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Review article

7th US National Conference on Wind Engineering: A Summary of Papers

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1. Introduction

This paper summarizes recent developments in the area of wind loadings on structures. The following text is based upon technical papers presented at the 7th US National Conference on Wind Engineering, which was held at the University of California at Los Angeles on June 27–30, 1993. The technical papers have been summarized and have been placed into the following categories based on the subject matter:

1. Wind field models and extreme wind events
2. Low-rise buildings
3. Roofing
4. Glazings and curtain walls
5. Flow field/wind-induced pressure simulations
6. Snow and particulate/stone transport
7. Performance of structures in adverse weather conditions
8. Wind effects on electric power lines and towers
9. Fatigue and structural integrity
10. Damping systems
11. Aerodynamics of bridge decks
12. Risk and damage assessment

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2. Wind field models and extreme wind events

Most of the studies presented at the UCLA conference which address extreme wind events are devoted to the study of hurricanes, perhaps inspired by the recent US hurricanes such as Hugo and Andrew. The hurricane studies which follow focus on prediction methodologies for hurricane wind speeds through simulations based on historical data. Much emphasis in these studies has been placed upon the importance of developing hurricane wind fields which allow for estimates of the wind speed at different locations and may aid in preliminary damage assessment. Other topics represented in this section include the development of a new wind speed map based on peak wind gusts, the application of extreme wind data to estimate the wind speeds at an uninstrumented site, the use of climatology in studying tropical storms, and the simulation of tornadoes using wind tunnel models and computational fluid dynamics.

An improved prediction methodology for hurricane wind speeds, with an emphasis on the importance of hurricane wind fields, is discussed in "Prediction of hurricane wind speeds in the US" by Vickery and Twisdale. The paper cites the central pressure difference (Δp), the translation speed (c), and the size, defined at the radius to maximum winds (R_{max}), as the parameters which define a hurricane. To simulate the effect of the hurricane, the direction of storm travel (θ) and the distance from the site of interest (d_{min}) are also required. The paper calls upon the use of statistical distributions based on historical data between 1886 and 1991 to develop its models. The study simulates thousands of hurricanes, recording the maximum fastest mile wind speeds predicted by the Shapiro model and the ASCE 7-88 wind field model for each. A comparison of these simulations with previous historical data suggests that the Shapiro-based model, with the new gust factor curve and radial profile exponent equal to 0.5, provides a better estimate of the wind speeds. The ASCE 7-88 model clearly underestimates the maximum wind speeds by up to 10% and overestimates the lower wind speeds. For inland locations, the ASCE 7-88 model overestimates, due to the lack of a friction model to account for boundary layer growth as the storm moves inland. At near coastal locations, away from the maximum winds, both models perform equally well. Over water, the Shapiro model, with its gradual wind speed decay, appears to be the better simulator, since the ASCE 7-88 wind field model significantly overestimates the wind speeds on the left side of the storm. This was attributed to the questionable sudden wind speed reduction technique used in the ASCE 7-88 model. The paper also discusses two new storm decay rate models developed using the data from a total of 18 storms in the Florida, Georgia, and South Carolina Atlantic region. These models were found to be consistent with observations, with the decay constants found to increase with increasing values of pressure difference. In all 18 cases, the storms filled more rapidly than the models. The study also found dependence between several of the parameters, with the following correlation coefficients: (1) R_{max} and $\Delta p = -0.23$, (2) R_{max} and latitude = 0.47, (3) for storms between 22°N and 30°N, R_{max} and $\Delta p = -0.18$, with an insignificant correlation between R_{max} and latitude, and (4) for storms north of 30°N, Δp and latitude = 0.4, with little correlation between R_{max} and Δp. The final stage of the study compared simulated wind fields to actual storms. In Miami, the correlation between Δp and

Θ was consistent with the observation that storms approaching from the east are generally more enhanced than those in the Gulf. The correlation between the translation velocity and direction of the storm was consistent with the observation that storms that are recurving towards the north move faster than easterly storms. The comparison showed little difference between Shapiro's model, with radial profile parameters 0.4 and 0.5, yet both yielded higher predicted wind speeds than ASCE 7-88. The Shapiro model's larger wind speeds for long return periods were the result of its better representation of the radial distribution of wind speeds within the storm. In New York, the distributions, as in Miami, were all markedly influenced by changes in the sample subregion size. The ASCE 7-88 model predicted strong winds to approach from the north, while the Shapiro model predicted easterly, although southerly, winds. This discrepancy was due to the manner in which the translation speed is modeled. Along the northeast Atlantic coast, where hurricanes translate much faster than in the south Atlantic and Gulf regions, the impact of translation speed is more marked. Shapiro's model accounts for this properly. Also, the correlation between Δp and Θ is important in New York since storms moving easterly have travelled over land and are weaker. In conclusion, the study recommends using a subregion of diameter on the order of 500 km. For regions between 22°N and 30°N, R_{max} was found to be best treated as dependent on Δp, where above 30°N, dependence of R_{max} on latitude is most important. In New York, the modeling of R_{max} as a function of latitude instead of Δp produced a 5% increase in the 50-yr return period. As was shown in the New York case, where directionality varied between the models, the selection of the model is important.

There is interest in developing an actual surface wind field based on Hurricane Andrew data for South Florida and Louisiana. "Surface wind field analyses in Hurricane Andrew" by Powell and Houston uses data from Air Force reconnaissance planes, moored buoys, land stations, automated coastal platforms, and ships to create such an oblique analysis system. In order to insure the accuracy of the model, the input measurements had to conform to a common height, averaging period, and exposure. The average periods varied from a few seconds up to 15 min. Since the maximum sustained (1 min average) wind (V_{ms}) is the data released to the public in advisories by the National Hurricane Center, all the wind data was converted to that standard, if possible. Also, the study points out that during hurricanes, the surface winds can vary markedly depending on the roughness of the terrain an the size of obstacles to the flow. In Andrew, structures exposed to flow over open terrain were more susceptible to damage than those sheltered by houses or trees upwind. Many of the anemometers used to collect data were not in the open field, and therefore the data was not uniform. The team had to convert all input data over land to standard terrain roughness lengths of 0.03 m based on an open exposure found from photographic roughness characterizations of all major wind measurement locations. Coastal and offshore data, however, were not converted but are representative of the observed sea state. Failure of anemometers near the core of the storm resulted in sparse data were the highest winds were expected. The team had to use supplemental data from adjacent Air Force reconnaissance flight level wind measurements to the surface. The data was analyzed by an application of a computer code, producing a continuous wind field from which the maximum 1 min sustained wind speed is computed. The length scales of damage streaks (< 100 m), representative of sustained wind values of 85–135 m.p.h., indicate that time scales of the streak producing features are 1–5 s. Applying gust factors of 1.3 to the maximum sustained surface winds (V_{ms}) over land suggest peak wind gusts of 152 kt in the northern eyewall. The team does point out that the model did fail to properly resolve the maximum wind at the surface on the south and east sides of the eyewall. The study concludes that the availability and density of pre-landfall reconnaissance flight level wind measurements and coastal marine platform data, when analyzed in the storm relative coordinate framework, will allow for surface wind analyses to be computed in real time for oceanic exposures. Combined with a geographical information system with infastructure databases, the study speculates that fields will be available for preliminary damage assessment by emergency managers and infastructure coordinators in the event of a hurricane. Yet the study warns that data availability over land is likely to remain a problem until improvements are made in anemometer mounting systems, mast installations, and siting techniques. The study stresses that we must develop a network of pre-selected wind measurement sites with survivable meters carefully installed and maintained.

A shift in anemometer design toward the measurement of peak wind gusts as opposed to the traditional fastest mile of wind data have prompted the need to develop a new wind speed map for the ASCE 7 national wind load standard. "Extreme gust wind speeds in the US" by Peterka and Shahid addresses this. Hurricane coast winds were obtained from Monte Carlo simulations of hurricane wind speed, and the gust factors, obtained from ASCE 7-88 and other sources, were converted from fastest mile values or mean values to peak gusts. The peak gusts at 487 stations were corrected to 10 m. After that, the team then calculated the peak gust velocities at various heights for an open country location, with a log law used to fit the gust profile. Peak gust wind speeds for the continental US were calculated using the superstation concept to decrease sampling error. This technique relies on the demonstrated statistical independence between stations of measured daily extreme wind speeds, combining stations with short records into superstations with longer records to decrease the sampling error. The prediction of extreme wind speeds for each superstation was based on Type I Extreme Value Distribution. The method of moments was applied by the team to fit the data. The decay speeds for inland stations in hurricane winds were assumed to be linear and follow Batts' data. Conversion factors were developed to convert 50-yr speeds to other return periods. After the new map was created, several observations were made. Non-hurricane speeds on the hurricane coast were found not to be significantly different from the interior stations. Contour plots of the 50-yr peak gust speeds are quite uniform over the US, with peak wind gusts of 85–95 m.p.h., and decreasing toward the west coast. On the current ASCE 7 map, much of the non-hurricane region is at 90 m.p.h., with west coast states at 85 m.p.h. The average ratio of peak gust to fastest mile speed was found to be 1.2, serving as a conversion factor. Thus, the use of 90 m.p.h. speed for much of the non-hurricane US would translate into 90/1.20 = 75 m.p.h. fastest mile. The ASCE 7-88 also has areas with speeds significantly higher than 75 m.p.h., with large areas at

70 m.p.h. The team, however, did notice that speeds for Alaska in the new analysis were consistent with the ASCE 7 data. The team does caution the uses of the 500-yr speeds on the new contour map, since they have less accuracy, and care should also be taken when using the map in mountainous regions, since nearly no gust data was taken there.

It has been observed that extreme wind data obtained from locations with similar physiographic or meteorologic factors do exhibit common characteristics, thus extreme wind data from a specific region may serve as a good estimate of the extreme winds in a similar ungauged region. In "Regionalization of extreme winds," Cheng and Chiu attempt to obtain a composite, dimensionless extreme wind frequency curve which may be multiplied by the mean annual extreme wind speed at the project site to obtain an extreme wind speed for a specific return period. The paper divided this effort into the following steps: (1) Develop a basic probability function for the extreme wind distributions at various individual stations. Select the best suited probability distribution and perform point frequency analysis to portray the probabilistic behavior of extreme winds; (2) Perform statistical homogeneity test for the stations under consideration to discover agreements within the region so that the area of interest may be divided into homogeneous subregions; (3) Develop a composite extreme wind-frequency function for each homogeneous subregion. The composite frequency function is then constructed by taking the median values from site specific extreme wind-frequency functions in the homogeneous region. The curve was applied to the fastest wind speed series at 106 weather stations within the United States. The team studied the difference between the maximum velocity from the weather station data and the extreme wind velocity estimated by the regional frequency curves. The difference between extreme winds from the Gumbel lines of fitting historical annual fastest-mile winds and extreme wind speeds estimated from regional frequency curves is well below the standard deviation of the inherent sampling error of the historical records.

In but a few hours, as Hurricane Andrew passed over Florida, $100 million of damage per minute was observed, with the primary damaging force being wind. Due to the fierce impact of hurricane winds, many researchers have attempted to develop maps and techniques to estimate the wind speeds at various locations. A computer simulation of Hurricane Andrew's wind field to be used as a means to find new ways to estimate hurricane wind fields is presented in "Options for presenting hurricane winds fields: a different look at Hurricane Andrew" by Reinhold, et al. The model developed in the study uses the central pressure data and information on the storm track and radius of maximum winds to estimate the fastest mile wind speeds at a 10 m elevation across pressure 3 h before and after landfall to arrive at the central pressure, so there is some inherent uncertainty in the results and perhaps an underestimation of the winds. Several simplifications were implemented in the model as well. First, since Florida is flat, elevation changes were neglected. Furthermore, part of the area hit by the storm was regarded as "open country." Finally, due to the substantial urban zones in South Florida, the wind speed decreased as a result of increased surface roughness. The velocity contours produced offer some indication of the wind field for average surface conditions; therefore, in reality, some actual wind speeds will be less than those; some will be greater. The paper also addresses the debate over the most efficient means of presenting the data. Five types of presentation formats are discussed. (1) Standard map of wind field at 10 m in open country: This technique gives speeds that "would have occurred" if the terrain was actually open country. (2) Bracketing speeds to account for terrain roughness variations: Since hurricane winds over water are usually not the same as those experienced inland by structures, often the data must be interpreted on a site-specific basis. To do so, the average value on the map must be adjusted to the appropriate roughness/exposure factor. (3) Wind load map utilizing the local building code: By reading values from the map, dividing them by the code values, and squaring the result will yield a map of the velocity pressures imposed by the storm. (4) Frequency of occurrence of speeds: A method using statistical analysis to predict the return period for a certain wind speed. (5) Mapping to allow estimation of site specific wind speeds: This challenging approach can only be accomplished on a site-specific basis through a detailed account of the terrain roughness. In closing, the team stresses that the model presents an overall picture of the storm and cannot treat local effects with any significant accuracy and concludes by stressing that regardless of the method of presentation, the values found only predict typical conditions which would be expected in the event of a hurricane at a particular site; therefore, the engineer should always bear in mind that variations do occur.

Over the period of 1966–1980, 30 of the 108 tropical storms with hurricane-strength winds hit Mexico, and during the years of 1981–1986, 17 tropical cyclones hit the Pacific Coast. It has been observed that such cyclones which landfall may incur inland flooding in the South Central Plains of the United States. The team of Peterson and Warner, in "Landfalling Northeast Pacific cyclones affecting the South Central United States," explores the use of climatology in studying the North East Tropical Pacific (NETROPAC) storms occurring between 1900–1991. The team utilized rainfall statistics, satellite images, and ship gale data and found that between the years 1900 and 1991, moisture from at least half of the 79 landfalling tropical cyclones yielded rainfall over the states of Texas, Oklahoma, and eastern New Mexico. In this time period, hurricanes Norma (1981) and Tico (1983) produced the greatest rainfall in the study area, in some locations up to 20 in. The study concluded that most storms hit the Western Mexico coastline along a stretch of 450 km between 22°N and 25°N, during the dates of September 12 and October 30 of each year. The moisture from these storms was spread over the target area by southwestern mid- and upper-air flows. The front or trough provides an uplift force so the moisture is elevated and a more intense rainfall may occur. NETROPAC storms were found to produce the most rainfall in South Central and North Central Texas. In some cases, the rainfall was vital in relieving regional drought, while fall accumulation often hampered the cotton harvesting. The team further noted that the rainfall climatology of some areas of the south central United States may change if the frequency and location of NETROPAC storms changes.

