Wind Engineering Research and Development in the United States

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ABSTRACT

This paper provides an overview of the current direction in wind engineering research in the United States. While various projects in hazard mitigation and risk assessment have been prompted by recent hurricanes, other efforts have been devoted to improving current technologies. A wide host of active topics in wind engineering research, undertaken on the governmental, private, and university level, are addressed, ranging from bluff body aerodynamics to computational wind engineering.

KEYWORDS: turbulence, vibrations, hurricanes, tornadoes, reliability, hazard mitigation, low-rise building testing, computational wind engineering, bridge aerodynamics, building envelope

1. INTRODUCTION

Current research interests in wind engineering span a wide spectrum of topics from improvements in models of wind-structure interactions to the development of risk assessment models. Particularly, with the unprecedented destruction observed in recent hurricanes like Andrew, new awareness has been raised to deficiencies in current design strategies, prompting a host of studies. While it is impossible to fully address all the recent developments in the area of wind engineering, a concise summary is provided herein, discussing the activities at various institutions in the United States. Most of the information has been derived from the papers presented at the Seventh U.S. National Conference (USCWE) held in 1993 in Los Angeles, the Ninth International Conference on Wind Engineering held in 1995 at New Delhi and Hurricanes 92 in Miami, and abstracts of the 8th USCWE to be held in Baltimore in June. For convenience, the areas highlighted have been categorized by the following topics:

1. Hurricane Wind Speeds, Regionalization of Extreme Winds and Tornadoes
2. Performance of Building Envelope
3. Damage Control and Mitigation
4. Risk Assessment and Management
5. Bluff Body Aerodynamics and Unsteady Load Effects
6. Random Data Analysis, Modeling and System Identification
7. Tall Buildings and Engineering Structures
8. Mitigation and Control of Structural Response
9. Bridge Aerodynamics and Aeroelasticity
10. Knowledge-Based Expert Systems and Computational Wind Engineering
11. Wind Loading Test Concepts
12. Wind Engineering Research Applications

2. HURRICANE WIND SPEEDS, REGIONALIZATION OF EXTREME WINDS, AND TORNADOES

Hurricane wind speeds may be quantified by measurement of the footprints of its wind field near shore and after landfall. Based on these measurements, recent studies have shown that the gust factors in hurricane wind fields are higher than those presently used for extratropical storms. This is in part attributed to the movement of convective cell that introduces both nonstationarity as well as non-Gaussianity, thus precluding use of conventional analysis. On the simulation front, Monte Carlo-based simulations of hurricanes, applying phenomenological models, along with historical data on the wind field and filling of the hurricane, provide very useful information for design. Alternative simulations based on empirical schemes are also being studied which do not strictly account for the assumption of independence among the modeling parameters. In essence, the empirical simulation technique avoids, in a nonparametric way, the whole issue of joint probabilities among parameters by utilizing information based on actual historical data. Studies have also been conducted to compare Shapiro's model, featuring a new gust factor curve and radial profile exponent, with the ASCE 7-88 model for hurricanes into each model by feeding statistical information from previous hurricanes and seeing how well it simulates the winds experienced during the actual event, concluding that the Shapiro model, in most instances, appears to be superior to the more conservative ASCE 7-88 model. The applied Research Associates, National Institute of Standards and Technology, Hurricane Research Laboratory, American Association of Wind Engineers (AAWE), University of Notre Dame, University of Wyoming and University of Hawaii are involved in research concerning this topic.

In order to provide a better estimate of extreme

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winds at an ungauged site, regional zoning for extreme wind data collected at various weather stations in a large area is being developed. The applications are focussing on both regional zones and the entire U.S. Colorado State University, Texas Tech University, University of Hawaii and National Institute of Standards and Technology are working toward development of such regional zoning throughout the U.S. Reexamination of wind data and use of mega stations resulting from augmenting data from nearby stations has resulted in refinement of the ASCE7-95 wind speed map.

While hurricane damage has captured the attention of the wind engineering community, there is always concern for tornado-type winds. Studies of tornado wind forces have been conducted in low-speed, open-circuit wind tunnels coupled with an attachment to provide circulation of the flow, as angular momentum is introduced by the rotating of a wire screen. Such studies have proven the necessity of introducing surface roughness, via sandpaper, to wind tunnel simulations to accurately reproduce the vortex flow, delaying the transition to multiple vortices at low swirl ratios. A program has also been active at Texas Tech University and Colorado State University (TTU/CSU) in this area, attempting to identify major parameters and examine scaling relations and techniques for simulation of high-wind phenomena. These efforts have produced parameters for meaningful wind tunnel simulations and developed a tornado or microbust generator. Even through such efforts, it is still difficult to study tornado effects in wind tunnels because of the frequent changes in wind speed and direction. Consequently, efforts are now being devoted to exploring the use of computational fluid dynamics to study tornado effects. Such CFD models apply the 3D, incompressible, unsteady Navier Stokes equations, integrated by the control volume procedure, with convective terms approximated using hybrid upwinding, solved on a rectangular grid system. There is, however, the need for future study of turbulence models like the k-epsilon model or the Reynolds stress model, focusing on their lack of proper information on the turbulence statistics of tornado close to the boundary layer.

Besides research related to the effects of severe weather on infastructure pursued at universities, efforts by the federal government to better detect and define events during these storms are conducted at NOAA's Hurricane Research Division in Miami and Severe Storm Laboratory in Norman, Oklahoma. The thrust of work at these laboratories focuses more on the meteorological aspects which are useful for wind engineering applications.

