Journal of Wind Engineering and Industrial Aerodynamics, 36 (1990) 1-15
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Recent Advances in Wind Engineering: Part I

by

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Introduction

This paper summarizes recent developments in wind engineering, with particular reference to the wind effects on structures. This summary is based on the manuscripts of technical papers presented at the Sixth U. S. National Conference on Wind Engineering, held March 8 - 10, 1989. First, a summary of the theme lectures is presented, followed by summaries of technical papers presented in different sessions that cover the following topics:

1. Bluff Body Aerodynamics
2. Structural Resistance to Wind Hazard
3. Damage Mitigation
4. Measurement of Unsteady Load Effects
5. Random Data Analysis Modelling and System Identification
6. Tall Buildings
7. Structural Glazing and Curtain Walls
8. Mitigation of Building Motion
9. Engineering Structures
10. Dynamic Effects and Structural Reliability
11. Chaotic Vibrations and Aeroelasticity
12. Knowledge-Based Expert Systems
13. Wind Engineering Research Applications.

Theme Lectures

Physical modelling (PM) of wind and wind effects has become the primary method of gathering information for wind engineering design codification and research. Development of the boundary layer wind tunnel has facilitated modelling of the atmospheric boundary layer. This has led to the determination of wind loading of buildings and structures by means of physical models exposed to simulated atmospheric flows in wind tunnels. Applications of physical modelling have also been developed in other basic phenomena of concern in wind engineering — local wind characteristics, mass and heat dispersion, and sound and light transmission. The first two phenomena are utilized extensively for examining pedestrian wind environments and dispersion of air pollutants, respectively, whereas the third area is in its infancy. Other applications of physical modelling are emerging, e.g., determination of snow loads on roofs. "Physical-Modelling Investigations for Wind Engineering: Applications Beyond Wind-Load Determinations" by Cermak highlights the issues outlined earlier. Starting from dimensional analysis, the author describes the long history of the development of physical modelling. Flow facilities for PM of low-level wind, wind-load modelling, local wind characteristics, mass diffusion and transport, heat transport and transfer, and sound and light transmission are discussed, and a list of appropriate references is included for additional background.

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0167-6105/90/$03.50

"Bridge Aeroelasticity: Present State and Future Challenges" by Scanlan reviews the overall subject of bridge aeroelasticity, highlighting significant milestones in its development, emphasizing key contributions. The author surveys issues related to the aerodynamics of bridge deck from a historical perspective, beginning with the Tacoma Narrows Bridge disaster. Final deck cross-section shape is emphasized, because it leads to the identification of key aerodynamic instability mechanisms. A clear distinction is made between the flutter derivatives of air foil and bridge section. The flutter derivatives offer useful design information concerning not only aerodynamic damping. The response of a long flexible bridge to wind is sensitive not only to stability; buffeting due to incident turbulence also becomes important. Comprehensive dynamic or aerodynamic analyses of bridges have been done recently in the context of now-popular cable-stayed bridges. These studies point out that certain erection stages of cable-stayed bridges are extremely vulnerable to wind, often much more so than the completed bridge.

This article also addresses problems associated with the construction of free-standing bridge towers, including examples of some motion-control devices, such as sliding concrete blocks, providing friction damping. Wind-induced motion of cables and its solution is summarized.

This paper addresses future challenges and points out the responsibilities of designers, owners, and aerodynamic consultants regarding the performance of bridges. The role of the aerodynamicist in tailoring the bridge deck cross-section to incorporate aerodynamic adjustments into the earliest stages of design is emphasized. Finally, the author reviews a host of technical problems encompassing important issues, such as flutter derivatives, flutter theory, buffeting, and damper development. The author emphasizes the need to develop theoretical and experimental first-quality aeroelastic tools in order to proceed safely to the future realization of very-long-span bridges that may pose formidable problems of dynamics, aerodynamics, and aeroelasticity.

"The Impact of Structural Damage in Jamaica due to Hurricane Gilbert and the Prospects for Disaster Reduction" by Davenport examines the performance of various types of structures during Hurricane Gilbert and the impact of their failure on the severity of the disaster. This paper critically evaluates the performance of structures, citing instances where the structures did perform well and indicating survival factors. The role of building codes and the protection they offer to resist structural damage is examined. The author affirms the need for governmental enforcement of codes and points to the additional support necessary from other sectors for the proper implementation of codes.

The loss of roofing was very prevalent during Hurricane Gilbert. In some cases, entire roofs were removed due to poor anchorage, while in other cases, sheeting of roofs was removed through failure of purlins or fasteners. Buildings which suffered serious structural damage included those essential for post-disaster recovery, such as hospitals, refuges, communication centers, and police stations. There was extensive damage to industrial buildings throughout the island. Losses to the agricultural industry contributed significantly to the measure of the disaster. The damage to larger office buildings in downtown Kingston was relatively light, but there was extensive glass breakage. The author concludes that the key to the reduction of disaster in hurricanes is the improvement in the wind resistance of structures. This can be accomplished by the establishment of standards, education in their use, and in their application.

