accumulate and cover up the building. Therefore, it is necessary to design an aerodynamically clean structure, so that the snow or the sand will be blown away instead of accumulating around the structure. A comparison of the wind velocity distribution around two structures shows that the structure which is rounded both in the windward side and leeward side has much higher velocity around it. The chances of having snow or sand accumulation will be less.

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WIND TUNNEL SIMULATION OF ATMOSPHERIC ENVIRONMENTS

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Because of the complexity of the wind motions in the atmosphere, it is unlikely that quantitative solutions for most real life problems will be obtained solely by theoretical analysis. Moreover, the performance of full-scale experiments in the atmosphere to obtain empirical solutions is expensive, inconvenient, and time consuming since the enviroment is not controllable by the experimenter. Thus, in many instances, modeling in a properly simulated atmospheric environment produced in a laboratory may be the most economical, if not the only way to obtain the require information. However, before the full potential modeling can be realized, it is not only necessary to understand the requirements that the laboratory flow must meet but also to have a means for generating such a flow. We believe that many modeling studies which have been performed in the past have not properly satisfied the requirements for similarity between the model and atmospheric flows.

During the last several years Cornell Aeronautical Laboratory, Inc. (CAL) has been investigating experimental methods as well as the theoretical requirements for the laboratory simulation of small-scale atmospheric turbulence. Theoretical studies were performed to determine the similitude parameters which must be matched between the model and real flow. In the early theoretical investigations the important similitude parameters were determined. Subsequently, studies were made of the effects of attaining only partial simulation, that is, the effects of not fulfilling exactly all of the similitude criteria. The latter work was limited to conditions of neutral stability.

The experimental studies were directed towards attaining wind tunnel flows which best satisfy the similitude requirements. Tests showed that a flow which is a good simulation of the neutrally stable atmospheric surface layer up to an altitude of about 100 meters can be generated in the test section by a fence located upstream followed by a relatively long length of suitably chosen rough ground. It was found necessary to match the fence and rough ground carefully in order to attain proper simulation.

Current investigations will be continued with particular emphasis being given to non adiabatic flows, criteria for simulation of pollutants dispersion, and flow around structures.

ENVIRONMENTAL AERODYNAMICS

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My interest and work in wind loads lie in the area of environmental aerodynamics, the effect of wind on the comfort and safety of people and vehicles. The ground velocities that occur near tall isolated buildings have been subject to several ad hoc studies. There are two related problems that need further work.

The first is the determination of a proper wind shear profile for ground wind velocity evaluation. The time average velocity is not the primary parameter sought, but the "average peak" velocity. These peaks occur during a gust of sufficient scale to set up essentially a steady state flow corresponding to that of the mean flow plus the gust.

Instead of creating the time average mean flow and superimposing large scale gusts, it would be a simplication for environmental aerodynamics to determine and represent the mean flow plus the peak gust as a steady flow. Possibly a one seventh power distribution could represent a quarter power distribution with a large scale gust.

The second problem is the development of apparatus and techniques to better measure average peak velocities near the ground. Hot-wire anemometers, Kiel tubes and permanent set indicators all have their virtues and vices. More thought and development could produce better methods of rapidly accumulating and presenting such data in readily digestible form.

WIND TUNNEL STUDIES OF ENVIRONMENTS OF BUILDINGS AND STRUCTURES

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While experimental investigations have been conducted in the GALCIT* 10-Ft. Wind Tunnel for the purpose of determining wall wind loads and pressure distributions, the great majority of architectural investigations using this facility have been concerned primarily with the general flow field about structures as it affects pedestrian environment and natural ventilation related to the removal of auto exhaust gases and the location of building vents. Because of the greater frequency of requests to perform pedestrian environmental type studies it is only these tests that will be commented on here.

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The "windy day" pedestrian environment study at the GALCIT has typically consisted of the acquisition of only local wind direction and the order-of-magnitude wind velocity in the areas of interest and the correction of unacceptable areas by architecturally acceptable changes.

Data from these tests have been collected in the following manner. First, tufts (lengths of standard darning cotton) are attached to appropriate model surfaces and to the ends of small poles placed in the various areas of interest within the model complex (along walkways, roadways, etc.).The behavior of these tufts is observed at various test velocities from low ($\approx$ 10 mph) to high (> 100 mph) and the velocity above which there is no visible change in the tuft behavior is determined. The test velocity is then set well above this "critical" velocity and the tuft behavior photographically recorded for the wind directions of interest. From these photographs possible problem areas are defined and the flow directions are determined for the purpose of locating velocity measuring probes in these areas. The tests are then repeated with the velocity probes in place and local velocity data are collected.

Tests of this type have been sponsored by architects to "check out" completed structure designs or by planning committees who wish to establish design criteria at a given site. In either case the funding has been very limited and in many cases the only pretest information available is wind velocity and direction history recorded at a single height above ground level and often this record is made some distance from the site of interest.

Less than 50% of this type of environmental testing at the GALCIT is accomplished using wire screens upstream of the model to approximate the known or "guessed" wind velocity profile and the remainder are conducted without any attempt to simulate the vertical profile. There has been no attempt to simulate wind turbulence scale or intensity in this wind tunnel. Nevertheless results of these tests, where they could be compared to site observations, have been considered good since these areas have been located in areas of high building density and the flow field at the pedestrian levels is dominated by the surrounding buildings - not the level terrain wind profile or turbulence some distance away.