Due to the aggressive, transient nature of tornados, laboratory vortex simulations have proven to be an essential tool in studying tornado behavior. "Physical modeling of tornado-like flow and tornado effects on building loading" by Bienkiewicz and

Dudhia addresses the modelling of tornados and their effects on building models. The tornado simulation used in the study features a low-speed, open-circuit wind tunnel to provide updraft and an attachment to supply circulation to the flow. Angular momentum is then introduced by rotating a wire screen in the flow. Inflow with non-zero tangential velocity enters the generator, spirals inward, and exits. This combination of angular momentum and the axial velocity gradient make the tornado vortex. The team suggested, however, that roughness be introduced, by gluing sand-paper of 3 mm grain to the ground plate simulator, to provide a more natural simulation. It was found that the smooth plate produced a multiple-celled vortex, while the rough plate experienced blockage of inflow and a highly turbulent vortex core. It was therefore concluded that surface roughness does have a major effect on vortex flow, delaying the transition to multiple vortices at low swirl ratios. The study then discovered the significance of the swirl ratio. It was found that when the swirl ratio increases, transition from single-vortex to multiple-vortex occurs, and pressure magnitude decreases near the generator centerline. The team also concluded that the magnitude of the prerssure coefficient weakly depends on the Reynold's number for high swirl ratio values and moderately rough surfaces.

Tornado damage is difficult to study in wind tunnels because of the frequent changes in wind speed and direction. To date, most tornado study is a post-disaster analysis of structures which were victims of the storm, with the damage assessed by calculating the upper limit of the failure load due to a straight line wind approximated as 300 m.p.h. However, tornados produce translational and rotational effects on the building, which are neglected by this straight line wind approximation. Also, as the speed of the tornado changes, inertial and drag forces are introduced. In "Computer modeling of tornado forces on buildings," Selvam attempts to model the actual effect of tornados on buildings using computational fluid dynamics. The computer model requires knowledge of all the details of tornado wind speed and turbulence up to 100 m above the ground. The boundary conditions of the model were established as 100 m from the building on all sides and 70 m from the ground for the top boundary. The computer model developed by Selvam focuses on the three-dimensional, incompressible, unsteady, Navier–Stokes equations integrated via control volume procedure, with convective terms approximated using hybrid upwinding, and then solved on a rectangular wind system. The building was discretized into $43 \times 36 \times 28$ cells, with the tornado assumed to move in a direction of 9.1 m. At each step, the x, y and z forces are calculated by considering pressure only. The model concluded that the severe wind from thunderstorms (SBL), which is the straight line wind used in post-tornado damage estimates, is greater than the effect of thunderstrom downdraft on the building for the same wind speed 10 m above the ground. The tornado, however, produces forces five times greater than SBL flow in the forced vortex region, while being of the same magnitude of the SBL flow in the free vortex flow. In the forced vortex region, one can see how SBL approximations underestimate the tornado's effects. The study further emphasizes that the difficulty in turbulence models like the k–ε model or the Reynolds stress model: these models do not have the proper information on the turbulence statistics of the tornado close to the boundary layer.

3. Low-rise buildings

As mentioned above, recent US hurricanes have also stirred interest in the design of low-rise buildings which have traditionally suffered significant damage during such events, partially due to poor construction practices but also attributed to poor design. In light of recent disasters, engineers presented numerous studies at the UCLA conference calling for improved construction techniques, better technology, and revision of low-rise building codes which consider hurricane-resistant design specifications. The research presented in this section addresses wind tunnel testing of low-rise building designs and the simulation of the wind forces on such structures, revisions of building codes and construction practices based on wind tunnel experimentation and post-disaster study, and retrofit schemes.

Due to the variety of low building shapes and the varying aerodynamic responses that result, there is much difficulty in specifying appropriate wind loads in building codes. Such codes must balance the probable load distributions with the likelihood of failure, incorporating safety specifications. "The codification of low building wind loads" by Davenport, et al. focuses on specifying such wind loads for the safe design of low buildings. The results of the study are compared to current building code requirements through the reliability theory. In the study, wind loads were measured in simulated, complex environments, chosen statistically, to embody the spectrum of possible loading scenarios. The study concludes that the generally satisfactory performance of engineered structures designed under present codes (such as NBCC codes) for moderate winds indicates that only slight changes are required in the minimum code levels of wind loading. The study further concludes the existence of high variability in pressure distributions, while criticizing the limitations of traditional wind tunnel simulations for low buildings. Such simulations tested low buildings in open plains without any surrounding buildings. The addition of peer structures, thus increasing the complexity of the environment, significantly reduced the expected load. The distinct differences in these two environments would suggest that sheltered (suburban) and exposed (open country) situations be separated into a more complex, yet more accurate building code. The study also references the "0.8 factor" and compares it to other approaches.

While most traditional wind tunnel simulations utilize uniform roughness fields, such approximations rarely duplicate the natural terrain. The findings of Fang and Sill, presented in "Variation of pressures on low-rise buildings in random roughness simulations," suggest that a more complete physical model would include the effects of random roughness. The findings were based on experimentation involving various upward roughness fields in a wind tunnel, simulating the wind loads on low-rise building models. Of the fields tested, one was a uniform field of two inch cubes while the eighteen others were random fields of selected element heights. The family of boundary layers generated simulated the terrain roughness of "sparsely built-up suburbs." The study concluded that modelers should consider the randomness of the prototype terrain in situations where wind loads are large ($|C_p| > 0.3$), because (1) the variability in pressure coefficients was greater in the random field simulations than in the uniform field, and (2) the uniform field may, therefore, underestimate the wind loads in the field. Since random roughness generates more variability in the pressure coefficient during the simulation, Fang and Sill suggest randomness should be utilized in modeling to preserve the wider variability of the prototype system and also to avoid discounting the randomness of the natural environment. In addition, the study suggests that a 30% range of safety be used for both mean and extreme pressure coefficients for the design wind load based on random simulations.

The Uniform Building Code for conventional construction provisions was not intended for regions subject to basic winds between 80 and 100 m.p.h. As a result, the improved high wind requirements of the 1991 uniform building code, designed to mitigate the damage experienced by such structures, were reviewed in "High wind requirements of the 1991 Uniform Building Code" by Armstrong. The new code provisions contained in Appendices 24 and 25 hope to reduce the damage due to high winds and floods. Appendix 24 provides prescriptive masonry construction criteria for typically non-engineered buildings. Topics addressed include: requirements for complete load paths, vertical reinforcement of walls, and connection details for the roof. Appendix 25 illustrates construction requirements to reduce damage to wooden structures. Points of interest include: lateral bracing for walls, limiting of overhangs and eaves to reduce uplift, and a decrease in anchor ties for masonry veneer. In addition, the study addresses action for minimizing flooding, since most of the strucures subject to these wind loads lie in regions victimized by wave action and tidal surge. Armstrong concludes by emphasizing the need for proper instruction and enforcement of the new codes, which will result in improved structural performance during high wind events or flooding.

The wake of destruction left by Hurricane Andrew prompted a panel of engineers to assemble and develop recommendations for updating building codes with hurricane-resistant measures. A summary and assessment of the ideas presented in this workshop are presented in "Hurricane Andrew recommendations for building codes and building code enforcement" by Cook. Several topics were addressed in this meeting. (1) Wind speeds and wind loads: ASCE 7 requirements should be implemented for residential structures. Furthermore, all structures within 20 miles of the coastline should be designed to withstand hurricane wind gusts. (2) Prescriptive building code requirements: Detailed prescriptive building codes should be established for non-engineered buildings based upon engineering principles and not those techniques regarded as "rules of thumb." (3) Protection of weather envelope: The exterior of structures must be more adequately protected since the failure of roofing materials, windows, and doors accounted for the majority of the damage costs. (4) Inspection and education: All members of the construction process, including engineers, architects, and inspectors should be educated and licensed in hurricane-resistant design. (5) Manufactured housing: Standards for prefabricated homes must be elevated to the standards of on-site construction.

A post-disaster study was undertaken on the island of Kauai after Hurricane Iniki to determine how building codes could be improved. "Structural performance in Hurricane Iniki" by Chiu, et al. examines the performance of various structures and determines where improvements were needed. It was determined that the exterior of the building needs to be addressed in the building code. There was no adequate coverage of the building envelope, i.e. the roofs, windows, and doors. Once the roofing or other exterior devices failed, high levels of water damage occurred. Similarly, the report stressed attention to detail. Most of the damage could be traced to inadequate fastening of roof coverings, roof anchorage of the roofing system to the walls, and poor connections of the stud walls to their foundations. Metal framing anchors should be required rather than simply nailing stud walls directly into the base sill. Also, the environment surrounding a structure must be considered for codes concerning buildings near mountains, gorges, or shore lines. Increased wind speeds in these regions had significant impact. The building codes must also consider increased internal pressures that result from failure of windows or doors. In addition, footings should be protected from the possibility of erosion due to flooding, and all footings should be anchored into stronger soil material, i.e. lava rock, rather than sand. Shear walls should be oriented normal to the beach line, while "break away" interior partitions should be used to relieve hydraulic forces during storm surge and wave action. Furthermore, light gauge metal sheathing should be replaced with an alternative roof fastening method. Of equal concern was the poor performance of roofs on essential emergency buildings such as hospitals, whose survival during such a disaster is paramount.

During the months of August and September of 1992, the Pacific Islands of Kauai and Guam were victimized by Hurricane Iniki and Typhoon Omar. The destruction in Kauai encompassed one-third of the homes and demolished the island's power grid, while the island of Guam only witnessed the desolation of less than 10% of its residences. The article, "Survey of building performance in Hurricane Iniki and Typhoon Omar," by Sheffield, stresses that the 1991 Uniform Building Code provides low-rise structures with significant protection from the wind forces of a hurricane or typhoon, the author continues to explore several factors which impacted the performance of low-rise buildings: (1) Noting that 90% of 1–2 family dwellings lost roofing materials, Sheffield concluded that attachment methods for roofs must be reviewed and stresses the fact that roofs with hip geometry functioned better. (2) Attention must be paid to improving the wind load resistance of roof converings, over-hangs, windows, and garage doors in residential structures. Failure of these components allowed extensive water damage to occur. (3) When open building design in involved, the engineer must account for the increased internal pressures, since such pressures can trigger failure of the walls and roof. (4) Proper connections are essential in construction. Sheffield stresses that attention to detail may have prevented many failures, considering that much of the debris from poorly constructed homes became airborne, damaging adjacent structures. In addition, Sheffield comments on the importance of elevating homes above the flood base elevation to prevent the erosion of the foundation due to wave action. Finally, Sheffield discusses why structures in Guam performed better than those of Kauai. It appears the structures in Guam were constructed with reinforced concrete and controlled by building codes mandating that each structure be resistant to winds up to 155 m.p.h. and be approved by a licensed engineer or architect. Meanwhile, the structures in Kauai were primarily poorly-constructed, wood frame dwellings built to withstand winds of only 80 m.p.h. As a result, this paper suggests a more in depth examination of single wall (studless construction) performance under high wind loading.

The 1992 rampage of Hurricane Andrew rendered 10% of Florida's Dade County residences useless, leaving 160 000 people homeless, and resulted in an estimated $30 billion in damage. Such alarming statistics have prompted engineers to investigate the nation's building codes and push for hurricane-safe structures. One such example is Vognild's "Are building codes adequate for hurricane protection?" which examines the effectiveness of the US model building codes. Several building deficiencies were highlighted by Vognild in this paper: (1) inadequate attachment of roofs, which was the primary contributor to damage, (2) the especially heavy damage sustained by ridge and gable ends is sloped roofs and corners in flat roofs, (3) failure at the connections, (4) failure of windows and doors as the result of high wind loads, which lead to water damage and increased internal pressures in dwellings, and (5) the inability of manufactured/mobile homes to resist the wind forces of the hurricane. Vognild continues by stressing the importance of adequate connections of roofs, appropriate lateral bracing for gable ends, and the improvement of load-bearing capacity of windows (even suggesting the mandating of shutters). As for mobile homes, the paper suggests that specifications for mobile homes be raised to those of standard housing and that they be prohibited in high wind zones. Finally, Vognild emphasizes that the appropriate use and enforcement of any of the three existing US model building codes will mitigate all of the deficiencies mentioned, excluding those caused by wind-blown debris. This of course would require the active inspection and supervision of construction in hurricane-prone areas.

Traditionally, low-rise structures have manifested vulnerability in the face of natural disasters. As a result, there must be concentrated effort towards developing preventive strategies for such structures. Gaus, et al. detail some methods of protecting existing homes from wind-induced damage in "Reduction of wind-storm damage to existing low-rise structures through self-help activities." Unfortunately, most research has been dedicated to issues of new construction, rather than developing strategies to improve existing homes threatened by natural disaster. This paper appeals to the research community to undertake such studies. The study then highlights the need for revised building codes and construction procedures for non-engineered structures and serves as a call for improved construction practices overall. In addition, the team elaborates on several retrofit procedures for low-rise housing, including a professional retrofit service in high risk areas and "self-help" retrofit schemes to be undertaken by homeowners themselves. Such "self-help" activities would necessitate a media compaign to convince homeowners to invest their own time, money, and effort into such a program to protect their homes, coupled with possible insurance, governmental, and institutional incentives. The report details several procedures homeowners can personally undertake: (1) roof sheathing using the simple application of construction adhesive to roof rafters and trusses, (2) corner anchoring, requiring installation of new connectors, (3) gable bracing, which may require professional assistance, and (4) rafter tie-down requiring the use of tension straps. The study concludes with the hope that such retrofit plans will not only be economically feasible but also preserve the lives and homes of countless Americans.