3. PERFORMANCE OF THE BUILDING ENVELOPE

Several institutions in the U.S. are actively involved in researching the structural resistance to wind hazards. These institutions include: Texas Tech University, Texas A&M University, Clemson University, the University of Florida, Florida International University, Universities of Missouri at Columbia and Rolla, University of Notre Dame, University of Washington, Colorado State University, State University of New York at Buffalo, University of Hawaii, American Association for Wind Engineering, Applied Research Associates, Roofing Industry Research Institute, Lawrence Livermore Laboratory, Glass Industry, Underwriters Laboratory, and Model Building Codes. The research effort spans areas concerning documentation of damage from past disaster studies to performance of building envelopes, i.e. cladding, roofing and glazing, and quantification. A detailed discussion of these topics follows.

Efforts to better design and improve the performance of structural glazing, cladding and curtain walls are taking place at several academic institutions, within the glass industry, and among curtain wall consultants. Problems with performance of such systems are associated with the special nature of hurricane winds, being turbulent, sustained, varying in direction, and are often containing wind-borne debris. Measures to improve the performance of glazing in these respects are being investigated to ensure integrity of the building envelope following impact from wind-borne debris and the subsequent repetitive action of wind gusts. Coupled with studies to improve building envelope strength, are those dedicated to addressing this problem at its source by minimizing some of the air-borne debris, particularly roof aggregates. For the application of repetitive wind pressure with desired intensity and temporal characteristics on a portion of cladding, pneumatic chambers are being utilized. The University of Missouri at Rolla and Texas Tech are involved in glass studies, whereas Clemson University is pursuing both envelope and roofing studies. Applied Research Associates, Inc. have also developed a risk analysis model which predicts the failure due to wind borne debris. This is discussed in more complete detail in the section on risk assessment and management.

Some attention in research has also been devoted to sealant performance. While previous studies had indicated that sealants are capable of resisting cyclic loadings, current studies have been considering their performance under the joint effects of cyclic loading and environmental factors. A research project at Texas Tech University has investigated the failure strength of sealants under random wind loading. Still, while improvements in glazing and cladding quality are emphasized, researchers insist that integration of the designs of glass, mullions, frames, and frame anchorage would improve overall cladding performance.

Most of the studies concerning structural roofing have been initiated following major U.S. hurricanes in which it was observed that the primary failure of roofs during such extreme events occurred near roof corners and ridges. Wind tunnel studies, coupled with post-disaster investigation and full-scale measurements, have proven to be vital tools in developing better roof designs. In one study, an analysis of hurricane damage was used to determine the best roof design under hurricane conditions and the impact of slope on roof performance. Work has also been dedicated to the destruction of roof tiles under the impact of wind-borne debris, determining impact damage as a function of missile mass and velocity. Some work has also been done in the area of fatigue characteristics of roof pressures, using the rainflow count method as opposed to the upcrossing method to observe the characteristics of these fatigue characteristics.

Post-disaster studies have also been useful in determining the negative aspects of roofing structures, pointing out the need to fasten metal edge flashing, copings, gutters, aggregate, and rooftop air conditioners and equipment which may be ripped from the roof damaging it or becoming wind-borne missiles themselves. In one instance, a local filtering technique using the Haar function was applied to investigate the relationship between the approach flow and the dislodging of loose-laid roof pavers. Future roofing studies at Clemson will focus on measurements of flow over the roofs of scale models in a boundary layer wind tunnel using a three component fiberoptic laser Doppler anemometer system.

Most of the interest in low-rise building testing and codes has been spawned by the destructive path of the recent U.S. hurricanes, e.g. Andrew, Hugo. Based on the observations of engineers during the aftermath, suggestions have been made on the improvements to low-rise buildings, which were neglected in most engineering study until now. Many wind tunnel simulations are underway to develop improvements in building design to be incorporated into building codes. One study at Clemson utilized a device, BRERWOLF, to apply fluctuating pressures to cladding panels to study its effects under loading. Current research at the University of Notre Dame will also turn toward the development of a dynamic wind load simulator to investigate the performance of building components and systems under dynamic space-time variation of loads. Such tools were used to develop retrofit roofs to withstand severe winds and improve cladding so it may better function as a structural resistance and load path. Recent studies stress the improvement of the building envelope, consideration of increased internal pressures due to envelope rupture, and the need for retrofit measures to improve the connections on existing structures.

While some research projects have devoted themselves entirely to roofing, low-rise building tests, or cladding tests, one joint project has undertaken investigations of all three topics and others, thus warranting appropriate attention. A joint research effort Texas Tech University (TTU) and Colorado State University (CSU), CPWE, under the sponsorship of the National Science Foundation (NSF) to investigate various topics in wind engineering, of which include areas of cladding, roofing, and low-rise structure testing. TTU possesses a field laboratory, WERFL (Wind Engineering Research Field Laboratory), established in 1987, ideally suited for the study of low-slope roofing systems and the measurement of wind speeds and the associated wind-induced structural response of a one story test building. Not only has WERFL proven to be a source of data for the study of single-ply membrane roofs, but it has also proven to be a vital tool in determining the average wind pressure acting on a roof purlin and the wind pressures above and below loose-laid concrete pavers over an adhered single-ply membrane roof covering. WERFL has also been used to measure wind-induced pressure coefficients across the building centerline and the internal pressure coefficients for no opening, static openings of 1%, 2%, and 5% and sudden openings of 2%, providing insight into the increased internal pressures following the rupture of the building envelope. All this data has gone on to provide a basis for the development of analytical models for the stochastic modeling of wind speeds and the determination of wind-induced pressures and admittance functions of the modified quasi-steady theory. Other work has also been devoted to structural sealants, the details of which were mentioned earlier, as well as information on other topics which will be alluded to in the appropriate sections.

Colorado State University's contributions to this joint effort are mainly in the investigation of fundamental and applied topics of wind engineering using physical modeling, performed in their long-test section boundary layer wind tunnel, analytical solutions, and more recently, numerical simulations. The data collected from wind tunnel simulations at CSU may then be compared to the full-scale measurements from WERFUL at Texas Tech. The good agreement between these two data sets verifies the accuracy of wind tunnel studies, which will enable researchers to study the effects of parameters affecting internal building pressures not easily replicated through full-scale investigations.