Bluff Body Aerodynamics

Over the past several decades, much attention has been focused on the aerodynamics of streamlined bodies; however, our knowledge of the aerodynamics of sharp-edged bluff bodies in turbulent boundary layer flows is far from complete. The primary obstacle to understanding lies in the structure of separating/reattaching flow features and their sensitivity to approach flow characteristics. These flow-structure interactions pose difficult and interesting problems of practical interest that require further investigation, problems related to the aerodynamics of structures and road vehicles.

The various research topics undertaken in the area of bluff body aerodynamics involve extensive measurements of the pressure field around prisms and cylinders and the motion of a bridge deck section. "Effects of Incident Turbulence on Pressure Distributions on Rectangular Prisms" by Tieleman and Akins analyzes mean and fluctuating pressure-coefficient measurements on three-dimensional rectangular prisms. As a result of these measurements, the authors conclude that the small-scale spectral density parameter has a significant effect on the surface pressures on the sides and rear faces of rectangular prisms subjected to turbulent flow. The importance of proper scaling sampling is also emphasized; it accounts for the turbulent intensity, the longitudinal integral scale, and the measure of small-scale turbulence. The small-scale turbulent energy which affects the development of the separated shear layers is quantified using the small-scale spectral density parameter first suggested by Melbourne. A consistent relationship between pressure coefficients and the small-scale spectral density parameter is demonstrated, using data from several sources.

Measurements and analyses of the space-time structure of random pressure fields and area-averaged loads acting on prismatic building models in simulated atmospheric flows are presented in "Measurements of Pressure and Force Fields on Building Models in Simulated Atmospheric Flows" by A. Kareem. This study not only broadens the overall understanding of wind-induced surface pressure fluctuations around buildings and increased insight into the aerodynamics of prisms immersed in turbulent boundary layer flows, but also gathers a knowledge base concerning the spectral description of integral loads on buildings and their respective correlations. The conclusions drawn from this study include that an increase in turbulence intensity in incident flow induces early reattachment and pressure recovery on the side faces. The spectral description of the pressure field on the side faces is comprised of broad-band and narrow-band contents associated with the recirculation in the separated flow, flow characteristics in the reattachment zone, and vortex shedding, respectively. The spanwise correlations on the side faces are very pronounced in the separation bubble; whereas, near the downstream edge, less evidence of correlation is exhibited. The spatial extent of the instantaneous peaks in the spanwise direction, derived from conditional sampling, exceeds the chordwise direction.

"Shielding Factors from Wind-Tunnel Studies of Prismatic Structures" by English presents quantitative descriptors of shielding factors on mean aerodynamic forces. The shielding factors for a structure located in the wake of an identical upstream structure have been found to be most sensitive to separation distance, building aspect ratio, turbulence characteristics, and wind angle of attack. In this study, the influence of the first three variables has been investigated.

"On Uniform Flow Around Rough Circular Cylinders at Critical Reynolds Numbers" by Farell and Arroyave discusses flow regimes around rough circular cylinders on the basis of measurements of mean and fluctuating pressures. For cylinders with large roughness, there are two regimes — subcritical and transcritical — separated by a critical transition

occurring over a narrow range of Re. From the data utilized in this study, two subranges within the critical transition are identified. One of the subranges is characterized by symmetric pressure distributions, an increase in lack of uniformity along the cylinder span, and spectral peaks which vary as the Reynolds Number increases. The second subrange is characterized by oscillating, asymmetric pressure distributions, and spectra without well-defined, strong shedding peaks. According to this study, the transcritical regime is characterized by sharp vortex shedding peaks and the disappearance of the low-frequency fluctuations.

A series of section model studies to evaluate the aerodynamic performance of the 49-year-old Deer Isle-Sedgwick Bridge, a suspension bridge located on the coast of Maine, and the findings from those studies, are presented in the paper entitled "Section Model Studies of the Deer Isle-Sedgwick Suspension Bridge" by Bosch. In this study, wind tunnel tests were performed on a 1:25 scale section model which represents of a 125-foot segment of the main span. During the testing procedure, the model was subjected to laminar and turbulent flow, and it exhibited a number of undesirable tendencies. Various shape modifications were designed and evaluated, and, as a result of an asymmetric modification of the bridge cross-section, its overall aerodynamic performance was improved.

Structural Resistance to Wind Hazard

"Improving Wind Resistance of Wood-Frame Houses" by Liu, Gopalaratnam, and Nateghi discusses techniques to improve weak links present in wood-frame houses and describes new research aimed at developing an analytical method to calculate the response of wood-frame houses to high winds. Post-disaster investigations have been the principal source of information on wind damage to wood-frame houses; however, analytical studies can be used to predict the effect of wind on wood-frame houses under a variety of conditions which are otherwise difficult to vary and simulate in full-scale tests or post-disaster observations.

The research presented in "Masonry Walls Subjected to Wind-Induced Lateral Loads and Uplift" by Shoemaker and Womack experimentally evaluates the load-deformation behavior of a typical masonry wall when it is subjected to a combination of lateral wind pressure and uplift forces transmitted through a bar joist anchorage. A series of tests were conducted involving walls carrying uplift forces caused by bar joist anchorage, with and without the presence of lateral loads. Walls are being tested with and without reinforced masonry beams to evaluate the effectiveness of reinforcement in improving their strength. The information in this project may help engineers to better quantify the anchorage capacity of a concrete masonry wall that is not reinforced when it is subjected to both lateral loads and uplift, while providing insights into further research regarding the possible review or revision of current codes and practices.