"Comparison of field and wind-tunnel measured spectra" by Thomas, et al. focuses on the comparison of the field and model data to access the quality of the simulation, i.e. the extent of the simulation in the wind tunnel and the scatter in the field data. There are several critical parameters of the approach flow that are of interest: the frequency and energy, as well as the surace pressures. The physical model used is WERFL, a 30 × 45 × 15 ft test building and 160 ft meteorological tower located in flat, open terrain. The building is designed to fully rotate in order to control the wind angle of attack and gather wind data via pressure taps positioned at various locations on its facade. The meteorological tower functions as a data collection device for the wind speed, direction, temperature, relative humidity, barometric pressure, etc. The wind tunnel used in the study was capable of winds from 2 to 124.6 ft/s with flow modifications in the form of spires, angled vanes, etc. available to achieve the desired profile and flow characteristics. Five vertical oscillating blades may be used to augment lateral, low frequency content. Spectra for both the longitudinal (u) and lateral (v) velocity components at roof height from typical field wind speed records, with the angle of attack 268.1°, and from the wind tunnel simulation were compared. The u spectra was concluded to be in excellent agreement in both data sets, except for $nz/u > 0.25$, which was attributed to the insufficient response of the field cup anemometer to higher frequencies. The v spectra was also in good agreement, except for the model deficiency low frequencies ($nz/u < 0.003$). The pressure spectral analysis of field data was found using the pressure coefficient data from the pressure taps on the test building. The study found reasonable agreement with pressure data compared to wind tunnel simulations on a 1:100 scale model. The paper concludes by noting the need for further study of pressure comparisons.

In South Carolina, the damage incurred by Hurricane Hugo totaled $7 billion, even though Hugo's winds were less than or equal to the design levels at nearly all locations. Thus, there is a definite need to address the resistance of light construction to hurricane force winds. Such topics are explored through the testing on a model structure and actual building components using an atmospheric boundary layer wind tunnel and BRERWULF, the results of which are presented in "A program to mitigate wind hazards to low rise buildings" by Sill, et al. The wind tunnel based was capable of speeds of 65 ft/s and can simulate winds for a variety of terrain types. BRERWULF is a device used in the experimentation that enables fluctuating pressure to be applied to cladding panels to study its performance under loading. The study, equipped with these tools, looks at various tasks. Task 1 studied "The evaluation of loads resulting from strong winds." The task was concerned with developing retrofit roofs to withstand severe winds and also focused on the reduction of loads on structures by positioning the building in a strategic location based on the cover provided by the terrain. Task 2 is concerned with "Evaluation of resistance of enclosures" which stresses that the building enclosure must protect the structure as well as the building contents, and in some cases, offer lateral stability. The studies currently proposed by task 2 include: an investigation into the influence of cladding of a metal building on the structural resistance and load path, a review of the current testing procedures for cladding, and the use of BRERWULF to test the wood and metal deck roof panels, involving both dynamic loading and the more conventional stepped static loading which is currently used to rate systems. Task 3 focused on "Stability of low rise wood and masonry buildings," since these materials are the primary components of residential and school buildings and often do not resist severe winds. The task 3 completed product consists of an aerial photo survey of 3700 structures hit by Hugo in which 90% of the 3000 homes had no structural damage, but the common failure of loss of the roof and sheathing dominated. Task 3 is also currently assembling codes, standards, recommendations, and technical reports to identify the state-of-the-art practices for storm resistant structures, as well as, identifying the strengths and weaknesses of the existing practices for low rise wood and masonry construction in South Carolina, and evaluating the capacities of various roof sheathing fasteners. The final task number 4, is interested in "Improvement of codes, standards, construction, and inspection practices." The task 4 products are currently comprised of manuals, software, video tapes, and CD technology to pass on data throughout the engineering and construction community.

4. Roofing

Once again, the interest in roofing practices has also peaked following the extensive failure of roofs attributed to the US hurricanes. During these events, roof failure was observed at the corners, edges, and ridges resulting in water damage to the building contents. Research to improve roof designs has utilized wind tunnel simulations, post-disaster investigations, and full-scale measurements to address issues like the impact of slope, type and shape of roof survival. While many alterations in general design and shape are suggested, simple measures such as securing and properly fastening roofing components may prevent future damage. The studies which follow address these issues in addition to specific studies on roof suction, the influence of low parapets on roof corner loads, and design precautions for essential buildings, like hospitals, which must survive in disasters.

At times, ground level assessments of hurricane damage may be inadequate since most of the damaged area cannot be examined due to the limitations caused by unsafe conditions and obstructive debris. In one instance, following Hurricane Hugo's demolition of South Carolina on September 21, 1989, aerial photos were utilized to gage post-hurricane damage. The findings of this aerial study are detailed in "Aerial photo interpretation of damage caused by Hurricane Hugo" by Rickborn, et al. The team analyzed aerial photos, provided by the Coastal Geology Unit of the US Army Corps of Engineers Waterways Experiment Station, of the three barrier islands of Charleston, South Carolina (Isle of Palms, Sulivan Island, Folly Beach). The 1:4800 scale photos, taken 2 weeks following the hurricane, were enhanced by a 7 power circular aspheric magnifying glass and compared to 1988 maps from the South Carolina Coastal Council. Although the damage shots were taken two weeks following the disaster, significant repairs had not yet occurred due to downed power lies, gas leaks, and debris. The study focused its attention on the types of roof damage, specifically missing/damaged roof coverings and missing roof sheathing/structures (i.e. rafters and trusses). Statistical findings of the damage proceed as follows: (1)

shingle damage of structures with shingles: 51% of houses, 31% of townhouses, 2% of condos, (2) 52% of houses with metal roofs and damage, (3) 57% of flat roofs were damaged, (4) loss of sheathing: 2% of houses, 4% of condos with pitched roofs, (5) loss of roof structure: 3% of houses, 23% of condos, (6) 7% of houses were demolished due to wind/flood/rain forces, (7) destruction of homes on the three islands: Isle of Palms – 5%, Sulivan Island – 8%, Folly Beach – 90%, (8) 41% of structures showed no damage, and (9) 49% of structures had damage to the roof only. The team further observed that most of the demolished buildings near the oceanfront were not elevated high enough and were thus subjected to storm surge. In addition, findings concluded that only 20.5% of the total damage could be solely attributed to the wind, with the majority of the roof damage occurring at the corners, edges, and ridges, while the primary source of damage was due to flooding and rain. Examination of the Standard Building Code confirms that its standards were adequate to withstand the storm, with building code maximum wind speeds of 100 m.p.h., which were consistent with the Hugo's winds of 85–102 m.p.h. Since condominiums and commercial buildings sustained the most damage, the study suggests that all condominiums, public buildings, and commercial buildings be designed by professional engineers to ensure that they are capable of sustaining higher wind velocities.

Insurance firms have a stake in the survival of structures and often employ the services of engineers to aid in improving their business. "A statistical analysis of wind damage to single-family dwellings due to Hurricane Hugo" by Amirkhanian, et al. is an example of a damage assessment for Hurricane Hugo which will be used for insurance purposes. During a storm like Hugo, with a mean recurrence interval of 20–50 yr, insurance companies estimate 30% of the insured value of structures to be lost. Accordingly, the average total hurricane damage to homes was 25.5% of the home's insured value; however, in only 11% of these cases was wind the sole damaging factor. In 95% of the cases studied, more than 95% of the direct wind damage was to the roof, allowing rain to enter and resulting in water damage. While wind was a primary contributor aiding other forces to damage structures, the actual damage of the wind alone averaged only 6.5% of the insured value of the home. The report then shifted its attention toward roofs. In the assessment it was found that tip roofs functioned better than gable roofs, while gable roofs functioned better than flat roofs. It was also found that, barring the example of the flat roof, slope had little to do with the extent of the damage. Other trends mentioned indicate that while oceanfront properties had more likelihood of damage, major damage to homes was independent of location. Insurance companies were also interested in the performance of buildings built after 1971. Such buildings were to be constructed in accordance with the Standard Building Code. It was found that such buildings suffered less direct wind damage than their predecessors, but this may not be a result of the code alone, but may also be a result of the newness of materials and updated maintenance post-1971. The code did succeed in reducing minor damage and managed to preserve the minimal structural integrity of the buildings, with few buildings actually collapsing.

Many buildings constructed in tropical regions during the colonial era allowed for air flow between the roof and the room's ceilings to improve the indoor comfort. Such roofs, called "parasol roofs," can actually also change wind loads. "A wind tunnel study of the influence of an architectural feature on classroom roof wind loads" by Aynsley et al., addresses the use of such architectural alterations to prevent failure of single-story wood framed classrooms. Failure of such classrooms in Western Samoa in 1992 were the direct result of uplift wind loads on the verandah roof, when the wind direction was toward the verandah side of the building. The upward pressure on the underside, due to the partial stagnation of approaching air flow trapped under the extended verandah roof, accompanied by negative upward wind pressures above the verandah roof, resulted in the failure of the structure. (A common point of failure was at the connections between the roof trusses and the walls.) The study then posed the question: "Does venting space, provided by an alteration like the 'parasol roof', under wide eaves overhang on windward side of a classroom reduce the mean wind loads on the eaves overhang?" This question was explored by observing surface pressure measurements on a 1:50 scale model of the standard Western Samoan Government Public Works Department classroom design. The findings confirmed that the uplift forces near the midpoint of the design of the classroom verandah roof, normal to the wind, can be reduced around 20% by creating a "parasol roof" with an opening around 10% of the wall height. It was also found that by increasing the "parasol roof" opening to 20% of the wall height triggered a 30% reduction in uplift wind forces, but was accompanied by disturbing pressure increases elsewhere. It was therefore advised to keep the parasol roof opening at 10% of the wall height.

There has been much concern for the intensity of suction near the roof corner of flat-top buildings. Accordingly, research has been devoted to mitigate such suctions. In "Suppressing extreme suction on low buildings by modifying the roof corner geometry," Lin and Surry compare the quality of a 1:50 scale wind tunnel model of the Texas Tech Experimental Building, victimized by such suctions, with actual full-scale experimental results. Using this data, the team conducted an investigation at Boundary Layer Wind Tunnel Lab (BLWTL) at the University of Western Ontario (UWO) exploring possible mitigation strategies. The suction was attributed to vortices which were generated near the corner by adjacent straight, sharp edges and swept the upper surfaces, much like the delta wing vortices generating high lift on planes. The study concluded that high suctions (peak $C_p = -12.0$) did exist near the edge and close to the corner under oblique winds. Experiments at BLWTL confirmed even greater suctions (peak $C_p = -16.0$ to -18.0) closer to the corner during wind tunnel simulations. It was found that extremely high suctions occur along rays between 10° and 22° with respect to the edge where a corner vortex exists. Several mitigation strategies were then suggested, and three are explored in the paper: (1) Partial parapets of width $0.12H$ and height $0.06H$: the parapets reduced extreme suction close to the corner by 24–40% for negative peak C_p, by 10% for mean C_p, and by 20–30% for rms C_p. Clearly, the parapets had a greater effect on the fluctuating pressures. It was discovered that the sawtooth parapet was more effective than the rectangular parapets, which may have actually induced additional vortices; (2) The application of rooftop cylinders decreased suctions near the corner by up to 60% (peak C_p), 50% (mean C_p), and 55% (rms C_p). The single cylinder configuration primarily affected the rms C_p, with a 20% reduction, while the dual cylinder approach had a greater effect on the peak and mean C_p. The success of the cylinders decreased with increased distance from their position, citing a definite drawback to this mitigation technique; (3) round edge configuration, achieved by attaching round edge plates of radius $0.1H$ to the wall: This approach was by far the best, reducing the peak, mean, and rms pressure coefficients by over 60%.

Studies have shown that low parameters may increase the roof corner loads, while high parapets ($H > 1.0$ m) generally reduce local suctions on flat roof corners. Since such reports provide vital information on the magnitude of pressure coefficients (C_p) measured on flat roof edges and corners, there is an acute concern for the accuracy of these results. This being the case, it is important to note how the proximity of pressure taps of roof corners affects the accuracy of assessments of local and area-averaged pressures acting on these regions, especially when parapets are involved. This is the topic of "Wind induced suctions on flat roof corners – the effect of parapet revisited" by Stathopoulos and Munteanu-Badian. Their research involves the use of a plexiglass model of a flat-roof building 61 m × 61 m in plan that was tested with and without parapets in a simulated open country and suburban terrain. The effect of various parapets on the wind loads was examined by testing parapets of 0, 0.5, 1.0, 1.5 and 3.0 m loaded at 5 cycles per second. The findings concluded that the largest, negative $C^{\bar{p}}(-3.6)$ and $C^{pv}(-6.0)$ occurred with the use of the 1.0 m parapet. The 0.5 and 1.0 m parapets increased the roof corner suctions for low buildings. All other parapet heights reduced the mean and peak corner loadings, with results bettering as the parapet height increased. With an increase in height, the suction peak became lower and broader, moving inwards from the roof edge; therefore, if there are no pressure taps close to the edge of the roof, inaccurate results will follow. Also, it was found that the influence of tap location was stronger for oblique wind directions. This influence was even greater for buildings without parapets and became less significant as parapet height increased. The study further stated that parapets < 1.5 m increase suctions for oblique wind directions. In general, high parapets decrease suction independent of wind direction. The report concluded by comparing the findings with the pre-existing building codes. For the most part, the standard provisions are consistent with the results, but the Supplement of the National Building Code of Canada apparently underestimated the values for edge area near the roof corner and for low parapets, especially for area-averaged pressures. The American Standard ASCE 7-88 code also made similar underestimations, underestimating the suctions for tall buildings, and providing no provisions for buildings with no or low parapets.