4. DAMAGE CONTROL AND MITIGATION

Several studies are focussing on efforts to control or mitigate damage by eliminating poor design or construction practices, which emphasize neither the provision of redundancies nor the elimination of weak links in structural systems that can lead to failure at wind speeds well below design values. Some of key items of interest include improved wind code specifications, better code enforcement, changes in practice from facts cited post disaster investigations, incorporation of redundancy and ductility in manufactured homes, improved standards for building envelope systems, utilization of expert systems and computer graphics technology, and negotiation of self-help retrofit activities.

One area receiving attention is the application of reliability theory to develop models of structural performance under extreme loads. One study undertaken at Texas A&M uses the theory to estimate damage to components. The model is capable of generating damage functions for structures along the Gulf and Atlantic coastlines by considering the time of construction, quality of construction, quality of building codes, building contents, regional construction practices, and quality building materials.

Aside from the concentrated efforts of individuals at several institutions devoted to damage control and mitigation, there are focussed group efforts to improve performance of structures under extreme wind events. The two leading examples are CSU/TTU Cooperative Program, mentioned earlier, and a program at Clemson University. A brief description of the program at Clemson is given here. Funded through the State of South Carolina and the Federal Emergency Management Agency (FEMA) the focus of this program is to mitigate wind hazards to low rise buildings. The major tasks include: evaluation of loads resulting from strong winds; evaluation of the resistance of enclosures; stability of low rise wood and masonry buildings; and improvement of codes, standards, and inspection practices. In addition, FEMA is also an active sponsor of extensive post-disaster analysis through their Building Performance Assessment Teams (BPSTs), deploying these teams over thirty times since 1979.

On a larger scale, the American Association of Wind Engineering (AAWE), formerly known as the Wind Engineering Research Council, Inc. (WERC), established in 1970, has also taken an active role in promoting wind hazard mitigation. AAWE hopes to implement a plan for legislative action that would foster the initiation of a National Wind Hazards Reduction Program. Such a program would provide support for wind engineering in the U.S. through improvement of understanding and codes, providing advanced methods for predicting wind loading, and encouraging the development of new technologies. AAWE also hopes to accomplish numerous tasks, among which include initiation of an active sharing of technology within the field primarily through their publication, "Wind Engineer," promotion and prioritization of wind engineering research, and leadership in learning from wind storms through post-storm data collection and analysis. Currently, AAWE is involved in establishing a post-storm data base containing a detailed description of the building, damage, and extreme event. The data was collected following the Hurricanes of Marilyn and Opal, various groups ranging from the Insurance Institute for Property Loss Reduction (IIPLR) to FEMA to the National Oceanic and Atmospheric Administration. The data base relies on wind speeds generated by the wind field models of the National Oceanic and Atmospheric Agency.

5. RISK ASSESSMENT AND MANAGEMENT

The area of risk assessment has some basic focus on gathering data after a disaster and using such findings to develop or validate a model to assess the risk of failure of constructed facilities and provide a quantitative measure to estimate the extent of damage under a particular intensity of wind storm. This includes damage to the structure as well as building contents as a result of storm winds and wave action. To this effect there are various groups, academic, private, and governmental, who are actively researching risk assessment schemes, among these are Risk Management Solutions, Inc., IIPLR, State Farm Insurance Company, FEMA, and the National Oceanic and Atmospheric Administration. Various subcommittees in the U.S., including the U.S. Subcommittee on Natural Disasters Reduction (SNDR), have made it their goal to reduce human fatalities and suffering, environmental damage, and economic loss caused by natural disasters.

Computational schemes, through this effort, are being developed to forecast the probability and severity of hazardous events, namely hurricanes, over varying temporal and spatial scales. These schemes are based on a synergistic combination of essential ingredients of risk assessment, with the damage potential is being assessed through damage probability matrix, neural networks and fuzzy logic, as well as the use of probability trees. Artificial neural networks have been also developed to predict the damage of individual buildings. Work has been devoted to developing ways of expressing frequency, probability or level of confidence, and probability of the likelihood of an event. For hurricane models, features would include relations of the geophysical environment, including global warming, and features of the hurricane itself. Methods considered in such an analysis include the Monte Carlo simulation and the extended bootstrap simulation, as well as numerical models which predict the sea surface elevations and currents due to mesoscale processes like tides and storm surge. The overall risk assessment is also being considered in the light of projected consequences of global climate change. Studies in this area are being done at the University of Notre Dame, Clemson, Texas Tech, Texas A&M, University of Washington, Stanford, National Institute of Standards and Technology, and Applied Research Associates. The results of risk prediction models may then be displayed by geographic region by the Geographic Information Systems (GIS).

In addition to university involvement, risk assessment has been approached by other organizations and private firms. The INEL Advanced Combined Environments Test Station (ACETS) Program hopes to develop a sound, scientific, engineering and economic basis for evaluating the ability of a building to resist wind loads and wind effects which will lead to reduced losses in wind storms. Its first goal is to establish realistic test methods for evaluating the performance of the building components, connections, and systems in severe wind storms. Then, INEL will focus on the development and improvement of assessment tools which will be used to identify key areas of building deficiency as well as identify appropriate levels of economic expenditure to upgrade construction practices or for expenditures for retrofitting. Thus a cost/benefit assessment scheme will be developed. Other groups involved in risk assessment include the Texas Department of Insurance, funding a program for Texas A&M University. The Texas Department of Insurance has produced a new building code to provide adequate wind resistance for one and two family homes along the Texas coastline and a corresponding study by Texas A&M has evaluated the cost-effectiveness of retrofitting existing structures.