"Wind Performance Limits of Roof Ballast Pavers" by Pardo documents various wind test methodologies and identifies other relevant parameters in this area of study. A standardized wind test format is defined based on the "Micro-Zone" concept. This permits the evaluation of full-scale roof system elements in the relatively smooth flow environment of aeronautical wind tunnels. This permitted an evaluation of the influence of roof fascia geometry, degree of element interdependence, and underlock air infiltration on the performance of roof elements. The findings in this study confirm not only that the failure of roof micro-structures by wind uplift is primarily dependent upon highly localized nonlinearities in pressure distributions, but also that these nonlinear effects are a function of wind speed, longitudinal air turbulence, and roof fascia geometry. The effects of perimeter

securement of ballast pavers to the roof eaves are substantial, as is paver interlock, that results in significantly higher resistance to wind uplift, due to the corresponding increase in tributary area over which concentrated uplift loads are distributed.

"Impact Resistance of Common Building Materials to Tornado Missiles" by McDonald identifies the most probable missiles transported by tornadoes, estimates the maximum speeds of these missiles, and determines the speeds required to perforate walls used in ordinary construction. The two most common missiles are a 2 x 4 in. 15-lb. timber plank and a 3-in. diameter 75-lb. steel pipe, with acceleration capabilities of up to 170 mph and 90 mph, respectively. Some of the interesting conclusions drawn based on the results of the impact tests of the timber plank are that conventional residential wall construction will not stop a missile in transport by tornado winds, that horizontal joint reinforcement has little or no effect on missile impact resistance, and that the shape of the end of the missile is not significant.

A post-collapse analysis of the sudden structural failure of the Pope's Tower in September of 1987 is presented in "Wind Damage to Pope's Tower in San Antonio." In addition to a structural analysis, this article presents a constructed scale model to evaluate the causes of the catastrophic collapse of the twin towers. Appropriate design needs for such towering structures are discussed. In this study, the internal cable system is found to be an adequate alternative method of providing lateral stability for this type of structure. Other important conclusions to note are that temporary structures should be designed using the same safety factor as permanent structures and that there is an overwhelming need for the development of specifications for temporary structures.

A number of post-disaster investigations have suggested that most of the damage from extreme wind events, especially hurricanes, is caused by lack of wind-resistant construction rather than by the severity of the storm. Provision of adequate fastening, anchorage, and bracings for houses and control of the availability of wind-borne debris may significantly reduce damage caused by extreme wind events. The session on "Structural Resistance to Wind Hazard" addressed some of the topics related to the structural resistance to wind hazards.

Damage Mitigation

"Mitigation of Wind Damage to Non-Engineered and Marginally Engineered Buildings" by Sparks and Saffir examines the causes of wind damage to non-engineered and marginally engineered buildings by focusing on the building code requirements under which they are constructed and the use of expert systems as a check on empirical design rules. In addition, the authors make suggestions for improving future construction, including increased involvement of insurance agencies and the general public to encourage stricter building codes and better enforcement.

The serious and costly problem of wind damage during the construction phase is discussed in "Mitigation of Wind Damage to Structures During Construction" by Ratay. This research explains how wind damage of the completed structure can be mitigated by anticipating possible problems during the design stages and controlling the sequence of erection during construction.

The damage patterns inflicted by Hurricanes Camille, Frederic, and Elena are reviewed in "Performance of Metal Buildings in High Winds," and mitigation strategies for reducing the damage to metal building systems are suggested. This paper identifies the engineered metal building as a competitive form of low-rise construction. The structural performance

of these buildings is well understood, and adequate code provisions are currently in place to ensure satisfactory behavior in high winds. This study also suggests additional steps to reduce wind damage and ultimately protect lives.

"Wind Damage Mitigation Strategies for the United States" by Liu and Turner provides insight into the tasks of the American Society of Civil Engineers (ASCE) Task Committee on Mitigation of Severe Wind Damage. Strategies to reduce wind damage include improvement in housing construction techniques and building codes, use of insurance to provide incentives for better wind-resistant construction, public education, technology transfer, and adequate funding for wind hazard mitigation research.

In "A Review of Standards of Practice for Wind-Resistant Manufactured Housing" by McDonald and Mehnert, wind load criteria and construction practices are examined, and strategies are presented for improving wind resistance in manufactured homes. The authors of this study conclude that wind damage mitigation can be achieved without affecting the popularity of manufactured homes, as one of the least expensive forms of housing available. However, the construction of both the manufactured home structures and their foundations must be carefully examined through research and development to provide structures that have the redundancy and ductility needed to prevent sudden and catastrophic failure when they are subjected to severe windstorms.

Poor design philosophy, which emphasizes neither the provision of redundancies nor the elimination of weak links in structural systems, can lead to failure at wind speeds well below design values.