The majority of hurricane-resistant designs focus on tying down roofs and tracing load paths through the frame, yet one must realize that sheathing and even drywall contribute to the structural integrity of the typical home. "Complexity and contradiction in the structural performance of wood-frame houses in Hurricane Andrew," by Morse-Fortier, explores interplay of housing components in hip-roofed and gable-roofed ranch homes. This paper contends that while the gravity loads are carried primarily through the axial and bending response of framing members, the addition of sheathing causes load sharing among adjacent elements. Even when diagonal set-in brancing is used, shear stiffness of sheathing elements plays a central role in resisting lateral loads. Furthermore, it is often the case that roofs and walls are enabled, by their geometry and construction, with structural potential, but actually compete against each other and alternate load paths on the basis of their actual stiffness. The author explains that walls are actually load-bearing members which transfer gravity loads to the foundation. The wall studs act as columns, bending due to the attachment of roof and/or floor. When high winds strike, an uplift force is generated on the roof, resulting in tensile loading of the perimeter walls. The walls, when loaded perpendicularly, resist wind and seismic forces via bending and transfer their loads to the roof or ceiling, while loading parallel to the wall causes the wall to act as a vertical shear diaphragm, transferring loads to the foundation. The author further states that the effects of gypsum wall board and structural sheathing are additive, since walls have long, uninterrupted surfaces, thus comprising substantial structural elements themselves. There were several competing load paths explored in the paper: (1) Monolithic roof plane: In the case of the gable home, shear accumulated over the entire house length and was thus transferred into the endwalls through gables. The hip-roofed home witnessed shear accumulation up to the hip point and then was transferred through the triangular hip plane into the end walls. (2) Roof acting as diaphragm with shear fastened to lower truss chords: In this case, shear is transferred out of roof planes into interior partitions and directly into the floor slab. This reduces the shear loads on the endwalls; therefore, there is virtually no accumulated load on the gable or hip planes. (3) Roof acting as diaphragm not connected to interior partitions directly, but through hurricane anchors into top-of-wall tie beam: Here, the tie beam can resist loads via transverse bending, with upper windward corners of interior partitions acting as lateral supports, thus the interior walls are shear walls and endwalls are relatively load free. It is emphasized that if this sheathing is lost by suction, these three load paths will be lost. The three other load cases reconsider the first three but with gypsum ceilings combined with top-of-wall tie beams to form a stiffer diaphragm in the ceiling plane. By attaching trusses to the time beam, interior partitions and endwalls will be engaged to resist lateral forces. The paper then stresses that these load paths will compete and may even alternate as the storm damage changes their relative stiffness, until the damage is so great that none will function, resulting in failure. The paper contends that the loss of sheathing was a major cause of failure in Hurricane Andrew. The actual response of the building will depend on the relative stiffness of the competing load paths; however, this stiffness is compromised by the effects of soaking of gypsum ceilings and wall boards by rain, as well as by the continual degradation of load paths with time.

When natural disasters strike, it is of the utmost importance that the essential facilities survive (i.e. fire stations, hospitals, evacuation shelters, etc.). Although such buildings may not exhibit severe damage to their primary structural members, even roof failure can hamper activities and risk lives. Although the ASCE 7-88 code mandates "importance factors" in the design of such structures, "Preliminary design guidelines for wind-resistant roofs on essential facilities" by Smith and McDonald discusses further considerations for the design of essential facilities. The first topic addressed is the roof deck and framing. Breach of building envelope must be prevented to secure against failure. Since the roof deck provides lateral bracing of the compresion elements of roof joists and purlins, its materials and fasteners must be made to resist the uplift loads at corners and perimeters, with generous factors of safety. There were even the suggestions that the US should mandate fatigue standards for fasteners. Among the roof deck designs suggested in the paper were: (1) cast-in-place concrete: the authors described this as an excellent design, (2) precast, pre-stressed concrete: the team suggested 50% increase in safety factors (SF) to account for uplift, (3) gypsum or light weight insulating concrete over bulb trees and form-board: the study stressed attachment practices and SF = 3.0, (4) steel deck: Smith and McDonald suggested minimum 22 gage thickness, (5) wood plank: the paper stressed correct installation of nails and SF = 6.0, (6) plywood or oriented strand board: the authors suggested SF = 6.0 with special attention to the length of nails, thickness of deck, and nail spacing, and (7) cement–wood fiber panels: the study highly recommended for use in essential structures with SF = 4.0. The next component of the paper was concerned with the internal pressure. While the ASCE 7 code warns for increased internal pressures due to "openings," which may cause roof to fail, the quality of doors and windows must also be improved so that they do no fail, due to wind loads and impact by debris, and contribute to the "openings." The primary modes of roof failure were addressed next, focusing on the removal and launching of "missiles" or airborne pieces of metal edge flashing, copings, gutters, aggregate, rooftop HVAC or communications equipment, and concrete pavers. Such "missiles" may damage roofs and cause leakage, requiring the application of secondary water-proofing membranes. "Missile" damage may be minimized by incorporating safety factors in the attachment of roof coverings, rooftop equipment, metal flashing, and coping, and prohibiting the use of aggregate on roofs of essential buildings in hurricane zones. The team also stressed the failures due to multiple load cycle fatigue, inadequate uplift resistance, and deterioration of components. Finally, the study addressed the repair strategies for roof damage, stating that the existing membrane and insulation must be removed, followed by adequate inspections and improvements of the roof deck and framing.

5. Glazings and curtain walls

The impact of wind-borne debris during extreme wind events, such as the hurricanes mentioned earlier, is a source of great concern among designers of structural glazing, cladding, and curtain walls. In addition to this, developers must also consider the repetitive action of turbulent wind gusts present during hurricanes. The studies presented herein stress the importance of the building envelope as a necessary component of the structure essential to the building's survival. The areas of interest addressed include: improvements of standardized codes to include hurricane-strength winds and account for increased internal pressures following rupture of the building envelope, the performance of sealants under both cyclic loadings and environmental factors, and the importance of integrating glass, mullions, frames, and frame anchorages in construction and design.

The external building envelope represents the single largest expense for the building project; therefore, there is great hope in reducing the mass of the exterior to reduce the building materials and labor costs. However, the trend toward lightening the exterior of structures in order to minimize expenses requires a greater understanding of the possible pressures and forces that the structure may encounter. The paper entitled: "Glazing system performance under typhoon wind loading: three case studies" by Ashford highlights the various typhoons which have struck Guam and comments on the adequacy of building codes in preparing structures for the possible pressures a tropical storm may induce. The author stressed the need to alter the US building codes to account for Guam's cyclone exposure. For many years, the codes did not consider the integrity of the building envelope essential to the building's safety. The author points out that the building codes in Guam are actually based on typical wind cycles for the continental US which does not experience the same extreme wind and higher pressure gradients of this region. US codes are based on winds found in typical thunderstorms which are insufficient to ensure building integrity in the event of a storm containing a steeper profile or cyclonic winds. The study then conducts a comparison of the 1991 Uniform Building Code, ASCE 7-88 Minimum Design Loads for Buildings and Other Structures, and AS 70.2 Minimum Design Loads on Structures, Part 2: Wind Loads (Standards Association of Australia, 1989). The AS 1170.2 code, unlike the US codes, requires the designer to: (1) design the glazing system to reject wind-borne debris without producing openings in the building envelope; or (2) assume that at least some window glass will break and design for full pressurization. The code also requires impact load consideration from wind-blown debris and a methodology is provided to estimate wind speed over the crest of hills and steep terrain. These considerations become highly significant in tropical cyclone wind design, as is needed in Guam. The paper then presents 3 projects designed between 1989 and 1991 and discusses the pressure considerations in the designs. The author highlights that the present design practices in the US account for the local effects of wind gusts on building structures, but this is not carried over into the wall components and the building cladding. The study also notes that the lack of hard data on velocity and directional components of the tropical cyclone winds have forced designers to use their own judgement. The paper also advises that, since in the mainland US the effects of terrain on wind speed are significant compared with the negligible impacts of an island small enough to fit into the eye of a storm, pressure coefficients for a category D terrain would be more appropriate. The author stresses improvement in the selection of the proper glass which is vital to maintaining the integrity of the building envelope. The paper concludes by reminding designers that building codes only estimate the minimum standards, which do not adequately describe extreme conditions and the forces and effects of tropical cyclone winds. The three cases considered in the paper illustrate that a good understanding and application of the current building codes can lead to successful designs.

There is a growing trend in construction toward the use of glazing, the attachment of cladding panels and window glass lites to the building frame with adhesives. The sealant applied must be able to withstand cyclic loadings resulting from wind and earthquakes, as well as, temperature fluctuations and harsh environmental conditions such as cleaning agents, acid rain, ozone, ultraviolet light, and moisture. A common failure that occurs in sealants is cracking which leads to water damage. "Fatigue behavior of structure silicone sealant" by Norville and Sheridan focuses on the behavior of such structural silicone sealants, one of the most popular sealants used, which provides a flexible yet sturdy attachment and prevents water seepage, in response to cyclic loading. The loading imposed in the study was a constant load amplitude, with a slower cyclic loading so that thermal effects do not come into play. Previous studies had indicated that sealants appear to be sufficient versus cyclic loading, but the authors emphasize the consideration of the combined effects of cyclic loading, environmental factors, and the effects of non-zero mean stress cyclic loads. The loading used in this study was sinusoidal at 1 Hz with zero mean and various stress amplitudes of 20, 28, 30 and 40 psi. Each specimen consisted of a $6 \times 2 \times 2$ in. aluminum block, a $6 \times 2 \times 0.5$ in. piece annealed glass, and a $2 \times 0.5 \times 0.5$ in. strip of GE Ultraglaze SSG 4000 structural silicone sealant. The study concluded the same *S–N* curve as a previous study, but found that the number of cycles to failure at any given stress level was greater than those of that study. The team concluded that this was due to technical advances in silicone design in the past 5–8 yr. Also, a hyperbolic function appeared to fit the data better than a semi-log function. The study found that while the cost of the sealant is minimal relative to overall building cost, its importance to the integrity of the building requires attention from the designer. The study states that care must be exercised when designing and installing sealant systems, since a properly applied sealant will more than pay for itself during the life of the structure, emphasizing the need for studies to observe the coupled environmental effects and cyclic loadings that the sealants are subjected to.

Historically, there have been problems with the performance of architectural glazing systems in hurricanes due to the airborne debris-ridden, turbulent, sustained winds with multiple attack angles. Designs must account for these effects to insure the structural integrity of the building envelope following impact from debris and the application of repetitive wind bursts. Often the failure of the windward cladding wall leads to pressure increases and results in structural failure. “Architectural glazing systems in hurricanes: performance, design criteria, and designs” by Minor and Behr examines five hurricane events to illustrate the effects of wind-borne debris on cladding. In one example presented, Hurricane Andrew, the failure to integrate the designs of glass, mullions, frames, and frame anchorages left one or more components of system subject to failure. The failures in Andrew included: (1) windows broken by debris, (2) windows broken due to wind-induced pressures, (3) deflections of window glass causing the glass plates to “pull out” of the glazing pocket, (4) vertical mullion failure due excessive loading, and (5) failure of connections which anchor the window frame to the building due to overloading. The first two types of failure were quite common among the other hurricanes studied by the team, but the other forms of failure were characteristic in Andrew alone. This was credited to the fact that the wind pressures in Andrew were at or about full design values and that the glazing systems were not designed for full hurricane effects. The study illustrates that most codes neglect the post-glass-breakage effects in buildings and the pressures which result. The study points out that a opening windward of as little as 5% will produce full internal pressurization. This must be considered in design, so that glass can be resistant to debris impact. Such recommendations were followed by the Standard Building Code. Three glazing configurations were found in the study to pass the middle zone test criteria of the Standard Building Code: a special configuration of heat-strengthened laminated glass, a "sacrificial ply" configuration with outer ply of 7/16 in., and a PET film applied to the inside of a monolythic glass lite and anchored to all 4 sides of the window frame. The study concludes that hurricane prone regions must design glazing systems capable of withstanding impact of wind-borne debris.

6. Flow field/wind-induced pressure simulations

Computational Wind Engineering (CWE) has shown promise to become a valuable tool in the simulation of wind-induced pressures of structures, offering a possible alternative to physical models in wind tunnels. While useful, these techniques are limited in situations where both the structural geometry and flow field are complex. Most of the present work is concerned with accurately reproducing some integral features of the flow field and comparing the CWE model and physical models with the actual full-scale measurements. Current work in CWE modelling deals with different algorithms in use. In the following section, numerical simulations of fluctuating loads with non-Gaussian probability distributions are discussed. However, while CWE is developing, physical modelling is still the only means of accurately simulating wind loads. Therefore, the following section contains research concerning numerical and physical modeling of the flow around structures and associated load effects.

CWE utilizes computational fluid dynamics (CFD) to determine the wind-induced pressures on structures, and the wind velocity fields surrounding them. "Computational wind engineering – issues and concerns" by Stathopoulos discusses the growth of CWE and the issues, concerns, and applications in this field. The study begins by discussing the limitations of both computer and physical modeling. Since swirling flows and some gusts cannot be accurately modeled through wind tunnel simulations, wind velocities determined by measurements of the boundary layer in such simulations may be somewhat incomplete. Numerical methods, on the other hand, are challenged by complex building configurations and large areas of model domain requiring the definition of often complicated surrounding geometry, which require fine grids and are highly inefficient. The paper illustrates, however, that new CFD algorithms in the area of high-speed external aerodynamics and turbo machinery are being developed which can conquer such limitations; however, the team stresses that numerical accuracy, careful selection of boundary conditions, and refined turbulence models are all areas that require improvement. One model in frequent use for unsteady flow conditions is the large eddy simulations (LES), which has great accuracy, yet requires more CPU time and causes instability for high Reynolds number flows. While applications like these are vital aids in CWE, the paper stresses the need to verify CFD results with experimental data, when available. The study points out that most CWE applications use finite difference methods and the control-volume approach with a two equation (K-ε) turbulence transport model, yielding a mean flow condition with mean pressure and velocity. Usually, such models focus only on the wind perpendicular to the face of the structure, since that is the simplest to model and has the most critical overall load effects. The limitations of such models lie in the effects of other wind directions and the analysis of wind loads on non-rectangular or complex shapes. Another issue addressed by the study was computational costs. It was observed that both the IPC/12 and DELL 286/20 have the same Intel 286 microprocessor, but the high clock speed of the DELL takes less CPU time. Also, both the DELL and AST were found to have the same clock speed, but the AST, with the longer word length, consumed less CPU time.