Because of the cost of making on-site measurements of wind velocity profiles and turbulence and the additional cost of creating a flow similarity in the wind tunnel (many tests have been proposed but not carried out solely due to these costs) it would be worthwhile to work at establishing minimum criteria for the acquisition of reliable wind tunnel data of the type discussed here as well as static wind load tests which are also required with some frequency. These criteria should include not only minimum similitude requirements for velocity profile and turbulence but minimum requirements for the duplication of upstream terrain and building complexes, which materially increase the cost of test models and testing. In addition, the solution to wind tunnel wall constraint problems would permit the testing of larger areas during a single test rather than "section testing" where the downstream results of one test series must be artificially imposed on the upstream flow for a second test series.

In this area of wind tunnel data correction it should be possible to obtain useful wind static load data in the wind tunnel for the high rise building case or single building case by modifying the pressure data recorded above adjacent building height to account for wind gradient and the effects of turbulence, particularly on leeward building walls. Co-rections of this type would permit the use of the great number of aero-nautical tunnel facilities in this country without extensive modification and without the need of constructing many specialized facilities.

REPORT ON THE RESEARCH SEMINAR ON WIND LOADS ON STRUCTURES

Held at the University of Hawaii, October 1970

Arthur N. L. Chiu
University of Hawaii

A Pan-Pacific seminar on wind loads on structures was held in Honolulu, Hawaii during October 19-24. Many of the countries bordering on the Pacific Ocean are subject to intense wind storms and face the problem of how to build structures that are safe and economical. Because of its location and its continuing interest in relating the cultures of the east and the west it was appropriate for the University of Hawaii to host a conference focusing on the problems posed by typhoons, cyclones, and hurricanes.

The seminar brought together 28 engineers and meteorologists for the primary purpose of exchanging information on their activities in this subject. Represented in this group were 16 from U. S. A., 9 from Japan, and one each from Canada, Hong Kong and Korea. The participants presented a total of 24 papers distributed in the following categories: 5 in climatology and meteorology, 5 in wind-tunnel studies, 9 in full-scale structure studies, 4 in statistical methods, and 1 in engineering design.

After the presentation of each paper, ample time was provided for discussion of that paper, and additional general discussion periods were scheduled at the conclusions of the morning and afternoon sessions. One afternoon session was devoted to committee discussions in three smaller groups, namely, engineering meteorology, wind-tunnel studies and full-scale structures. The papers presented at the sessions will be published as a set of Proceedings.

This seminar permitted engineers and meteorologists to exchange information of mutual interest. The participants agreed that there is a need for more studies on the turbulence caused by large structures in urban areas, that wind tunnel studies should include the study of diffusion as well as the effects of the geometry of structures, and that there is a need to corroborate data from wind tunnel studies with prototype behavior.

A central data bank for wind data in the Pacific region, and even an expansion to cover the entire range of atmospheric data, could be located in Hawaii. Such a data bank would be the critical step towards creating a research center for the purpose of gathering, interpreting and exchanging of information useful to engineers and meteorologists.

The conference was jointly sponsored by the National Science Foundation and the Japan Society for the Promotion of Science under the U. S. - Japan Cooperative Science Program.

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V. OTHER MEETINGS AND CONFERENCES

Wind engineering as a discipline with its own identity has really emerged only in the past decade. It seems to be generally agreed that an important event marking its emergence was the International Conference on Wind Effects on Buildings and Structures in 1963 which was organized jointly by the National Physical Laboratory, the Building Research Station and the Institutions of Civil Engineers and Structural Engineers of Great Britain. A second one was held in Ottawa in 1967 and the third one will be in Tokyo this year. The proceedings of these conferences are a valuable reference source of research material.

The list below includes these three and several other international or semi-international conferences, as well as a number of other recent national meetings that have helped to stimulate interest and exchange of information between workers in the various areas of wind engineering.

Conference on Wind Effects on Buildings and Structures, National Physical Laboratory, Teddington, England, 26-28 June, 1963. (Proceedings in Two Volumes. Her Majesty's Stationery Office, 1965.)

International Research Seminar on Wind Effects on Buildings and Structures, Ottawa, Canada, 11-15 September, 1967. (Proceedings in Two Volumes. University of Toronto Press, 1968.)

Third International Conference on Wind Effects on Buildings and Structures, to be held in Tokyo, Japan, 6-11 September, 1971.

Meeting on the Aerodynamics of Atmospheric Shear Flows, Fluid Dynamics Specialists Panel of AGARD, NATO, held at Munich, Germany, 15-17 September, 1969. (AGARD Conference Proceedings No. 48.)

U. S.-Japan Research Seminar on Wind Loads on Structures, (A. Chiu, ed.) University of Hawaii, Honolulu, October 19-24, 1970.

Proc. of Technical Meeting Concerning Wind Loads on Buildings and Structures, National Bureau of Standards, Gaithersburg, Md., January 27-28, 1969. (R. D. Marshall and H. C. S. Thom, eds.) (Building Science Series 30, Supt. Documents, U.S.G.P.O., $1.75.)

Chicago Design Symposium on Wind Effects on High-Rise Buildings, (R. A. Parmelee, ed.) Northwestern University, Evanston, Illinois, March 23, 1970.

Conference on Tornado Phenomenology and Related Protective Design Measures for Faculty and Practitioners in Architecture and Engineering, University of Wisconsin, April 26-28, 1970.

A Symposium on Wind Effects on Buildings and Structures, held at Loughborough University of Technology, 2-4 April, 1968. (Proceedings in Two Volumes, Loughborough Technical University.)

Meeting on Ground Wind Load Problems in Relation to Launch Vehicles, NASA Langley Research Center, June 7-8, 1966.