Applied Research Associates has recently developed a first-principle quantitative methodology for evaluating building envelope vulnerability to windborne debris to determine what level of protection, i.e. strength of building envelope, is required to protect homes in residential suburban settings under strong hurricane winds. The initial model performed such evaluations based on peak gust wind speed, spacing of the houses, and other factors; however, improvements now allow the model to consider failure based on specific missile types and/or degrees of damage by explicitly modeling the interaction between the missile damage and the increasing damage caused by internal pressures for a variety of building geometries under the impact of various missile types. The group has also established an integrated model considering the chain reaction initiated by envelope rupture, by coupling the missile damage probability with the increase in internal pressure, which increases the probability of roof failure. Another study undertaken by the group uses decision analysis formalism to illustrate how risk management decisions can be evaluated under conditions of uncertainty ranging from uncertainty in the modeling of loads to the age and condition of the facility. The model treats uncertainties in repair and replacement costs so to evaluate risk transfer, through insurance.

Another risk assessment group mentioned previously, Risk Management Solutions, Inc., comprised of researchers from universities and the risk assessment industry, insurance actuaries, and systems analysts, has developed models to assess monetary loss to individual and groups of properties due to hurricanes, analyzing the losses in a financial framework used by the insurance industry. Wind speeds in these models are derived from a wind field model based upon a historical storm data base.

While previous discussion of risk assessment has focused on the property damage and its relationship to the hazard, a society must view this topic from a holistic point of view and extend it to ascertain the impact of disasters on the socio-economics of the region. A principle which considers all changes in the system that occurred with the disaster and all changes that would have occurred had the disaster not taken place also needs to be considered. Meanwhile, the calculation of economic damages considers both the interruptions of production processes and the damages to assets. Such damages are direct damages. Secondary damages must also be assessed, which include the effects of the disaster which trigger a sudden reduction in demands for outputs within the effected region. Other considerations include those of cultural asset loss, i.e. the loss of historic sites or other sides which would be desirably passed on to future generations. While market values derived through appraisals are often used to estimate such losses, typically these losses are evaluated at a variety of different levels depending on the "significance" of the site. Work in this area is being done at several institutions, with Colorado State University and Texas A&M focusing specifically on wind.

6. BLUFF BODY AERODYNAMICS AND UNSTEADY LOAD EFFECTS

Over the past several decades, much attention has been focussed on the aerodynamics of streamline bodies; however, our knowledge of the aerodynamics of sharp-edged bluff bodies in turbulent boundary layers is far from complete. Efforts in this direction are in progress at several institutions, e.g., University of Notre Dame, Colorado State University, Clemson University, University of Minnesota, Virginia Polytechnic Institute, Johns Hopkins University and Florida Atlantic.

The various research topics undertaken in the area of bluff body aerodynamics involve extensive measurements of the pressure field around prisms, cylinders and bridge deck sections. These studies have examined the influence of scale and intensity of turbulence on pressure fluctuations. In addition, measurements and analyses of the space-time structure of random pressure fields and the area-averaged loads acting on the surface of prismatic and cylindrical bodies of different aspect ratios, exposed to simulated turbulent or turbulent boundary layer flows in various configurations, has vastly improved our understanding of the complex fluid-structure interactions. While most of the efforts have been focused on determining the mean forces and pressure distributions on these bodies, some interaction studies on groups of cylinders have also provided a measure of the fluctuating components of drag and lift forces and their corresponding spectra in the alongwind and acrosswind directions, yielding some vital insight into the dynamic response of a cylinder. Studies have also been concerned with the correlation structure of wind pressure fields on prismatic bodies of finite height immersed in a turbulent boundary layer flows, recognizing its importance to the characterization of wind pressure fields in that it determines the resulting aerodynamic effects on the body.

Several wind tunnel facilities in the U.S. have been involved in the development of measurement schemes to monitor unsteady load effects on such bluff bodies. These include both measuring fluctuating integral or local loads on buildings and bridge models and similar measurements on the full-scale structure. The measurement schemes include area-averaged pneumatic manifolding schemes, ultra-sensitive high frequency force balances, and second generation force balance to account for multiple level force measurements. The use of high speed scanning systems to monitor a large number of pressure taps are being developed that have the potential of replacing high sensitivity force balances. The senior writer has, in addition to the preceding schemes, utilized piezoelectric films to monitor area averaged loads, but the complexity of installation and the film's sensitivity to temperature, in addition to pressure, has limited its applications.

7. RANDOM DATA ANALYSIS MODELLING AND SYSTEM IDENTIFICATION

The analysis, modeling and system identification of random data are very important aspects in wind engineering studies. Recent advances in stochastic analysis and modeling provide useful tools towards improved representation and interpretation of data. The studies in this area focus on time series modeling of random data, e.g., auto regressive and moving averages modeling (ARMA), estimation of frequency response of structures, identification of load effects on structures, simulation of stationary, nonstationary and non-Gaussian signals, conditional simulation and wavelet transforms. Activities under this topic are being pursued at different levels of concentration at various institutions involved in wind engineering research, e.g., Cornell University, University of Notre Dame, Johns Hopkins, Colorado State University, University of Southern California, Cal Tech, Princeton and Rice Universities.