The calculation of wind loads can be extremely tedious due to the complex nature of wind pressures and their variations with time. This becomes even more complicated if the structure is wind-sensitive, necesssitating wind-tunnel studies; however, for the most part, low and mid-rise structures are comparatively stiff with respect to wind loads. Fortunately, the development of CAD and GIS graphics procedures allow loading specifications to be linked directly with the actual loading calculations and design, producing designs that automatically obey building code specifications. Such developments are discussed in "Integrated wind load design using computer graphics technologies" by Gaus and Small. Such computational tools relieve hours of tedious calculations, while allowing one to exercise different building codes on object-oriented structures. Such systems require topological information with pressure or loading information. The paper illustrates how CAD programs provide an evaluation of topological information with built-in macro language to generate the required data not directly defined by a software program. This allows the user to substitute different loading modules for different loading standards. On the other hand, GIS programs evaluate topological aspects of the wind loading and include relational data handling capability, allowing for interface with other components of a larger system. An example of this is the ARC/CAD combination system which incorporates both GIS and CAD. The topological data provided through CAD and GIS are readily available and can be run on microcomputers. The paper further develops the need to characterize the wind environment, i.e. the roughness category, standard maximum design wind, and an importance/safety factor when using wind loading standards. The paper closes by commenting on a computer model that would utilize the established CAD, GIS, and expert system shells, and graphical display packages as modules in overall systems, that would allow one to input the topological module. The system would then use a procedure based on standard building codes to analyze and aid in the design of the structure consistent with the standard codes. The system would output the results of the analysis using a graphics interface. By also providing a data class interchange structure, it would then be easy to interchange the system modules and substitute in other loading standards to be used for analysis.

Numerical analysis of the flow field around a structure with arbitrary incidence wind angles is relatively difficult when the computational method is based on ordinary finite difference, finite volume systems. The paper entitled "Numerical study on flow field around structures with oblique wind angle based on composite grid system" by Mochida, et al. proposes a new method for numerical prediction of the turbulent flow field around a structure with oblique wind angles based on a composite grid system. The method consists of the composite grid technique which connects 2 or more grids supported by a fortified solution algorithm to simulate 3D flow fields for various wind angles. The composite grid system applied to the arbitrary wind directions consists of two grids arranged at an oblique angle to one another. Each computational domain is then discretized individually by using a structural grid based on general curvilinear coordinates. A coarse grid is used for the entire domain, with a fine grid around the sub-domain surrounding the structure. The fine grid may be rotated as the incident wind angle changes. The team then conducted experiments on two types of applications to test the model. In both, the K-ε model for turbulence was applied. First the velocity and pressure fields surrounding a cube with oblique wind angles of 0°, 22.5°, and 45° were studied. For the 0° simulation, results consistent with previous studies were observed, but the new model was successful in reducing the number of grid points by 35%. The 45° angle case also yielded acceptable results. In all three angle cases, pressure field results were reasonable and the distributions connected smoothly, especially in the reverse flow region, reflecting the advantage of the connection method used in the fortified solution algorithm. A second case study of the flow and diffusion field around a cylindrical cooling tower was conducted with the use of both rectangular and polar grids. The study concluded that there was distinct advantage to using the polar grid near the cylindrical tower and rectangular grid in the downstream region.

Can the numerical K–ε model be used for predicting wind velocities around buildings? "Evaluation of the use of the numerical K–ε model Kameleon II for predicting the wind velocity distribution around buildings" by Livesey and Mikkelsen examines the reliability of this numerical model in predicting wind velocities around simple cubes and buildings by comparing model results from wind tunnel studies and full-scale measurements. The Kameleon model is a 3D finite volume code using the K–ε turbulence model. The paper examines the model's ability to correctly reproduce and maintain a boundary layer profile in a domain without obstacles and the degree to which modelling of oblique surfaces influences the model's predictions. The first test will require a 2D calculation to be performed in a domain without obstacles. Unfortunately, in the Kameleon II model, the geometry of the input obstacles is limited to a rectangular grid forcing curves to be modeled as a series of steps. The test modeled a cube with 0° incline and one with 45° incline to the flow and found them in good agreement. Thus, the study concluded that this limitation of the model did not pose too great a problem. Comparison of the wind tunnel data and calculated values on the cube shows large discrepancies in front of the block, in the separation bubble region, and in the wake behind the block. This may be due to the fact that single-wire, hot-wire anemometers were used and do not measure exactly the same numerical quantity as the model, since in turbulence, the anemometers cannot distinguish between flow directions, unlike the numerical model. Further study was performed on a housing development in Frederikshavn, Denmark. The study focused on a narrow passage between two houses. A model was built to 1:50 scale with houses and was also modeled on the computer using a finer grid in the vicinity of the narrow passage to test the dependence of the results on grid refinement. In the passage without a fence, high speed winds were present. The application of a fence was found to block this and force the wind over the roof, reducing the wind at the pedestrian level by 50%. The study found the numerical model and wind tunnel model in agreement. The refinement of the grid was also found to have no particular impact on the results. The limitation of having to use steps to model oblique surfaces seemed to pose no severe threat to accuracy.

Ever since Hurricanes Andrew and Iniki violently illustrated the inability of roofs on low-rise buildings to survive hurricane force winds, engineers have been focused on improving roof design. A vital tool in these efforts is the use of physical models in wind tunnels; however, such models in the past have agreed poorly, in the case of low rise structures, with the full-scale data. In "Full/model scale comparison of surface pressures on the Texas Tech experimental building" by Tieleman, et al., comparison of the full-scale location and the physical model constructed is conducted to estimate the success of the modelling effort. The study was conducted on the Texas Tech University 50 m tall micro-meterological tower and experimental building. From the dates of April 1, 1991 through July 22, 1992, 860 wind data sets of 15 min lengths were recorded, 700 of which were acceptable for study. These data reflected the flow characteristics about the building. North and South winds revealed log velocity profiles that exhibited slope changes credited to increased upwind surface roughness. The turbulence was found not to be in equilibrium with the underlying terrain and was assumed to be associated with rougher upwind terrain and/or unstable thermal conditions. The study concluded that despite the flatness and uniformity of the terrain, mean flow and turbulence exhibited evidence of being developed over non-uniform terrain, with turbulent intensities, especially the lateral component, being clearly affected by the convective conditions on summer days. The study also found that the average intensities at the roof height exhibit significant variations with wind direction. The study then took this data set and compared it to flow characteristics observed on 1:100 and 1:50 scale models tested in the wind tunnel simulation identified as CSU RII. The team concluded the following from their comparisons of the actual data with the three following simulation techniques, which utilize the addition of spires in the flow: (1) CSU RII simulation with standard spire roughness methods [2 inclined horizontal spires far upstream of the model]: This simulation had a better duplication of the turbulent stress distribution and closer geometric similarity in the streamwise turbulence integral scale, while being deficient in small-scale turbulence content. (2) UWO Flow G [7 small spires in various locations] & UWO Flow B [5 larger spires in various locations]: These simulations, with small spires upstream of the model, exhibited better duplication of horizontal turbulence intensities and improved simulation of small-scale content; however, the roof pressures were generally best duplicated by the UWO Flow G simulation.

In recent times there has been growing concern for the local cladding loads on building surfaces which have caused failures in glass, cladding, and roof covers. Traditional fatigue tests, utilizing cyclic loading, do not adequately estimate fatigue strength for the building envelope, since the test does not reflect the characteristics of the real fluctuating load with features like high amplitude spike-like events and a non-Gaussian probability distribution. "Computer simulation of non-Gaussian wind pressure fluctuations," by Seong and Peterka, addresses the need to define and simulate the long time history of pressure fluctuations during the cladding lifetime. The study suggests using a linear autocorrelated Gaussian model, such as the autogressive moving average (ARMA) model using non-Gaussian white noise, but even such approaches have difficulty in reproducing the natural shape of spike events. The paper then proposes a technique which uses the Fourier transform method, the autogressive model with non-Gaussian input processes, and phase transformation of Fourier coefficients in the Fourier representation of the time series. Through this procedure, the study found that the sharp spike events in the fluctuating signal are strongly dependent on the organization of the phase part of the Fourier transform of the signal and that the proper phase shifting of the Fourier transform in the Fourier representation of the signal can significantly alter the fluctuating features of the time series without changing the autocorrelation dependency of the signal. The study also found an appropriate spike generation model with phase shift for generating various fluctuating features in the simulated signal. The simulation produced the typical fluctuating features in the surface pressure under a roof corner vortex flow, with sharp spikes and non-Gaussian distribution. The study witnessed extreme values of the model which corresponded well with the measured signal for the mode and dispersion values.

In post-hurricane studies it has been observed that the increase in internal pressures due to the sudden rupture of the building envelope has led to failure of roof structures. It has been found that the breakage of windows and doors during windstorms can increase internal pressures, of particular concern is the extent of overshoot following a sudden opening and correlation of the internal and external pressures. Such topics are addressed in "Field study of internal pressures." Using a field research facility, Yeatts and Mehta perform a cross-correlation analysis for internal pressures, resulting from such openings, and external pressures, and then compare the internal pressures to those pressure values given by ASCE 7-88. The internal and external pressure data was collected in the Wind Engineering Research Field Lab (WERFL) at Texas Tech University. WERFL is a fully rotatable, $30 \times 45 \times 13$ foot building with doors and windows that provide 5% and 2% of the wall openings, respectively. A fitting may also be placed in the window to provide an additional 1% wall opening. The data acquired from repeated observations confirmed that the permeability of WERFL was independent of the building position and was consistent with results from previous research on high-rise buildings. Further analysis was conducted to uncover the effects of static openings, those which do not change during the data acquisition, and the response of internal pressure following a sudden opening in the windward wall of the test building, such as the breaking of a window. The study concluded that the variation of the internal pressure with windward opening area shows that windward wall openings as small as 1% produce maximum internal pressure coefficient values. The study also found that there was no overshoot of internal pressures following a sudden breakage of glass. The observed response time for internal pressure to reach its peak value was in the range of 0.38–0.73 s. The study further concluded that there was a high correlation between the internal pressure and both the windward wall and roof pressure. It was observed that as the internal pressure rises, the roof pressure falls. The magnitude of cross-correlation coefficients were in the range of 0.7–0.9 for time lags up to 1 s. The ASCE 7-88 code gives internal pressure coefficients (GCpi) for cladding and component design as ± 0.25, for a building with no openings, and $+0.75$ and -0.25 for specific opening conditions. The study found that the test building, with near uniform permeability, would need a wall opening of 5% or more before a GCpi of + 0.75 can be used. According to ASCE 7-88, a building with no openings, with 2% windward openings, with 2% leeward openings, and with 2% side openings would all require GCpi = ± 0.25; however the study found that both the mean and pak GCpi measured values for the 2% windward opening scenario exceeded this recommendation. For the side and leeward opening scenarios, the mean GCpi values fell near the suggested ± 0.25 range, but the team found that the peak measured values did exceed the wind load standard range.

It has been found that motion-included vortex excitation (MIE) can be characterized by fluid-interaction of motion-induced vortices (MIV) and the Von Karman Vortex (KV). In a practical sense, there is great concern for the vortex excitation of girders of long span bridges. Since the effect of turbulence of MIE has not been sufficiently developed, there is hesitation on the part of designers in installing aerodynamic attachments like flap plates, deflectors, or edge farings, which have been recommended by wind tunnel tests. This is the focus of "The vortex-interaction of vortex-induced vibration of fundamental structural sections in smooth and turbulent flow" by Shiraishi, et al. Their study looks at the effects of MIV and KV on several cylinders of varying slenderness (B/D) ratios. Several conclusions were presented in the paper: (1) MIE is significantly interfered by KV, and this interference can suppress MIE. It was shown that MIV and KV are closely related for cylinders with $B/D = 2.8 - 6.0$; therefore, the MIE of these cylinders should be affected by KV; (2) Turbulence with a splitter plate can suppress KV and MIV. For the $B/D = 3.0$ cylinder, it was found that the addition of a splitter plate can drastically change the turbulence effect on the heaving response of the vortex excitation. The study concluded that the splitter plate can amplify MIE response by suppression of KV, whose shedding frequency is close to that of MIV for a cylinder with $B/D = 3, 4, 5$, and twice the frequency of MIV for $B/D = 6$ in smooth flow. The study further concluded that installation of a splitter plate in turbulent flow has no effect because of the suppression of KV by turbulence, proving that turbulence can indeed suppress KV similarity with the installation of a splitter plate in the wake; (3) MIE-response is stabilized by turbulence. The turbulent stabilization ratio varied with B/D and the Scruton number (Sc) with $B/D = 5$ being most sensitively stabilized by the turbulence and $B/D = 6$ being the least affected; (4) Cylinder $B/D = 6$ shows a different MIE, with 2 vortices on a side surface, manifesting a second mode MIE, whose onset reduced velocity $[(1/2)(B/D)/0.6]$ is close to the inverse of the Strouhal number; and finally (5) The amplitude of MIE for small values of Sc was found to decrease with an increase of B/D in smooth flow. Furthermore, $B/D = 2$ was most significantly stabilized by an increase in Sc.

7. Snow and particulate/stone transport

As mentioned earlier, the impact of wind-borne debris or "missiles" on the building envelope not only results in water damage but also triggers an increase in internal pressure which may lead to structural failure. The primary culprit is gravel and rooftop aggregate which are dislodged and become airborne in extreme winds. This area of concern is addressed in the following section. However, while the disastrous effects of wind on structures during hurricanes and tornadoes are readily recognized, few may realize the havoc winds play in everyday life: erosion, reduced visibility, and even disease. Accordingly, the topic of particulate transport was also addressed at the UCLA conference, and the resulting studies are presented below. The studies have focused on the mitigation of erosion and reduction of snow movement to reduce property damage and protect both plant and human life.