Measurement of Unsteady Load Effects

An energized 500-kv transmission line in Oregon is used by the Bonneville Power Administration to measure the response of conductors in high winds. In "Field Data Analysis of Electrical Conductor Response to Winds" by Mehta and Kadaba, 23 records of wind speed, wind direction, and conductor response are obtained as field data, and a statistical analysis of the data is performed to assess the transverse response of a conductor under wind loads. Although the variability in the field-measured data constituted a large scatter in the results, some of the authors' important conclusions are that the field-measured effective force coefficients for conductors range from .48 to .74, that the conductor response spectra shows noticeable peaks near frequencies of .12 and .22 Hz, and that the aerodynamic damping varies from 18% to 91%, with most of the estimated values falling between 30% and 60%.

An experimental system for the measurement of motion-induced forces on a base pivot model, that makes use of a rigid geometric model, is developed in "On the Measurement of Motion Induced Forces on Models in Turbulent Shear Flow" by Steckley, Vickery, and Isyumov. The system provides a check for potential negative aerodynamic damping and provides a tool for fundamental research into motion-induced forces. A high degree of resolution can be obtained and small variations of motion-induced forces with oscillation amplitude can be distinguished. The authors demonstrate a reliability check of the pivot mode activator system.

The objective of the study entitled "Pressure Measuring System for Wind-Induced Pressures on Building Surfaces" by Ng and Mehta is to obtain a reliable data base for external pressures on building surfaces. The assembly of the pressure-measuring system and the verification of its performance is described. The dynamic response of the system is good up to 20 Hz. Although fluctuations in the reference pressure cause some problems,

the authors found that using a constrictor in the tubing reduced the fluctuations. The installation of a solenoid valve for each transducer that permits zero reading helped eliminate drift in the transducer signal.

The dynamics of a taut string in steady viscous fluid flow are treated in "Dynamic Interaction for a Viscous Incompressible Flow Past a Taut Cable at Moderate Reynolds Numbers" by Seelinger and Wauer. The authors study the mean flow past the cable and solve the linear stability equations. They also calculate a critical flow velocity and discuss the influence of the flexibility of the string. This research reveals the influence of the flexibility of the cable on the eigenvalues of the stability equations and on the critical value of the velocity and justifies these effects.

Random Data Analysis Modelling and System Identification

"ARMA Systems Representation of Wind Field" by Li and Kareem focuses on the development of procedures to simulate realizations of wind loading with small time increments, which are often required by time-integration schemes. A three-stage matching method and a scheme which combines autoregressive moving average (ARMA) and digital interpolation filters to simulate wind loads. The authors also present a more general technique which involves the generation of time series by the ARMA model at convenient time increments. A subsequent interpolation to a desired time increment offers a computationally efficient simulation scheme for processes which otherwise pose difficulty in using straightforward ARMA models.

A method to expeditiously determine ARMA algorithms for simulation realizations of multivariate random processes with a target spectral matrix is presented in "MA to ARMA Modelling of Wind" by Spanos and Mignolet. The authors of this study rely on minimization of frequency domain errors for the computation of the parameters of the ARMA model. Finally, the new method's usefulness is demonstrated by an examination of a trivariate spectrum commonly encountered in wind engineering, and it is found that an excellent match between target and ARMA spectral matrices can be obtained with a very small number of coefficients.

A method for studying the response of a transmission tower structural system that is subjected to wind loads is presented in "Frequency Response Function of a Transmission Tower Subjected to Multiple Loadings" by Liew and Norville. The authors consider the wind speeds and the loads from the conductors as the loadings on the transmission tower structural system and the stresses in selected members as the responses of the transmission tower structural system. After collecting data to be used in determining the frequency response function of the transmission tower structural system, the authors obtain the measure of response by subjecting the system to multiple loadings. The direct effect of wind speed is not significant on the transmission tower structural system; the frequency response functions for conductor loads are observed to occur at the fundamental frequency of the tower; the response of the transmission tower in the longitudinal direction has an effect on the diagonal members of the transmission tower. These are some of the conclusions obtained through this analysis.

"Transfer Function Models for Determining Dynamic Wind Loads on Buildings" by Islam, Ellingwood, and Corotis determines modal forces arising from wind pressures using a technique based on statistical integration and time series modelling. The authors examine the use of transfer function models in creating a statistically consistent ensemble of records, using partial records available from several nominally identical experimental observations.

It is necessary to carefully consider many technical issues in order to accurately measure and properly analyze the random response of systems. "Waveform Analysis Techniques for Interpreting Wind and Bridge Motion Data" by Bosch and Miklofsky presents the key aspects of waveform analysis techniques. Local wind environments are characterized, and the behavior of old and new bridge designs are documented, in order to gain a better understanding of wind-structure interaction. As a result of this research, instrumentation systems have been developed, deployment and maintenance of these systems has been explored, and software for analysis and evaluation of data has been devised.

Tall Buildings

Active control systems are proposed for the structural control of wind structures in "Active Control of Wind Structures" by Pantelides. Active control is shown to be a reliable method for reducing dynamic response, occupant discomfort, and nonstructural damage. Consequently, it is a means of increasing building safety. These systems are also recommended for controlling wind-induced vibrations of bridges or other structures where vibration limitations are critical.