Computer simulations have been developed for multiple wind pressure time series which are strongly non-Gaussian due to skewed spikiness in fluctuations and have strong cross-correlations of fluctuating features. Such simulations produce the exact sample cross-spectra as well as the autospectra of the target signals and have great flexibility in controlling non-Gaussian fluctuating features and some statistical properties of simulated signals, while preserving the target auto- and cross-spectral characteristics. Simulations of non-Gaussian features of wind pressure fluctuations under separated flow regions using higher-order spectral transformations and transient events by wavelet transforms have been performed. This approach leads to stochastic processes which represent non-Gaussian and non-stationary features, respectively. This is one of the current focuses of wind-related research at the University of Notre Dame. The resulting studies address the analysis, modeling, and simulation of measured full-scale wind pressure and velocity data sets which exhibit both non-Gaussian and nonstationary features. The PDF of the non-Gaussian pressure and pressure data are simulated in these studies, the latter by new static transformation techniques. The non-stationary portion of pressure data is isolated and decomposed into a set of localized basis functions using wavelet transformation techniques. Furthermore, studies at Colorado State have applied a mean multifractal plane to investigate nonstationarity and intermittency of the time series representing wind flow and wind-induced effects. Other probabilistic studies of the overall area-averaged pressures on the Texas Tech University building, as measured in a wind tunnel, have found that the skewed, non-Gaussian parent PDF may be approximated by a Gamma Distribution, while the peak PDF is best fit by a Fisher-Tippet Type I distribution. In the area of stationary processes, ARMA techniques have also been used in the simulation of the fluctuating component of wind and wind-induced pressures.

8. TALL BUILDINGS AND ENGINEERING STRUCTURES

In the area of tall buildings most of the innovations in structural system development come from industry, whereas, system response analysis, based on analytical considerations and wind tunnel studies, is generally conducted in universities (Colorado State University, CPP, Clemson, University of Notre Dame). Some of the work is focussed on research while other work is development related. In the research area, some work is still being done to refine the gust factor approach and to package it in a closed form expressions rather than the ASCE7-93 version that utilizes plots. One such approach has been adopted in ASCE7-95, ASCE Standard Minimum Design Loads for Buildings and Other Structures. Along these lines, a modified gust factor that accounts for non-Gaussian features resulting from the often ignored square of wind velocity term has been developed. This is particularly important for relatively stiff structures in high turbulence regions. The quantification of alongwind, acrosswind, and torsional loads for a wide range of buildings of different cross-sections and aspect ratios is essential for developing coupled lateral-torsional analysis of buildings. The analysis is being simplified for code application at the University of Notre Dame.

The torsional response of tall buildings has also been considered, since it has been observed that the torsional response can have a great effect on the total response of the eccentric building. There may also be some contribution to the response of an eccentric building, in the way of interference effects, by adjacent buildings. Such interactions have been studied through wind tunnel simulations, observing that, while an isolated building experiences inherent turbulence, the same building with interference from surrounding structures was found to manifest wake excitation. Special concern has also been given to situations in which the frequency of vortex shedding from the interfering building coincided with the natural frequency of the eccentric principle building, causing torsional resonant buffeting to the principle building.

The research in the area of engineering structures includes towers, transmission lines, chimneys, which has been actively pursued in both academia and industry. For example, in the study of powerlines, researchers have attempted to estimate the electric drag coefficients used in determining wind forces on transmission line structures via numerical methods based on 2D Navier Stokes equations for viscous, incompressible, steady flow. Many studies have also devoted their efforts to improvement of instrumentation on power lines and towers for data collection and often utilize free-air wind tunnels to compare the drag coefficients estimated in wind tunnel studies with actual open air results. Furthermore, efforts are also being devoted to improved design of sign, signal, and luminare structures, which, in recent years, have failed under high winds injuring pedestrians and commuters below. Studies have utilized the data from wind tunnel studies to establish the static drag coefficients and root mean square estimates of the lift-coefficients of tapered cylinders in order to develop alternative, more aerodynamic cross-sectional shapes (e.g. octagonal) and designs capable of resisting cyclic loads in order to avoid future failures.

More recently, offshore platforms are receiving increased attention due to structural damage to deck structures and appurtenances in the Gulf of Mexico in the aftermath of Hurricane Andrew. As a result of the new breed of deepwater platforms, which are very sensitive to the gusting action of wind, focussed activity on the behavior of such platforms under the combined action of wind, waves and currents has developed. For such behavior to be studied, the wind fields surrounding such structures must be accurately modeled. The wind field, however, is not so much influenced by the form of the sea surface, but rather is sensitive to the energy loss and rate of momentum transfer due to surface friction. However, if a relationship between on-land wind characteristics and over-water wind characteristics is developed, existing on-land models may be somehow extended over the water to predict the wind fields. There are some difficulties with these attempts for spatial separations which may exceed the turbulence length scales, since the correlation function typically used by land-based structures inadequately describes the spatial structure of the wind field over the ocean. Further development and clarification of this approach is one topic for current study. The senior author is also involved in modeling the stochastic response of tension leg platforms to random wind and wave fields. In these studies, both the time and frequency domain procedures have been developed utilizing the Cray Y-MP to predict the nonlinear platform motion.

Under an Office of Naval Research (ONR) initiative entitled "Reliability of Nonlinear Ocean Structures Under Stochastic Excitation," several investigators are studying the response of ocean systems to extreme wind and other loadings. The senior author has a project concerning response statistics of ocean structures under wind, wave, and current loads. The major focus of this study rests upon the advancement of techniques for the determination of extreme response of moored floating ocean structures to wind, wave, and current loads. These improved techniques are then to be implemented in predicting the performance of such structures in different ocean environments and, hence, in predicting loading patterns. Particularly, the present effort will serve to quantify structural survivability and serviceability as well as prescribed motion control strategies for improved structural reliability. Other universities and institutions that are addressing wind related topics include Rutgers, Florida Atlantic, Stanford, NIST, and several Naval Laboratories.

Proposed future off-shore structure investigations include improving quantification of windfield models, better modeling of shielding effects, investigation of overturning caused by uplift forces, understanding of overall wave profiles, better design for gust loading factors, and investigation of the vortex shedding-induced vibration on cranes and flare booms. Most research of this nature is being conducted by the R&D groups of oil companies. At the university level, work is being done at the University of Notre Dame and Texas A&M University.