Few may realize the threats posed by wind erosion in the southwestern United States. Dust storms in California triggered outbreaks of "valley fever," a mold spore carried in the wind, whose resulting infections claimed the lives of 129 people in 1992. In addition, the swirls of dust also caused decreased visibilities on interstates. The dreaded Interstate 5 accident, an excellent example, took the lives of 17 motorists involved in a 164 vehicle disaster when visibilities were reduced to less than 50 feet. The team of Wilson, et al., in "Analysis of the 1991 California wind erosion disaster," created a mathematical model to simulate the California dust storms that occurred in the fall of 1991 and then uses this model to determine tillage techniques to mitigate the damage. The visibility and maximum transport rate, a function of wind speed, threshold friction velocity, particle size and distribution, and the surface cover, found by the model were successful simulations of the November 29 and December 28, 1991 storms. The paper then discusses countermeasures, such as the soil conservation techniques in West Texas, to reduce erosions along highways and on agricultural land in California. Clod cover was found to reduce wind erosion and double visibility, while taller plant cover was found to work even better.

Dust storms may produce extensive damage to plants, disperse agriculturally rich top soils, decrease visibility, the cause air and water pollution. The disastrous effects of such storms has prompted Singh, et al. to develop a dust storm simulation outlined in "Erosion to dust: a fundamental prediction procedure." The prediction process presented in the paper consists of: (1) prediction of soil detachment and maximum transport rate and generation of the mass flux in the saltation layer, (2) estimation of saltation layer depth for uniform size particles, (3) calculation of mass concentrations in the saltation layer, (4) estimation of reference concentration height in saltation layer, (5) calculation of dust concentration with height for each particle size in the system and the total concentration height, and finally, (6) prediction of visibility at different heights due to local dust concentrations at that height. The wind erosion process modeled consisted of three phases: the detachment and initiation of soil movement by the wind, the transportation of the soil via saltation, surface creep, and suspension, and finally deposition. The model used the settling velocity to determine whether each particle will enter into suspension or move only in saltation, thus contributing to the dust concentration reference height. The visibility determined by the model was found by estimating the probability of the light penetration through all concentrations of varying particle size. The team concludes by warning that these results, while consistent, are conservative estimates due to the uncertainty of the percentage of clay in primary or aggregate form.

At times, during high wind storms, the roof gravel used to cover flat roofs may dislodge and act as a missile breaking the windows of adjacent buildings. Among the solutions to alleviate such damages include increasing the rock size so it is not easily swept away, reducing the missile size, or creating stronger windows. Such solutions are addressed in "Roofing design that avoids glass breakage during high winds" by Gregory, et al. The study focuses on determining the maximum stone size that will not break a certain thickness of glass under specified winds, the minimum layer of large stones required to provide the same UV protection as small stones, and finally the possibility of using an expandable plastic grid (GEOWEB), placed on a roof to protect the small particles from eroding winds. The study was based on the assumption of maximum damaging impact velocities of 80 ft/s and minimum damage impact velocities of 40 ft/s. On the topic of strengthening windows, the study concluded that maximum impact velocities of 120 m.p.h. would require resistant glass of thickness 0.08–1 cm, while 80 m.p.h. impact velocities predicted only a glass of 0.4–0.48 cm would survive. Addressing UV protection, the paper states that the thickness of the UV resistant layer is proportional to particle size, finding that a depth of 5 times the particle diameter will result in only 1% of the light penetrating to the surface below the layer. The final strategy discussed, was the use of GEOWEB, which reduced the energy that is transferred to the erodible surface. GEOWEB is a "honeycomb" grid composed of strips of a high density polyethylene material which also resists deterioration from UV rays. In wind tunnel simulations on GEOWEB cells at a cell depth 3.5 cm, vertical eddies developed and the sand still eroded. This was not a major setback since this phenomenon may have been eliminated by using larger particles with higher threshold velocities.

"Wind tunnel studies to mitigate snowdrift into rooftop air-handling ventilators," by Meroney and Tan, involved the physical modelling of 86 smoke visualizations and 40 "snow-storm" simulations. A 1:150 scale model of a hospital complex was used to gage flow patterns while a 1:50 scale model of the upper floors and penthouse region were used to evaluate the snow accumulation. The study rated the effectiveness of the 16 snow control strategies in deterring snow flow and stagnation near the vents, with the results listed below: (1) vacuum intake: It was found that the use of fans forced the smoke over the surface and had no effect on the snow accumulation; (2) vent location: It was found that the vent location caused flow separation to occur and had no effect on snow accumulation; (3) solid fence: The three types of solid fence had a tenancy to slow and lift smoke but did not significantly reduce the amount of smoke reaching the vents. The fences did prove to be successful in controlling snow drift problems on the roof; (4) porous fence: The four types of 50% porosity fence also slowed the smoke slightly, but did not prevent smoke or snow entrance into the vents; (5) canopy: The canopies of varying heights and overhangs did deflect the smoke more as the height decreased and overhang length increased. It was the most effective of all strategies in keeping the smoke from the vents. In addition, it reduced the snow at the vents by a factor of 10; (6) fence and canopy combo: Only a fence oriented in the upwind direction had promising effects, projecting the smoke over the canopy roof; however, its performance in the snow simulation was disappointing; (7) flat roof cover: The smoke trapped under the canopy was unfortunately sucked into the vents: however, it was slightly more successful than the canopy in controlling the effects of snow; (8) flat roof cover and solid fence combo: The strategy was the most effective in preventing smoke from entering the vents and deterring snow accumulation, when a short fence was positioned under the cover's inside perimeter; (9) site orientation (N, NE, S, SE): the orientation of the winds only had an effect for NE and SE winds, which split at the buildings's corners and convected over the intake vents. The effects on snow accumulation were minimal: and, finally, (10) wind speed: Wind speed had no effect on the smoke simulations, but was a factor in moving snow drifts on the roof.

Aeolian wind tunnels provide a valuable tool in studying wind transport of sand and dust; however, these tunnels do not simulate sand transport on slopes, which is a common occurrence in nature, an obvious case being sand dunes. A sloping tunnel was then developed in Aarhus, Denmark, but its dimensions were too short to run many simulations. In "A variable slope wind tunnel for testing wind-blown sand" by Rasmussen and Iversen, the tunnel was modified with turbulence spires and roughness blocks to simulate a boundary layer which matches the dynamic saltation layer roughness and boundary layer depth of the natural surface of drifting sand. The use of spires allowed for an increase in the boundary layer thickness, δ, from 6 to 10 cm. Results indicated that the effective surface roughness for the saltation tests was found to be constant at both the entrance and the exit of the tunnel, which was the desired effect. The team concluded that this technique successfully simulated the aerodynamic roughness and boundary layer characteristics due to a saltating sand surface. The team does warm, however, that there are some uncertainties in estimates of the friction speed (u^*).

8. Performance of structures in adverse wind conditions

As the previous section has illustrated in its discussion of the mitigration of erosion, the harmful effects of wind do not only manifest themselves in extreme events. The impact of even mild winds on structures must be considered since modern buildings are constructed with increasingly light facades and low damping abilities. Thus, modern buildings are readily subject to excitation by wind. The following section presents a study that addresses torsional response of buildings with interference effects. Similarly, the risk of excitation is also present in offshore platforms which not only must withstand the threat of wind and waves but also, as in the case of platforms in the Gulf of Mexico, must be able to withstand hurricane force winds. The performance of such structures under the impact of extreme winds is also addressed below.

In order to properly design offshore structures, one must acquire an understanding of the environmental load effects and must develop an enhanced response prediction method. "Analysis and performance of offshore platforms in hurricanes" by Kareem and Smith discusses the performance and analysis of offshore platforms under wind loads as a function of the type of platform and the water depth. The analysis addressed is concerned with the quantification of wind load effects and focus on wind field characteristics, steady and unsteady loads, gust loading factors, application of wind tunnel tests, and provisions of the ANSI A58 1-82 (ASCE-7) and APIRP2A, with a special focus on the performance and failure of offshore structures during Hurricane Andrew. The paper points out that local effects concern the deck design, while integral loads are responsible for global effects like over-turning moments, a topic addressed later in the study. Kareem and Smith point out that wind loads account for 10% of the environmental focus for shallow water platform, but also have significant impact for deep water structures. In the Gulf of Mexico there are many shallow water, fixed-type jacket platforms which are more vulnerable to damage of topside structures in hurricanes like Andrew. The faulting local effects become significant in these cases as fatigue action induces premature failure of fasteners and components. To prevent damage, designers must understand wind fields and their effects in offshore structures. The study points out that it may be possible that relationships developed for on-land wind characteristics may be extended to flows over the ocean. A new spectral description is proposed in the study which adequately describes the full-scale data from the Gulf of Mexico, the North Sea, and the Pacific and Atlantic Oceans. The study then discusses the different frequency components near the sea surface that redistribute energy at different frequencies. These nonlinear interactions, if modeled correctly, will result in a second order contribution to the first order spectrum representing isotropic turbulence. The spatial correlation of the wind field is essential for describing wind loads that adequately reflect the true correlation structure of the wind field. The study notes that the correlation function typically used for land-based structures inadequately describes the spatial structure of the wind field over the ocean for spatial separations that may exceed the turbulence length scales. On the topic of wind effects, the team points out that steady wind loads are expressed in terms of wind velocity and aerodynamic force coefficients. The synthesized aerodynamic force coefficients for platforms are based on a projected area approach and do not consider the complex shielding, lifting forces, and other 3D flow effects. The codes and standards typically fail to predict the overturning moments caused by lifting surfaces. In the analysis of structural performance during Hurricane Andrew, packing winds above 100 m.p.h. violently impacted the older single well caissons built in the 1950s and 1960s which were designed for only a 25-year storm criteria as opposed to today's 100-yr value. Modern deepwater platforms were observed to perform well. 2000 out of 3850 offshore platforms in the Gulf of Mexico were exposed to Andrew's winds. Of those, 45 toppled, 89 bent over, 43 suffered irreparable damage, 100 suffered significant yet repairable damage, and 5 mobile drilling units were set adrift. Damage of the topside deck and some of the toppling may be attributed to wind. The study concluded that in order to understand the damage, one must also consider the age and number of storms the structure experienced in its lifetime, the design loads, and analysis procedures with information on the wind and wave fields in Andrew. The paper concludes with the several recommended topics for future investigation brought about by the study, including improved quantification of wind field models, better modelling of shielding effects, investigation of overturning caused by uplift forces, understanding of the local wave profiles, establishment of a map of wind conditions around the platform for human safety, better design for gust loading factors, and an investigation of vortex shedding-induced vibration on cranes and flare booms.

Modern buildings are often more sensitive to wind induced torsional excitation due to their complex shapes. Also modern structures are often built in groups introducing a complex flow field that may result in larger wind forces and moments. Therefore, it is vital to study the torsional response of structurally asymmetric buildings with interference effects, as is the focus of "Torsional response of eccentric tall buildings with interference effects" by Zhang, et al. The study points out that torsional response can have a great effect on the total response of the eccentric building. The study was particularly interested in the interference effects from adjacent buildings on the torsional response of the eccentric, square cross-section building, examined through a series of wind tunnel tests. The wind tunnel used was designed to simulate open terrain, and the model eccentric building was a $0.1 \times 0.1 \times 0.5$ m tall square prism. Two types of interfering buildings of the same height as the model building, but one with a 0.1 m square base and the other with a 0.06 square base, were utilized. The study used buffeting factor contours to find the critical locations of the interfering building and the intensity of the interference. For the isolated, eccentric building, the maximum torsional response occurred when the wind incidence angle was 20°. When the larger square interference building was introduced, the maximum mean torsional response of the eccentric model was reduced, in most cases. When the interfering model was placed upwind of the eccentric structure, a shielding effect was observed, reducing the torsional response by 70%. In one particular position, the maximum mean torsional response was zero. When the eccentric model was turned to 0° wind incidence angle, the shielding effect was found to reduce the dynamic torsional response, when the interfering model was nearby. When the angle of incidence was $-90°$ and the interfering model was nearby, the response was reduced by up to 50%. The study was able to determine that the critical location of the interfering model and the intensity of the interference was obviously dependent on the eccentricity position of the principle model relative to the wind incidence. The study found that the torsional excitation mechanism changed from inherent turbulence in the isolated building to wake excitation in the case of the building with interference. When the smaller interference model was introduced with the eccentric building at 0° angle of wind incidence, the critical location was found to be closer to the principle model when the interfering model was at a particular point downstream. The principle model's torsional response in this case increased by 1.2. When the wind incidence angle was at $-90°$, a larger buffeting factor was observed and a larger critical region developed than in the case with the larger interference model. At 90°, there was a larger increase in the torsional response, attributed to vortex shedding that was impacting the principle model at its natural frequency.

9. Wind effects on electric power lines and towers

Excitation of structures such as oil platforms and buildings, as mentioned earlier, is of constant concern for the engineer, but one must also consider the excitation of other, smaller structures that are often overlooked. In the following section, the studies to improve the design of electric power lines and towers are summarized.

During the passage of storms, failure of a luminare structure or the severing of a power line may not only disrupt electrical service, but may result in the loss of human life. The following articles address the need to improve the performance of these structures under wind loads by utilizing computer simulations and other procedures to calculate drag coefficients, exploring the accuracy of these techniques and suggesting aerodynamic modifications of luminare structures to reduce their excitation in wind.