The development of a methodology for the wind drift serviceability limit state design of multistory buildings is discussed in "Wind Drift Serviceability Limit State Design of Multistory Buildings" by Charney. This paper examines the need for a standard methodology to ensure the consistent design of buildings with equal levels of performance. This would ultimately result in a more consistent economical design. Such a standard methodology is developed in this research.

"Structural Systems to Improve Wind Induced Dynamic Performance of High Rise Buildings" by Banavalkar examines how the effective mass of buildings can be increased with a readjustment of structural stiffness and a modification of the fundamental vibrational mode shape of the structure. This paper discusses different economical structural systems through the modification of the vibrational fundamental mode shape and shows the corresponding increase in effective mass. The author demonstrates that providing externally applied dampers is not the only solution to the problem of reducing wind-induced response. A redistribution of stiffness can achieve the desired results economically.

"Wind-Induced Torsional Loads on Tall Buildings" by Lythe and Surry examines mean torsional loads on tall buildings, using a large data base measured experimentally in wind tunnel tests. This paper shows how the variability of torsion coefficients can be reduced by the use of appropriate normalizing factors and by grouping coefficients according to an approximate classification of the geometry of the buildings. In addition, a procedure for estimating mean torsions is presented. If the dynamic properties of the building are unusual, if the center of stiffness is significantly different from the center of mass, or if the planform centroid and torsional wind loads are significant to the design, the authors recommend expert advice or wind tunnel testing.

Structural Glazing and Curtain Walls

"Development of a New Glass Thickness Selection Procedure" by Beason and Norville focuses on developing a new set of glass design charts based on Beason's prior glass failure prediction model. These charts can be used to determine the 60-second

duration design load associated with a particular annealed glass plate with a probability of failure of 8 lights per thousand. Although the new glass thickness selection procedure is currently in the ASTM ballot process, it should be available within a year. Once it is adopted, the new procedure should provide a mechanism for regaining continuity in the glass design process.

A mathematical model designed to study the interaction between plates and enclosed air is developed in "Free Vibration Analysis of Insulating Glass Units" by Vann and Das. To determined the free vibration response of the system, the dynamic equations of the fluid-plate system are solved. It is noted that even plate modes are coupled with odd fluid modes and vice versa. Approximate numerical results show that the nondimensional fundamental frequency of the system depends only on a fluid-mass ratio and a fluid-gap thickness ratio, which cause small linearly varying percentage decreases in the fundamental frequency due to the addition of mass.

The maximum amplitudes, the corresponding periods of vibration, the maximum tensile stresses due to uniform lateral pressures applied suddenly on simply supported thin rectangular plates, and the results for various aspect ratios of glass plates are presented in "Nonlinear Dynamic Response of Window Glass Units" by Vallabhan, Das, and Kamineni. A mathematical model is developed to provide a relationship between maximum displacement, period of vibration, and maximum principal tensile stresses in any rectangular plate which has aspect ratios of 1, 1.5, 2, and 3. The authors recommend appropriate interpolation schemes for aspect ratios that fall in between the above.

The effects of different applied pressures on structural seal and seal shapes of four-sided glazed insulating glass units are presented in "Response of Structurally Glazed Insulating Glass Units to Wind Pressures" by Bailey, Minor, and Tock. The authors applied simulated wind pressures to one or both sides of each unit, and measured the changes in structural seal and seal shapes in order to better understand structural glazing systems.

In "SIROWET — A Comprehensive Dynamic Full-Scale Curtain Wall Testing Procedure" by Roonan and Howell, the authors develop a testing technique which simulates wind-driven weather conditions over the life of a building. This testing technique includes the simulation of combined exposure to wind gusts and rain on the outer face of buildings, evaluation of structural performance, air infiltration testing, and proof testing. The authors discuss performance of unusual designs, the testing methods used in this paper, and the future of facade testing. They also evaluate the development of more sophisticated testing techniques.

Mitigation of Building Motion

"Wind Induced Building Accelerations" by Ferraro, Irwin, and Stone examines two semi-empirical approaches to estimating wind-induced accelerations in tall buildings and compares them to results of wind tunnel measurements on scale models. The authors of this case study applied a code-based approach found in the National Building Code of Canada (NBCC) and an alternate semi-empirical approach which incorporates more detailed building and wind properties in the analysis steps to 48 buildings tested in wind tunnels. The alternate expressions perform somewhat better in comparison with the measured results than the NBCC code formula.

Experiments described in "Effects of the Orientation of the Principal Axis of Stiffness on the Dynamic Response of a Slender Square Building" by Isyumov, Steckley, Amin, and

Fatchi show that there are advantages to organizing the structural system of a building so that the principal axes of stiffness are aligned along the diagonals. Data illustrates the fact that the wind-induced excitation in this manner tends to become more disorganized or broad-banded, which significantly lowers the wind-induced peak accelerations and other dynamic effects. A minimum frequency separation of about 6% is required in order to maintain the motion of a building along its diagonal axes. Parametric studies presented illustrate that organizing the stiffness along the diagonal is practical and can be achieved without excessive cost.