Dynamic load effects, structural reliability and risk assessment are receiving an increased attention from researchers while the need for practical application of these concepts to design is increasing. Dynamic effects are treated in codes primarily through gust factor approach, which has been the focus of concentrated effort particularly to improve our understanding of hurricane wind fields. The dynamic loads introduced by the acrosswind and torsion effects are being studied for developing simplified procedures for code applications, primarily with a reliability based format. Studies focussing on this aspect for both the low and high-rise construction are helping to provide a basis for preliminary discussions on reliability-based design.

9. MITIGATION AND CONTROL OF STRUCTURAL RESPONSE

The current trend toward buildings of ever increasing heights and lighter facades has led to the construction of relatively flexible structures possessing quite low damping. As a result, the serviceability of these buildings is affected by the excessive accelerations experienced at the higher levels in wind storms which may cause considerable discomfort to the building occupants. Ever since the evolution of high-rise construction, efforts, both in industry and academia, to improve the performance of buildings have developed. Such efforts are devoted to a wide range of topics from considering alternative structural systems to aerodynamic modifications with particular emphasis on damping systems. Research in active and passive systems, which includes active mass dampers, tuned mass dampers, tuned liquid dampers and hybrid tuned liquid dampers in single and/or multiple damper configuration, is currently being undertaken. While passive damper study has investigated multiple damper configurations, the area of active dampers has considered frequency domain based on H_2 control strategies for wind excited structures. Further research in the areas of tuned sloshing dampers is exploring the use of screens, nets, floating styrofoam beads, and baffles to increase the damping ability. Semi-active systems are also being considered in which the building motion is monitored and fed into a filter designed to represent the features of the optimally tuned damper. For example, semi-active tuned sloshing dampers may be incorporated with a feedback system, which adjusts a moveable sliding screen over a fixed screen or regulates opening vanes to achieve optimal damping. Research in both active and passive systems for wind applications is being carried out at the University of Notre Dame. Currently 3M Corporation and Colorado State University are jointly analyzing the effectiveness of viscoelastic dampers through wind tunnel studies. Other institutions involved in active/passive systems studies include, for example, CPP, University of Washington, SUNY at Buffalo, USC, UC Irvine and UC Berkley.

The American Society of Civil Engineers (ASCE) has two special task committees; one has just completed a study concerning motion perception criteria and motion mitigation, another is related to damping systems. The senior writer is chairing the task committee and it includes membership from Japan. The primary focus of this task committee is to address three important aspects of structural damping systems: a survey of inherent damping in buildings and bridges, the various methods of assessing damping levels from ambient data, and investigation of the different active and passive damping systems and their performance (Japanese building industry's experience). This would also require technology transfer through documentation of design procedures for various damping devices, including passive, active, or semi-active systems, utilizing fluid and viscoelastic dampers, as well as inertial systems like mass dampers.

A joint research program in structural control between several institutions from the U.S. and China concerns the full-scale implementation of passive and active control devices in the Nanjing Tower, a free-standing tower approximately 1000 ft tall with two levels of observation decks, to minimize the effects of wind and earthquake loads. This project pools the knowledge of experts in structural, wind, earthquake, and control engineering to design, install, and evaluate performance of the passive/active devices. The field testing and performance analysis will provide useful insight into the validity of modeling procedures involving wind-induced response of both the tower alone and with the addition of control devices, as well as, assess the adequacy of the passive tuned liquid dampers and the need for future developments.

In 1992, the National Science Foundation (NSF) initiated a five-year research program on structural control for safety, performance, and hazard mitigation. The objective of this initiative was to address a number of important technological, as well as, practical issues of cross-disciplinary nature in order to forge close ties between industry, research and practice and to accelerate the process of implementation. The scope of this initiative includes the areas of earthquakes, natural and man-made hazard mitigation, controls, and structural and building systems. Typical areas of research funded by the program range from sensor technology, actuator dynamics, control concepts, damage control, uncertain and nonlinear systems, and the actions of wind and earthquakes. Several wind related projects are funded under this initiative which include sloshing dampers, the next generation of liquid dampers, and general topics in the control of wind excited structures.

Base isolation systems are also being explored in which passive energy absorption mechanisms are installed that significantly reduce the base shears felt by the building during a major event. Through such measures, the natural frequency of the structural system is shifted below those of the dominant excitation source, such as an earthquake or wind loads. Such isolators feature elastometric rubber bearings, with or without lead cores, which support the building superstructure, allowing deflection and sustaining the shear that would result if the building were fixed during an earthquake and may be used in conjunction with viscous dampers at the top of the building. The development of such systems has relied upon investigations of building response in both wind tunnels and on shaking tables.

10. BRIDGE AERODYNAMICS AND AEROELASTICITY

Both theoretical and experimental studies are being conducted to improve our understanding of the interaction of turbulent winds with the cable stayed and suspension bridges. While theoretical analysis is focussing on the effect of turbulence on flutter speed of long span bridges, experimental work has turned toward improved modeling and quantification of aerodynamic forces, considering their sensitivity to turbulence characteristics and the geometric form of the bridge section. A thorough understanding of these effects is essential for improvements in both design and theory. Some recent studies have raised questions about the validity of some assumptions made in modeling. For example, the existing quasi-static formulation of buffeting forces has been confirmed to give reasonable estimates of aerodynamic forces for streamlined bridge sections; however, its representation of these forces for bluff sections, where body-initiated or signature turbulence is prominent, has been deemed inaccurate. New approaches for modeling buffeting forces and aerodynamic admittance functions and incorporating signature turbulence, applicable to streamlined and bluff bridge sections, is currently being pursued. Another challenged assumption, the assumption that the correlation time of excitation is short compared with the relaxation time of the dynamic system, which allows the use of the Markov property, may not be appropriate when noise is modeled properly. Proper modeling of noise requires that when fluctuations are introduced, they cannot be modeled as white noise, but instead as colored. This is an essential consideration since colored noise does indeed influence the system stability quite differently than colored noise. Section model studies are also underway which investigate the effect of modifications of the deck cross-section, including the addition of plates, streamlined deflectors, and railings, to enhance aerodynamic performance as well as insure aeroelastic stability.