Computer simulated computations of electric drag coefficients (C_d) for a conductor at various Re values and a comparison of these findings to field results is conducted in "Methods to compute conductor drag coefficients" by Selvam and Paterson. The model utilized by the team consisted of the 2D Navier–stokes equations for viscous, incompressible, unsteady flow. The team discretized the equations using a nonorthogonal grid, and the Navier–Stokes and continuity equations were solved by the MAC method. An efficient, preconditioned conjugate gradient procedure called ICCG was used to solve the pressure equations. The advantage of ICCG is that it is vectorizable and ten times faster than the SOR procedure. The grid used in the model had equispaced points in the tangential direction and exponential spacing in the radial direction. The radial grid was extended 20 times the cylinder diameter outward and the following boundary conditions were imposed: on the remote boundary, the velocity vector was $1i + 0j$, with the normal derivative of pressure $= 0$, and on the cylinder body, the velocity and the normal derivative of pressure were taken as zero. The study found that the computer model verified available computed and measured results for flow over a smooth cylinder when $Re = 1000$. The computed drag coefficients concluded by the study were found to be greater than the field results for high Re, and it was suggested this may be the effect of simulating 3D conditions using a 2D model.

At present, there is no way to accurately predict the wind loads on conductors. There are several discrepancies between the wind tunnel produced drag coefficients and the full-scale field "drag coefficients." One such discrepancy has prompted the need to study the effect of horizontal and vertical wind gradients on conductor wind loads. Since the wind velocity along a lengthy conductor span is usually non-uniform, the vertical wind profile can vary considerably in a short duration of time. The EPRI is presently studying the horizontal and vertical wind gradients in a series of studies each addressed in "Overview of EPRI conductor wind loading experiments" by Shan. First, the free-air wind tunnel experiment is discussed. A 12 ft long specimen is attached and placed on a rigid frame at a 20 ft elevation. Data on the wind loadings was taken from a wind direction perpendicular to the axis of the test specimen. A large conductor model was used to get the field drag coefficients at high Reynold's numbers (Re). The study found that the drag coefficients in the open air agreed with those in the normal wind tunnel tests. The second study addressed is the TLMRC Full-Scale Field Experiment. A full-scale conductor wind loading experiment was performed on a TLMRC 2-mi test line located on Texas farmland. Three towers and two 1000 ft spans of conductors composed the set-up. The conductors were connected at a height of 63 ft and a sag of 31 ft. In the first method applied, an actual wind profile method, which uses wind profile data provided by anemometers that match the conductor geometric profile to calculate the wind loads, was used. The wind load on the conductor span was estimated by integrating the wind forces acting on the conductor segments represented by the wind anemometer data. The second method utilized relied on the reference velocity method, using wind velocity data from one reference anemometer. This method requires the adjustment for vertical wind velocity. The adjustment does not account for the variation in the horizontal wind distribution. Most of the data was observed to fall along the 45° line of a plot of the measured vs. calculated wind loads, representing direct correlation between the two data sets and demonstrating the effectiveness of the actual wind profile approach. However, as the averaging time decreased, the data variation was found to increase.

"Instrumentation for EPRI conductor wind loading experiments" by Crane discusses the experiments that an EPRI Conductor was subjected to in order to prevent failure under high winds. In the study, the initial implementation of a stand-alone instrumentation system with 48 channels of data supported a free air wind tunnel. The measurements were recorded on a short section of conductor which could be rotated into the wind, and load cells were positioned to measure the horizontal reaction force. A second set of experiments was conducted on a 2 mi long unpowered run of 2 conductors suspended from lattice towers. Testing was also being done at a similar set up in Rocky Flats, CO, at the time of publication. Anemometers were placed parallel to the length of wire and positioned in front of the wire relative to the wind direction. Anemometers were also placed on some of the lattice towers. The most critical parameters were found to be the load forces in the conductor support line, which is of steel bar stock and replaces the insulator string in an active transmission line. The static weight on the link was 2500 lbs. The angle given by the clinometer was the most accurate parameter from which wind loads were computed. Along with wind velocity data, ambient temperature, pressure, and humidity data were taken to observe their effects on the results. An ice sensor was also introduced to insure that ice had no impact on the data. Only wind speeds perpendicular to the test line were recorded in the study, and from the data analysis, the Reynolds number and wind loads were found. The paper goes on to present various instrumentation devices used to collect the relevant data.

Many sign, signal, and luminare structures have failed due to aerodynamically induced vibrations which may be triggered by even moderate wind speeds. Mitigation of such failures is discussed in "Aerodynamic properties of tapered cylinders" by Chesnul, et al., which calls upon the results of wind tunnel studies to establish the static drag coefficients and root mean square (RMS) estimates of the lift coefficient of tapered cylinders and discusses options to avoid failures by testing alternative road sign designs such as octagonal and tapered cylinders. Discussion begins with luminare structures, which may exhibit resonant conditions under even low frequency vibration and fall victim to the loosening of lamps in sockets and fatigue failures of the arms or anchor supports. High frequency vibration often causes bulb failure by breaking internal elements of the bulb from the base. In one instance cited in the report, major failures occurred on the east shore of Lake Michigan due to 25–30 m.p.h. winds, with a wind direction parallel or perpendicular to the bracket arm, and smooth or laminar flow of air currents with the occurrence of the second mode of vibration. The study does point out that other loads like dead loads and ice loads should be considered.

Live loads, which is a single 500 lb load distributed over 2 ft, are considered only for sign support structures with walkway and a service platform. The ice load suggested in the paper is 3 psf and is applied around the surface of the structural supports. Vibrations due to vortex shedding are assumed to occur when the shedding frequency approaches the structures natural frequency. In the wind tunnel experiments conducted in the study, a force balance was used to measure the static lift and drag forces. The drag coefficient for the non-tapered circular cylinder was found to be 1.60, which compared well to other laminar flow studies. The study also found the drag coefficients for the non-tapered circular and octagonal cylinders were roughly 9% and 33% greater than the recommended AASHTO values, respectively. Thus, the study concluded that tapering reduces the drag coefficients, and therefore the AASHTO drag coefficients are greater than necessary.

10. Fatigue and structural integrity

Thus far, attention has been paid to the modelling of the wind forces on various structures, with some discussion of the excitation which results. Logically, one may question how long a structure can continue to function safely following repeated loads of high intensity or even the effects of aging. Thus, after predicting the load on a structure, one must also predict the fatigue life of that structure. Such concerns are addressed in the subsequent summaries in which techniques for predicting fatigue life under random loadings, such as Miner's rule, and models for the damping behavior of structures under large amplitude forcing are discussed.

"Fatigue life prediction under random vibration response" by Wu describes attempts to develop a methodology to determine the fatigue/damage accumulation under randomly applied variable stress amplitudes. Using mathematical theories of plasticity or mathematical theories of fatigue, the fatigue life under random loading vibration loading/vibracoustic environments may be predicted. Narrow-band random vibration is listed by the study as commonly encountered in reality. It characterizes output from the elastic structure and represents the transformation of broad-band input brought about by the filtering action of the structure. The study points out that Miner's rule is the most common relation used in random vibration or acoustic fatigue studies to evaluate the structure fatigue life. The main shortcoming of this rule, however, is that it denies a cumulative damage rule and interaction of load cycles of different magnitudes, and the influence of the load cycle below the fatigue limit. The theories have several applications which are presented in the paper. First is the aluminium ring under random vibration due to wind forces in which the minimum failure time, predicted under 0.11 g sq. per Hz constant acceleration power spectral density, was approximately 1 h. The second application addressed a simply supported beam of aluminium 2024 alloy under a white noise input. The study observed that the fatigue life increased with increase in the structure natural frequency (ω), with increase in the exponential constant (b), with increase in the damping ratio (ξ), and with decrease in the stress displacement ratio (C). The third application studied an equivalent uniform power spectral density concept applied to the typical random variation power spectral density curve. The study found that the fatigue time will be longer than 60 min if the same parameters were used in the aluminum ring test.

A commonly asked question: "Can a structure continue to serve its purpose after being subjected to a high intensity or large amplitude forcing or even aging, and for how long will it continue to safely function? is addressed in "Integrity monitoring of structures" by Jeary. Jeary notes that other methods previously used to determine the answer to this question, such as an in depth evolution of the paths of the suspect structure and the dynamic testing based on an assessment of the entire structure, often required the shut down of the structure for extensive periods of time. The data required for such analyses include the natural frequency of the fundamental mode, the non-linear damping characteristic, the design load, the modal mass of the structure in the fundamental mode, and the amplitude of the response in the fundamental mode when the design load is applied. This data is then used to estimate the strength of vibration for the design load case. The paper then investigates the modelling of damping in structures, noting that frequency and damping are non-linear and that over a wide range of amplitudes, damping changes by 20–100% of the initial value while stiffness changes by approximately 3%. A new model for damping suggested by the study encompasses three phases: (1) low amplitude plateau damping values in which energy is damped via friction between the components, (2) the non-linear characteristic in which the damping value increases with increasing amplitude throughout the structure as even "non-structural" parts and the large of cracks start to "work" to dissipate energy; and (3) the phase when all cracks "work," reaching the high amplitude plateau signalling the earthquake region. The study also refers to a technique based on random decrement developed by NASA which produces statistically stable estimates of damping values, including non-linear effects, with as little as one hour of data. This procedure was tested by gathering one hour of data on amplitude and damping measurements for a 300 m tall building. Using the rate of change of the damping, frequency, and modal mass, the amplitude of the response of the structure at the design load was calculated. The results confirmed that the structure is affected by the use of nonlinear characteristics of the damping parameter.

11. Damping systems

In the effort to reduce building dynamic response and hopefully improve the habitability of buildings, damping systems are often utilized to supplement the natural damping of structures. Work in this area is steadily growing with a variety of damping systems currently available, including both active and passive dampers such as active mass dampers, tuned mass dampers, tuned liquid dampers, and hybrid tuned liquid dampers in single and/or multiple damper configurations. The damping ability of tuned sloshing dampers is also being improved through the use of floating styrofoam beads, nets, screens, and baffles. Semi-active systems are currently being developed in which the building motion is fed into a filter, designed to represent the features of the optimally tuned damper, which then regulates a fixed screen or an orifice appropriately to achieve optimal damping. Some of these topics were discussed at the UCLA conference and the design and performance of such systems are addressed in the summaries below.

The wind induced response of structures may reach a level that poses discomfort to the occupants which may be remedied by the use of tuned liquid dampers. Tuned liquid column (TLCD) and tuned sloshing (TSD) dampers are an effective means of mitigating wind induced motions of engineering structures, reducing the menacing response of buildings. In the case of the TLCD, the motion of the liquid in a U-tube provides the secondary inertial mass via the passage of the liquid column, with inherent head loss, through an orifice, while the TSD utilizes the viscous action of sloshing liquid mass. A discussion of the history and innovation of such systems is explored by Kareem in "Tuned liquid dampers: past, present, and future." Kareem points out that the trend toward taller buildings with lighter facades produces more flexible buildings with lower damping. These structures, when subjected to high excitation due to winds, must have their responses minimized. The TSD, one mitigation technique, in its shallow form can dissipate energy via internal fluid viscous forces and wave breaking, while in its deep form, baffles and screens are needed to enhance the damping. The disadvantage of the deep form is that a large portion of the TSD does not slosh and thus adds dead weight. The study notes that passive form of liquid dampers only reduces suddenly excited structural motions that follow the maximum sway and must be improved to withstand the transient loadings of squall lines and earthquakes. The study points out that most structures experience lateral and torsional loads; therefore, liquid sloshing models, at and near resonance excited by bidirectional motions of the primary structure must be studied. The paper cites that in order to achieve optimal damping, the damper parameters of liquid mass, damping, and tuning ratio need to be carefully selected. Kareem mentions that the TLCD will not be optimal at all levels of building motion; therefore the size of the orifice may be controlled by feedback on the level of liquid excitation in the tank. Along these lines, Kareem proposes a semi-active system in which the building motion is monitored and fed into a filter designed to represent the features of the optimally tuned damper. A sliding type valve can then be used to adjust the orifice size accordingly. For TSD's, damping may also be enhanced by adding submerged screens, nets, or floating styrofoam beads. In this case, a feedback system for opening the screen by sliding a movable screen over a fixed screen or opening vanes may be installed to achieve optimal damping. In addition, the study notes that TSD's do significantly reduce the building response due to transient loadings like a fast moving weather front or earthquake. Further improvement of liquid dampers in response to transient loadings may be accomplished by introducing active triggering of the liquid column oscillations, at the first sensing of building motion, through the use of a piston-type arrangement attached to an actuator.

"Wind study of buildings with passive energy dissipation systems" by Hart and Srinivasan attempts to identify the critical wind design limit state and propose a structural reliability based design criteria for this limit state. The paper shows how forces from wind tunnel studies that incorporate a statistical analysis of historical wind data can be used in the design of lateral resistance systems. The study points out that one must develop a structural design where the wind loading induces deformations in the structural components less than or equal to the yield deflection or curvature of the component, since the wind loading on a structure is a dynamic force component superimposed on a static mean force component. Unlike seismic loads, wind loads can cause an increase in the permanent set of the member and there is no unloading of the inelastic deformation. The paper stresses that this behavior must be taken into account for complex buildings whose lateral resistance systems may not have a non-linear response to two different levels of load. The paper then addresses base isolation systems, which is a passive energy absorption mechanism that significantly reduces the base shears felt by a building during a major event. Elastometric rubber bearings, with or without lead cores, which support the building superstructure, allow deflection and take the shear that would result if the building were fixed during a quake. The lead cores allow the building to maintain lateral stiffness when subjected to low level ambient forces below a certain criterial threshold. The study recommends that site/building specific wind studies be performed to satisfy the criteria that the base isolation system yield only during critical seismic events. On the topic of wind loadings, the paper found that the force proportional to the square of wind speed acting is a function of wind climate, terrain features, and the dynamic response characteristics of the building. The study shows that the return period can be computed from the mean maximum annual wind speed, the design basis wind (DBW), and the maximum capable wind (MCW) as wind speeds with exceedance probabilities of 10% and 4.5%, respectively, can be defined. The paper then defined the limit state as the yielding of the base isolators and concluded that the structural reliability formulation of the limit state isolator design is developed directly to include the yield force level of the isolators, the critical wind loading parameters, and the rational quantification of the desired safety for this limit case.