"Reduction of Tall Building Motion by Aerodynamic Treatments" by Dutton and Isyumov documents a wind tunnel study of a slender, tall building of square cross-section. The building's aerodynamics are modified by the introduction of openings in the upper half of the building. Different gap widths are examined, and information is presented on the effects of these gaps on overall forces and responses and on the time-varying pressures with a 2-dimensional model tested in uniform flow. The authors found that through-building gaps can be effective in reducing the across-wind excitation of tall buildings, but that effectiveness varies with the gap width. They also note that the effectiveness of these gaps may be influenced by the level of turbulence in approach flow.

"Reduction of Wind Induced Motion Utilizing a Tuned Sloshing Damper" by Kareem addresses a new approach to the mitigation of wind-induced motion of buildings, an approach which uses tuned sloshing dampers. Pertinent theoretical background is discussed, an example of a tall building equipped with a tuned sloshing damper is presented, and there is a brief discussion of other immediate prospects for practical applications. Some of the potential applications of tuned sloshing dampers include tall buildings, towers, bridges, and offshore platforms. This article demonstrates that a sloshing damper can effectively reduce the motion of buildings when the fundamental sloshing and building frequencies are synchronized.

The incorporation of viscoelastic passive dampers in structures to achieve desired levels of acceleration and therefore ease problems of occupant discomfort and serviceability, is discussed in "Method of Damped Energy Calculation for a Multilayer Viscoelastic (V.E.) Damper" by Mahmoodi and Keel. Based on the observations and results of their research, the authors found that, at higher temperatures, the viscoelastic material layers experience uniform temperatures and strains. In the case of multilayer dampers, the dependence of total energy loss on temperature is not simple; however, the temperature of the center layer can be used as a reasonable indicator of the overall damper temperature.

Engineering Structures

"Wind and Wave Loads on a Tension Leg Platform: Theory and Experiment" by Vickery examines the response of tension leg platforms to both wind and wave loads. The study of tension leg platforms in this research is the first to be carried out in a properly scaled wind/wave environment, and the results and numerical simulations are in good agreement with previous findings. The authors found that the effect of wind on surge response is found to be strongly dependent on the existing waves, although the wind-induced response tends to dominate the overall response in special cases where the over-water fetch is small and the wind is strong. In the case of large waves, the reverse is true. Among the author's other findings are that the sea state affects both the hydrodynamic damping and wave-induced response of the platform. In severe sea states, the hydrodynamic damping tends to be large, which reduces the dynamic response to wind loads. The hydrodynamic drift forces tend to be large when the waves are highly grouped.

The responses due to wind loads and second-order wave loads are similar in magnitude in the absence of grouped waves, which emphasizes the need for accurate assessment of wind loads.

The dynamic behavior of tension leg platforms under the simultaneous action of random wind and wave fields is investigated in "Stochastic Response of Tension Leg Platforms to Wind and Wave Fields" by Li and Kareem. The authors develop time and frequency domain analysis procedures to analyze wind-wave-current-structure interaction problems. The aerodynamic load effects are described by the space-time description of the random wind field, and the hydrodynamic loads are expressed in terms of a combination of viscous and potential effects. A computationally efficient computer code based on the boundary element method is developed to evaluate diffraction and radiation forces. In the time domain, ARMA, discrete convolution, differentiation, and interpolation models are developed to generate time histories that describe wind- and wave-related processes and resulting response. In the frequency domain, the concept of Hermite polynomial expansion of the nonlinear drag term is extended to describe multi-component drag forces in terms of bivariate and trivariate expansions correct up to the quadratic terms. A stochastic decomposition approach, in conjunction with iteration and perturbation techniques, is developed. The frequency domain approach retains the effects of nonlinear interactions and offers accuracy comparable to the time domain approach at a fraction of the computational time. The time and frequency domain results show excellent agreement.

Two pipeline suspension bridges are investigated for wind load responses in "Wind Analysis of Pipeline Suspension Bridges" by Dusseau. Based on the author's findings, the best profile for a suspended pipe appears to be one in which the pipe is flat over the middle two-thirds of the span and arcs downward with a constant radius curve at each end that terminates at ground level. Such a profile has adequate vertical rigidity to resist vertical wind oscillations and maintains sufficient longitudinal flexibility to allow for the necessary expansion and contraction of the pipe due to changes in temperature and pipe pressure.

Dynamic Effects and Structural Reliability

"A Generalized Definition of Gust Factor" by Solari surveys the present procedures used for calculating the gust factors of alongwind velocity, local pressure, equivalent pressure, alongwind displacement, and equivalent static pressure. A research program aimed at formulating a standard calculation technique and generalized gust factor definition is described. The basic hypotheses and the preliminary results are reported, and the advantages of the method are illustrated. The method proposed in this paper gives a general homogeneous picture of the gust buffeting problem and of the alongwind response. Simplicity makes it ideal for fast-paced engineering evaluations and standards applications.