A variety of theoretical studies have been initiated in hopes of developing mathematical simulations of the pressure forces acting on and excitation of bridge decks. Recent studies have focused on aerodynamic stability of bridges in buffeting and self-excited loads using flutter derivatives, vortex-induced vibration modeling of bridge decks, and the modification of linear analysis to nonlinear cases. One study has attempted to develop theoretical relations for bridge deck excitation by utilizing modifications of airfoil theory and exploiting the analogy of a streamlined bridge deck to a airfoil. In addition, the use of the Ibrahim Time Domain Method, the force oscillation method, and the system-identification technique in a single study confirm that good consistency in determining flutter derivatives may be achieved by using any of these three approaches. Researchers have now also found ways of utilizing computational wind engineering to determine the wind flow around and the forces acting on a bridge deck. Such techniques, one of which uses the 2D unsteady, incompressible, laminar, Navier-Stokes equations in a body-fitted, curvilinear coordinate system, may, in the future, allow designers to weed out bad bride deck designs before wind tunnel tests are applied. Furthermore, some time has been devoted to exploring the validity of the Discrete Vortex Method, finding it to be effective in simulating flow around a suspension bridge for modest angles and a Reynolds Number of 200. Full-scale studies are also underway to validate the theoretical and wind tunnel findings. Johns Hopkins University, the Department of Transportation, and the University of Notre Dame are engaged in topics under this area. Some of the work in this field has also been conducted at Princeton and Colorado State University.

Recently, accompanying the seismic retrofit of the Golden Gate Bridge, a aerodynamic stability study was initiated and the findings used as a basis for modifications to the bridge. After finding the critical flutter velocity for the torsional mode of vibration of the bridge to be extremely low, modifications of the bridge section were proposed to reduce aerodynamic instability. The group found that by rounding the sharp leading edges, through the introduction of fairings, and by replacing the very solid railing with a open one, the bridge's leading edge would become extremely airfoil-like, producing a stabilizing downward lift and increasing the critical flutter velocity to 105 m.p.h. In addition, another study analyzed the effect of viscous dampers, installed to dissipate energy during a seismic event, on the buffeting response of the bridge. By assuming that the supplemental damping manifested itself as additional modal damping, the study was able to conclude that the external dampers will increase flutter stability and reduce the buffeting response. This implies that external dampers may be employed to overcome problems of low flutter speeds or excessive buffeting deflections in long-span bridges.

Future studies should be devoted to investigating length scale, turbulence, and intensity effects and the dynamics of the vortex formation near separation. Furthermore, a multi-disciplinary research project to investigate the effects of turbulence length scale and intensity on the aerodynamics of bridge deck sections utilizing actively generated turbulence flow fields is currently being initiated at the University of Notre Dame. The study utilizes active turbulence generation devices, consisting of controlled air jets and oscillating screens in a large cross-section wind tunnel to identify the effects of properly scaled turbulence on the aerodynamics of a variety of generic deck sections. The use of active systems in this research allows for the simulation of turbulent length scales that cannot be produced with passive turbulence-generation techniques, while the jets add energy throughout the spectrum to supply energy that the grids are incapable of supplying and to ensure that the flows contain the appropriate fine-scale turbulence. Thus, this technique, by allowing for large models, permits the inclusion of additional deck geometric details that are often omitted due to scaling requirements. In order to determine unsteady buffeting and self-excited aerodynamic loads on the deck sections, synchronous pressure, pneumatically averaged pressure, and force measurements are collected.

11. KNOWLEDGE BASED EXPERT SYSTEMS (KBES) AND COMPUTATIONAL WIND ENGINEERING (CWE)

Knowledge based expert-systems can offer intelligent assistance to designers and planners in performing a vast array of tasks. Though KBES are not without their limitations, the potential applications of KBESs in wind engineering are many. They may include analysis and prediction of extreme winds, risk and damage assessment, design and synthesis, monitoring and control, urban and coastal community planning, and decision making for hurricane response. Currently, most of the effort in expert system development is focussed on damage and risk assessment utilizing expert system shells. The University of Washington, Stanford, Texas Tech, National Institute of Standards and Technology, Clemson University, and several consulting firms are active in this area.

An interactive computer program addressing the wind loading provisions of the ASCE standard7-95 has been developed at NIST. The software and the instructions for the user were developed by an expert system consultant with assistance from NIST staff in the interpretation of the standard wind loading provisions. Another knowledge-based program has been developed to overcome the problems of prescriptive of "Deemed-to-Comply" (DTC) standards. By creating the program in a user-friendly style, both the designer and builder of the structure may easily insure that the dwelling satisfies the wind code.

Recent advances in computational fluid dynamics are noteworthy, but major challenges remain in simulating flows common to wind engineering where both the structural geometry and the flow field are complex. Initial work in CWE has been focussed on a model which has succeeded in reproducing some of the integral features of flow field, but some discrepancies between numerical results and experimental data still remain. The flow field is modeled by the Navier-Stokes equations with appropriate boundary conditions. Turbulence models have been developed to simulate high Reynolds number flows that are not achievable with direct numerical simulation (DNS) due to computer limitations or to simulate a flow with a Reynolds number similar to DNS but with less computational effort. Currently the most widely used turbulence model is the k-epsilon method, which has the advantage of lower computational effort, but with a lower level of accuracy. The large eddy simulation (LES) approach has emerged as a more attractive scheme which has the promise of providing improved results with reasonable computational effort. In LES, fluid motion scales larger than the filter size are resolved and solved directly, while the scales smaller than the filter size are modeled by a subgrid scale model. The most commonly used LES simulation relies on the Smagorinsky model for subgrid scale viscosity. Coherent flow structures are responsible for the large scale pressure field rather than the eddies associated with the transport of momentum and energy, therefore, a scheme that models essentially coherent structures is appropriate for wind engineering applications. It is referred to as coherent structure capturing (CSC) to distinguish it from LES. One should not expect CSC to simulate flow field characteristics that are associated with small scales. The LES for capturing of coherent structures has shown improved accuracy, upon comparison of predictions and experimental data, but not without high penalty in computational effort.

A new method, using computational fluid dynamics, for numerical simulation of the turbulent flow field around a structure with oblique wind angles based on a composite grid, has been proposed in a recent study. The method consists of a composite grid technique which connects two or more grids supported by a fortified solution algorithm to simulate 3D flow fields for various wind angles. Another numerical model of air flows created by the TTU/CSU joint research effort has produced a model capable of predicting the detailed flow field surrounding a building or other structure. The technique adopts a version of the CSU Regional Atmospheric Modeling System (CSU-RAMS) which is a nonhydrostatic compressible model designed for large eddy simulation. Other studies have applied techniques like discrete vortex methods which seem to show promise over grid based techniques.

The development of different approaches are underway at various institutions to improve our modeling capability of wind engineering related problems (e.g., Colorado State University, University of Notre Dame, Texas Tech, University of Washington, University of Arkansas, Stanford, and Johns Hopkins University). Recent developments in CWE were reported at the 2nd International Symposium on Computational Wind Engineering held at Colorado State University in August, 1996.

12. WIND LOADING TEST CONCEPTS

Much of our understanding of wind events and their impact on structures has arisen from studies of small-scale models; however, for a complete understanding of how wind loads are transmitted through structural systems and the performance of building components under extreme winds, many feel that full-scale and large-scale testing is a necessity. To address these issues, NSF and NIST have sponsored a Workshop on Large-scale Wind Testing Concepts for Structures to be hosted by AAWE in Washington D.C. in May of 1997.

Several full-scale and large-scale testing concepts will be presented at the workshop including the wall of wind which calls upon 8-10 fans to generated artificial wind forces capable of testing complete and partial full-scale and large-scale structures and full medium-scale structures. Another artificial wind simulator, applying up to two fans, the mock up test, is valid for the testing of partial full-scale structures. Traditional modeled wind in the form of the Boundary Layer Wind Tunnel in a large size is valid for full and partial testing of full to medium-scale structures and even full small-scale structures, as opposed to its conventional form, applicable to only medium-scale, partial large-scale, and full small-scale testing. However, such a facility becomes quite prohibitive cost-wise. A final synthetic wind concept applies actuators in mechanical or electromechanic form to enable full and partial testing on medium to full-scale structures. A similar pneumatic technique referred to earlier, BRERWOLF, is also capable of partial testing for both full-scale and large-scale structures. It is hoped that these proposed testing schemes will lead to a new generation of full-scale and large-scale testing facilities.

13. WIND ENGINEERING RESEARCH APPLICATIONS

One of the major objectives of research in wind engineering is to improve our understanding of the wind load effects on structures for subsequent implementation in codes and standards. So in this context the major application of research is for the development of codes. Building codes in each locality are responsible for the design and construction of buildings. Most communities across the United States adopt, in large part, one of the three model building codes: the National Building Code of the Building Officials and Code Administrators International (BOCA), the Standard Building Code, or the Uniform Building Code. The provisions for wind loads in these model building codes are patterned after the ASCE standard on Minimum Design Loads for Buildings and Other Structures, ANSI/ASCE7-95. Recently, a major effort has been completed toward the next revision of ASCE7. A number of university researchers, practicing engineers and code officials have been working together to draw information from recent research findings for inclusion in the revised version of ASCE standard (ASCE7-97). A vital addition to the ASCE standard would be the inclusion of expressions for the acrosswind and torsional responses, which tend to have the greatest impact on occupant comfort. Internationally, few standards provide estimates of response in these two critical directions, despite the fact that their inclusion in standards would save time and money lost in unnecessary wind tunnel studies. Since response in these directions result from complex phenomena that is impossible to describe by the same quasi-steady or strip theory used in the along-wind direction, wind tunnel data must be collected to develop empirical expressions for the response in these directions, for various building aspect ratios and geometries, an area being addressed in current research efforts. This same set of wind tunnel data is also being used in a study both discussing various international standards and then evaluating their accuracy in predicting the along-wind and acrosswind response, where applicable, of a given structure.

In addition, since many of the expressions developed in ASCE7 are derived from wind tunnel tests, there is some concern for the standards by which the modeling is performed to insure valid results. Several criteria have been suggested to so that the high frequency turbulence, which is believed to affect the shear layer formation at points of flow separation, is sufficiently produced and to insure the overall accuracy of wind tunnel simulations on low-rise structures. These criteria address a variety of parameters from the mean velocity profile to the longitudinal integral length scale.

While one of the major objectives of research in wind engineering is to improve our understanding of the wind load effects on structures for subsequent implementation in codes and standards, the community also must insure that the knowledge acquired is disseminated throughout the scientific community. One example of such initiative is taking place at Texas Tech University. One strategy, sponsored by NSF, transfers wind engineering research results through CD-ROM packages for classrooms covering four topics: Thunderstorms, Tornadoes and Hurricanes -- A General Overview, Damage Caused by Hurricanes and Tornadoes, Impact of Windborne Debris, and Wind Loading on Low-Rise Buildings.

14. CONCLUDING REMARKS

In this article, an attempt has been made to summarize the wind engineering related activities in the U.S. Understandably, only general comments were made regarding the various areas of research interest; therefore, additional details should be obtained by contacting individuals at the institutions/organizations mentioned in this paper.

The author sincerely regrets an inadvertent omission of any institution from the different wind related activities listed in this paper. Most of the information has been drawn from the bibliography and through personal contacts.

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