In "Wind Effects on Base Isolated Buildings" by Henderson and Novak, the authors study wind forces on base isolated buildings in the boundary layer wind tunnel by focusing on the flow and wind force characteristics in the region close to the ground. A theoretical analysis of the response of base isolated buildings in the drag and torsional directions is performed. The authors note that base isolation substantially increases building response to wind and, therefore, there is a need for a wind restraint in the form of greater initial stiffness of the isolators or special devices.

A method for evaluating the lifetime risk of failure in terms of the probability of excessive inter-floor deflection exceeding a prescribed limit is established in "Lifetime Risk of Failure of Steel Building Frames Subjected to Dynamic Wind Loading" by Das and McDonald. For a class of steel buildings, wind loads are generated through simulation,

and the governing equations are solved. The numerical examples presented illustrate the application of the method as a convenient checking procedure on the adequacy of conventional design. Based on this analysis, lifetime probabilities of failure are found to vary, with the largest probability pertaining to the bottom story for a low-rise building and to the middle or upper stories for a moderately tall frame.

Estimates for the stationary response of a linear oscillator excited by wind loads are developed in "Reliability of Linear Oscillators Subject to Wind Loads" by Buss and Grigoriu. The analysis is based on the characteristic function approach, moment approach, and path integral approach. These methods use some form of discretization, and each provides somewhat different information, but all may be used for estimating the reliability of the system.

Chaotic Vibrations and Aeroelasticity

An experimental investigation is conducted to determine the flow field around different arrangements of cylinders in cross flow in "Longitudinally and Transversely Spaced Cylinders in Cross Flow" by Ahmed and Ostowari. Results are presented as surface pressure distributions, turbulence intensity and velocity maps, and flow visualization photographs. The authors' findings indicate that the fore-body separated flow field significantly influences the aft-body flow characteristics.

"Modelling Spanwise Correlation Effects in the Vortex-Induced Response of Flexible Bridges" by Ehsan, Scanlan, and Bosch describes two methods for modelling the effect of an imperfect spanwise correlation of aerodynamic forces on the vortex-induced response of long-span flexible bridges. These methods are based on a semi-empirical nonlinear mathematical model for the vortex-induced response of bluff bodies and the results of wind tunnel tests on bridge-deck section models. The application of these methods requires knowledge of the spanwise behavior of aerodynamic forces on a prototype bridge undergoing vortex-induced oscillation. In addition, a method of approximating this behavior using measured spanwise correlation of forces on a two-dimensional, rigid section model is described, and examples of the application of the proposed methods are provided. The main advantage of the new method is that simple experimental and numerical techniques are used to obtain an approximate solution to a complex problem.

Experimental investigations examining the flow features around a pair of elastically supported square cylinders and the associated flow-excited vibrations are carried out in "Vibrations of a Pair of Elastically Supported Tall Buildings Models in a Uniform Stream," by Su, Lian, and Lin. The square cylinders are placed parallel to model adjacent buildings and placed in a recirculating water channel. The flow field is visualized using the hydrogen bubble technique and time sequential photography is used to map the flow structure around prisms. Depending on the flow speed, clearance, and support stiffness, three distinct modes of excited oscillations are observed. Although the patterns of oscillation and flow features appear to be a function of flow velocity, the critical speed over which the modal transition occurs covers a finite range.

"Wake Resonance Mechanisms in Bluff Body Interactions," by Ramsay, discusses wake resonance mechanisms in the context of the interaction of turbulent shear flows with downstream bluff bodies. The results of the analytical and experimental studies show that the interaction of the homogeneous upstream turbulence is well described by linear theory using the proper parameters. Two regimes — buffeting and wake resonance — are identified in the interaction of a 2-D turbulent wake with a downstream bluff body. The findings suggest that the results of linear, inviscid vorticity dynamics can be used for

inhomogeneous turbulence when the scale of the turbulence is well-removed from the wake resonance condition.

Numerical simulations of the behavior of a periodically forced square galloping oscillator yield results showing that the behavior of this system has similarities with the behavior of the circle map in "Chaotic Motions of Forced and Coupled Galloping Oscillators" by Cook and Simiu. Lock-in regions were found to be ordered as rational numbers obtained by the Farey construction. Preliminary tests in a wind and a water tunnel demonstrated the feasibility of the experimental study of both the forced oscillator and the autonomous coupled oscillators. Numerical studies were performed on an autonomous system consisting of two elastically coupled galloping oscillators.

Knowledge-Based Expert Systems

An overview of the basic concepts and techniques required to develop expert systems is presented in "Development of Knowledge-Based Systems in Wind Engineering" by Kareem and Allen. The processes of knowledge-elicitation and knowledge-representation schemes are discussed, and it is demonstrated how these systems can offer intelligent assistance to designers and planners in performing a vast array of tasks. An example of an expert system is presented, and it is concluded that such a system can effectively advance the state of the art in wind engineering.

Although research efforts have been made to improve the methods of using short-term records to estimate long-term extreme winds for design purposes, recent approaches incorporate the use of Markov models. "An Expert System for Extreme Wind Simulation" by Cheng and Chiu illustrates the application of this approach. Whereas the application of simulation models is quite tedious and time-consuming for the inexperienced user, the expert system presented here generates encouraging results to facilitate the application of these models in a microcomputer environment.

The expert system described in "A Micro-Computer-Based Expert-System for the Design of Wood-Framed Houses to Resist Wind Loads" by Sparks and Singh uses as its basis the prescriptive One- and Two-Family Dwelling Code, along with ANSI A58.1, to design wood-frame houses. The program provides a listing of the design wind loads suitable for use by a professional designer and a list of modifications of current codes for use when the form of construction in the code fails to provide sufficient resistance to calculated wind loads. An example is also presented which verifies that, by properly accounting for the building's exposure, most deficiencies formerly encountered with the use of the CABO One- and Two-Family Dwelling Code can be corrected.

"Wind Loads on Buildings Expert System — WINDLOADER," by Sharpe et al., highlights some of the problems encountered in the development of the expert system WINDLOADER and its benefits for users. The ultimate success of WINDLOADER has yet to be proven in widespread engineering applications, but it has already contributed extensively to the validation and enhancement of the Australian wind loads standard. A user-friendly interface, the ability to quickly refine design parameters, and a fast low-cost PC software package are a few of the current advantages of this system.

The development of a prototype knowledge-based system for structural safety assessment, with emphasis on wind effects, is presented in "Structural Safety Assessment" by Chen and Reed. The system contains a rule-based module for guidance and wind engineering background information, a module for causal network modelling of the structure under consideration, and a module for the numerical evaluation of the causal

network. The causal network is described in detail and is found to provide a simple and efficient estimation of the safety of the system using input probability of failure values for individual components.

Wind Engineering Research Applications

In "Performance Tests of Tornado-Type Wind Turbine Models (TTWT)" by Hsu and Minachi, power coefficients and pressure distributions in the vortex tower are measured for two Tornado-Type Wind Turbine models in a wind tunnel and in a real environment. The power coefficients indicate that the TTWT machine is able not only to extract the total kinetic energy, but also to extract part of the pressure energy of the captured wind. The power coefficients of the TTWT can be further improved if the vortex can be further intensified and the geometrical configurations of the wind machine are optimally designed.

A selection of different scale rotor blades is evaluated in "Upstream and Lateral Wind Turbine Wake Effects on Nearby Wind Turbine Performance" by Neff et al., with dynamometers, force balances, and wake measurements used to select a rotor model which correctly simulates the full-scale behavior of an actual wind mill. A wind-tunnel measurement program is carried out on a set of five dynamic (operating) wind mills placed at various heights and orientations, and the interdependence of wind-turbine performance on such spacing is determined.

"High Sided Road Vehicles in Cross Winds" by Coleman and Baker describes a series of wind tunnel tests performed on a tractor-trailer model mounted on a model bridge deck. The tests are performed in low turbulence flow with the atmospheric turbulence simulated. Measurements of the vehicle forces and moments, surface pressure, and surface visualization are taken. The results show the effect of turbulence on the aerodynamic properties of the vehicle, as well as the importance of turbulence simulation in assessing the risk of failure that is significantly increased with increased turbulence.

"Design and Aerodynamic Characteristics of the University of Minnesota Boundary Layer Wind Tunnel" describes the construction of a closed-circuit atmospheric wind tunnel at the St. Anthony Falls Hydraulic Laboratory. This facility can be used as a closed or an open circuit facility which is best suited for applications in which foreign particles must be introduced in the air stream. It will also be possible to operate this facility under very cold temperatures by shutting off the heating to the top floor of the laboratory when the tunnel is in the open circuit mode.

A computer program, TEAM, designed to simulate windstorm erosion and soil deposition, is described in "Windstorm Erosion and Soil Deposition Simulation" by Gregory, Borrelli, and Fedler. This simulation model is based on verified cause-and-effect relationships that match physical boundary conditions. Applications of the model are given, and it is shown that the relationship between the locations of highways and railroads can have a major effect on wind erosion and soil deposition. Although the present program is capable of simulating many combinations for single wind-storm events and some average annual conditions, further development is needed. From the examples presented, it appears that farmers must be careful to maintain at least a minimum fraction of clod cover if clods are to be used to control wind erosion. The findings of this research indicate that such a computer program can help engineers, city planners, and mine managers to keep costs minimized.

Concluding Remarks

This paper presents a brief overview of the papers concerning wind effects on structures that were presented at the Sixth U. S. National Conference on Wind Engineering. A total of three theme lectures and papers presented in thirteen technical sessions are covered in this summary paper. Several new topics of research and innovative ideas concerning wind effects on structures have been introduced in these papers. Specifically, the contributions in the following areas are noteworthy: the measurements of unsteady loads on oscillating models; the development of second generation force balance; the ARMA (autoregressive and moving average) modelling of wind load effects; the tuned sloshing dampers for mitigating wind-induced motion; the dynamic behavior of tension leg platforms to combined effects of wind and waves; wind effects on base isolated buildings; chaotic vibrations and modelling of wake-induced effects; and knowledge-based expert systems. The opinions presented here are primarily those of the original contributing authors and do not necessarily reflect the views of the writer.

Acknowledgements

The support for the preparation of this paper was provided in part by the National Science Foundation Grant BCS-835223 and matching funds from several industrial sponsors.