The use of tuned sloshing water dampers (TSWD) transforms a structure from a single degree of freedom to two degrees of freedom and thus results in two closely-spaced resonant peaks. TSWD effectiveness depends on the easily found frequency ratio and mass ratio, but inherent damping is difficult to estimate and even more difficult to set a sufficiently high value to achieve effective operations. Such features of the TSWD are addressed in "Effectiveness of a tuned sloshing water damper to reduce the wind-induced response of tall buildings" by Fediw, et al., in which a prototype TSWD is mounted on top of a 240 m tall building located in a downtown region, to serve as a response-mitigation system while meeting the water storage demands of the building. The fundamental periods of vibration were estimated to be 7.5 s in both sway directions and 6 s in torsion. The study found the response to be dominated by the E–W component, so the fundamental sloshing frequency of the TSWD should correspond to the fundamental sway frequency in the E–W direction. This, along with linear wave theory, was used to develop the dynamic characteristics of the 50 ft $(L) \times 10$ ft $(W) \times 6$ ft (H) tank with a mass ratio of 0.25%. The study then conducted forced vibration tests on a 1:13 scale model to determine the response, develop a method to increase the inherent damping, and evaluate the TSWD's ability to mitigate the response of the system. The team found that for all excitation amplitudes, the response was non-linear and estimated the inherent damping on the order of 0.5%. For the analogous TMD, the team expected an optimum damping between 5–10% of the critical value. In order to significantly reduce the response, the team had to increase the inherent damping by adding a set of screens with porosity of 60%, located in the central area of the TSWD, which would increase the damping by one order of magnitude. The study investigated the effects of two types of screen: type I – 60% porous and type II – 30% porous. The model response was found to decrease when the TSWD was added and even further upon the increase of the inherent damping. The study showed that while the TSWD alone is non-linear, its combination with the structure produces a linear result, yet the non-linearities of the TSWD will increase with amplitude. Full-scale analysis required the monitoring of building acceleration for one year before the application of the TSWD. The tank was then tuned to the calculated 6 foot depth and screens were installed to achieve the inherent damping of 5% of the critical, with new response data still being gathered at the time of publication. The effective damping of the building along was found to be 2.6% and 3.5% with the TSWD, with two closely-spaced, discernible peaks present in the spectra.

12. Aerodynamics of bridge decks

While most of the studies presented thus far have focused on loadings, dynamic behavior, and mitigation strategies for buildings, much of the work in wind engineering is also concerned with the excitation and performance of cable-stayed and suspension bridges. While theoretical analysis is focussing on the effects of turbulence on the flutter speed of long span bridges, experimental work has turned toward improved modelling and quantification of aerodynamic forces, considering their sensitivity to turbulence characteristics and the geometric form of the bridge section. Several studies in this area, in addition to discussion of the validity of some modelling assumptions, were presented at the conference and a brief summary of each is presented below.

Since reported studies have not considered the correlation time of turbulence and non-linear fluctuations that occur in the s.d.o.f. torsional instability, the effects of turbulence on the deterministic stability of section models are studied by Shinozuka and Billah in "Stability of long-span suspension bridges in turbulent flow." In most existing works, in the analysis of bridge stability, there is the assumption that the correlation time of excitation is taken as short compared with the relaxation time of the dynamic system. This assumption allows for the use of the Markov process, but when proper modelling of noise is considered, the Markov property may not be used. The team stresses that all physical fluctuations are correlated. Also, due to the fundamental quadratic relation existing between the flow velocity and the dynamic pressure, the assumption of white noise must be made with extreme care. The study concludes that when fluctuations are introduced, they must be modeled as colored noise. For the numerical solution generated by the team, turbulence is generated by simulating stochastic processes from a given non-white power spectra. The authors reported that this numerical procedure was found to be consistent with the experimental model used in wind tunnel simulations. Two types of simulations were carried out: the first involving both linear and nonlinear noise, and the second neglecting nonlinear noise. The findings of these simulations were consistent with experimental studies and confirms that: (1) in general, colored noise influences the system stability quite differently from white noise, (2) finite correlation time can stabilize torsional motion, (3) the square term of noise can play a significant part in stability analysis, (4) a s.d.o.f. model can effectively portray the change to stability as well as instability under turbulence, (5) Stratonovich interpretation of stochastic differential equations is not the only possible physical interpretation, and (6) these results cannot be obtained from analytical methods so far.

The section model testing of a bridge is a powerful tool in predicting the flutter instability of long-span bridges, usually tested in low turbulence low, and allows for the determination of the eight flutter coefficients used in the linear description of aeroelastic flutter phenomena for full, long-span bridges. For this reason, a model used to discover these flutter derivatives is developed in "Identification procedure for 8 flutter coefficients from section model test in two-dimensional flow" by Raggett and Scanlan. The model used in the study assumes a linear motion description, since the motions are constrained to be very small, and unsteady aerodynamic loads are linear functions of the model motion. The term then developed all the relevant equations to obtain the flutter derivatives. Once the flutter derivatives are obtained, they are used in the analytical model of the entire bridge. The results proved that the assumption of linearity in the aerodynamic loads is valid. Since the aeroelastic flutter coefficients cannot be predicted theoretically, with accuracy, a direct comparison of experimental results with theory cannot be made, but the coefficients can be used with confidence to predict the model response. The study stresses that the best proof of the reliability of this method is the fact that it has been used in the design of many of the bridges still standing today.

The current theories for bridges depend strongly on the use of classical pseudo-static force coefficients and their derivatives with respect to the wind structure relative inclination and so-called flutter derivatives. Due to the importance of flutter derivatives in deck design, a collection of examples of bridge deck cross-sections and their flutter derivatives are presented in "The relationship between geometric form and aeroelastic characteristics of bridge decks" by Jones, et al. The data illustrate that there is a strong dependence of these parameters on the geometric form. The examples show that judicious modifications to the deck cross section are effective in not only ensuring aeroelastic stability but also enhanced overall aerodynamic performance. In the first example, three cross-sections were presented: (A) an "H" section which is unstable, (B) a modified version of (A) with relatively streamlined deflectors, and (C) a modification of (B) with additional plates parallel to the centerline of the deck. According to the flutter derivative data, (A) becomes unstable early and more unstable with increased wind speed, (B) shows dramatic improvements, and (C) is even better, with strong aeroelastic damping at higher wind speeds. In the second example provided, a trapezoidal steel box girder 38 m wide and 4 m deep, with 4 steel rails beneath the deck and 6 railings, is tested. In case I, the test is conducted on the model with the railings modeled to maintain reasonable similitude. This configuration was found to be aerodynamically stable. In case II, the railings are modeled as impermeable by covering them with electric tape, producing a highly aerodynamically unstable torsional motion that diverges at a much earlier stage. In case III, the model has no railings and is very aerodynamically stable. The study went on to calculate the 8 flutter derivatives for these three cases. The study concluded that the careful attention to and modification of geometric features of bridge decks can strongly influence their aeroelastic stability and aerodynamic performance. The section model proves to be a cheap, effective, and easy way to model such a structure.

The unsteady, aerodynamic properties of a streamlined deck are examined in "On the unsteady aerodynamic forces on a bridge deck in turbulent boundary layer flow" by Larose, et al. The study focuses on wind tunnel investigations of the deck of the Storebaelt East Bridge using a 1:300 scale model and a 5 m long taut strip model. The response of the model to the simulated atmospheric boundary layer flow was measured for three levels of turbulence intensity and used to predict the response of the prototype structure. The span-wise coherence of the aerodynamic forces acting on the streamlined deck and the aerodynamic admittance was measured, while the aerodynamic derivatives were extracted from the forced oscillations of the model in turbulent flow. The measured aerodynamic properties included in the analytical prediction model successfully reproduced the buffeting response of the taut strip model within a satisfactory 15%. When the quasi-steady assumptions were used, the analytical prediction model overestimated the buffeting response by a factor of 1.5–2. In the experiment, the mean and fluctuating aerodynamic forces were obtained from the integration of the synchronous surface pressures from the wind tunnel tests. The aerodynamic derivatives were obtained from the forced oscillation tests in turbulent boundary layer flow and uniform flow. Both the span-wise coherence of aerodynamic forces and the velocity fluctuations were measured for the same turbulent boundary layer flow to verify the validity of the "strip assumption" for the deck. The results were as follows: (1) the effect of turbulence is negligible for reduced velocities lower than 6 and (2) at higher reduced velocities, a reduction of the aerodynamic derivatives can be seen with increasing turbulence intensity generated by the grids. The reduction was found to be stronger for the derivative obtained from the torsional excitations. This suggests dependence of the aerodynamic damping of the turbulence intensity for a higher range of reduced velocity. The vortices for boundary layer flow were much bigger than those of grid-generated turbulent flow. The vertical amplitude of motion chosen in the study was much greater than that used in common practice. The study concluded that the amplitude of motion has little effect on the derivatives except at or near the vortex shedding reduced velocity and that the aerodynamic forces have a stronger span-wise correlation than the wind fluctuations. The results indicate that: (1) the span-wise coherence of aerodynamic forces is larger than that of oncoming turbulence, confirming that the "strip assumption" is not a conservative assumption for this deck cross section, (2) the coherence curves do not collapse for differing span-wise separations suggesting $\Delta y/B$ dependence, and (3) the exponential decay-type relationship that has a first derivative approaching zero for smaller separation suggests that an effective width representative of the coherence of the torsional forces appears to be half the deck width.

"A comparative study of the aeroelastic behavior of three flexible bridges and a thin airfoil" by Sarkar, et al. compares the flutter derivatives of three bridges with streamlined box girder cross-sections to those of a thin airfoil. The three bridges featured are: the Tsurumi Fairway Bridge in Japan, the Great Belt East Bridge in Denmark, and the Pont de Normandie (Normandy) Bridge in France. The comparison was conducted to develop possible applications of airfoil-like theories for the preliminary assessment of the aeroelastic design parameters of streamlined decks. For the Tsurumi Bridge, the Modified Ibrahim Time Domain Method (MITD) was used to identify the eight flutter derivatives using a 1:200 geometrically scaled model of the bridge. For the Normandy Bridge, the streamline section was selected to reduce the adverse wind effects associated with the Normandy sea coast. The forced-oscillation technique was used to find the aeroelastic coefficients of the bridge from the section-model tests. A 1:70 scaled section model was tested in a wind tunnel from which the aeroelastic coefficients collected as data can be related to the flutter derivatives through a series of equations. For the Great Belt East Bridge, a 1:80 geometrically scaled section model was used along with the system-identification technique to identify the flutter derivatives from the oscillating pressure distributions. A forced-oscillation technique, similar to that used in the Normandy bridge, was applied to a section of 1:300 scale taut-strip model to identify the flutter derivatives. From the overall comparison, the study concluded that the streamlined cross-sections are indeed similar in aeroelastic behavior to a thin airfoil. The study also demonstrates that good consistency can exist among different techniques involving section models that are used to exact flutter derivatives.

The motion stability of a long-span bridge in turbulent wind is studied in "Stabilizing and destabilizing effects of wind turbulence on multimode motion of a long-span bridge" by Li and Lin. The bridge studied is assumed to be capable of two degrees of freedom: one torsional and one bending. The wind turbulence was modeled as bounded noise, with the relevant equations developed in the original study. Depending on the type of turbulence encountered, three cases were considered: (1) nearly-tuned narrow-band turbulence, (2) detuned narrow-band turbulence, and (3) wide-band turbulence. The results of the numerical model show that both the wide-band turbulence and the Von-Karman-type, detuned narrow-band turbulence have a stabilizing effect, in the sense that an increase in turbulence level is accompanied by an increase in the critical mean wind velocity (u), while the nearly tuned narrow-band turbulence has a slight destabilizing effect. The study concludes that this new wind turbulence model has bounded total energy and its spectral shape can be made to fit a target spectrum by changing the parameters of the model. The random deviation from the deterministic flutter model makes either the stabilizing or destabilizing effect of turbulence possible. For the bridge investigated, the peak location of spectral density of the turbulence was found to be critical to the stability condition. By changing the peak location of the spectrum, stabilizing turbulence can become destabilizing, even when the mean-square value remains the same.

"Numerical simulation of wind flow patterns and wind-induced forces on bridge deck section models" by Onyemelukwe and Bosch utilizes the finite difference method to solve the non-conservative form of the 2D, unsteady, incompressible, laminar, Navier–Stokes equations in a body-fitted, curvilinear coordinate system. This coordinate system was chosen by the team since it is efficient in examining irregular deck geometries. Using the Navier–Stokes equation, values of the velocity components and pressures were determined. The pressure coefficients were integrated along the body surface to obtain the force coefficient, drag, lift, and pitching moment. The application of this to various bluff bodies and bridge components showed excellent prediction of the wind flow patterns around the body, especially duplicating the vortex shedding phenomena. Since long-span bridges are quite susceptible to wind effects, the team chose to study the effects of wind forces on the deck to insure that this vital component of the bridge does not fail. Formally, this task was accompished by wind tunnel tests, but now computational wind engineering may be used. Through such methods, the designer can get some indication of the wind flow around the deck and the wind-induced forces on the deck. The results for such an analysis of the Ruck-A-Chucky suspension bridge are presented in this study. The streamline plots developed revealed flow separation at the sharp corners and the formation of vortices at early stages of the flow development. The team observed remarkable similarity between the computer flow visualization plots and the water tunnel visualization photo. The program also provided the unsteady wind-induced forces and pressures for the analysis. The team found that the instantaneous wind force coefficient from the simulation was in qualitative agreement with the mean values. The team contends that this mathematical model is useful because it can be applied before wind tunnel testing to rule out bad designs and it allows for more trial cross-sections. The study concludes that the use of computer flow visualization techniques to observe details of the flow development is superior to current lab procedures such as water or smoke tunnels.

Due to its frequent damage by winds, the aerodynamic performance of the Deer Isle-Sedgwick suspension bridge, located on the coast of Maine, is being monitored by the Federal Highway Administration (FHWA). The findings of this investigation are presented in "Monitoring the aerodynamic performance of a suspension bridge" by Bosch and Miklofsky. The bridge has a design similar to the ill-fated Tacoma Narrows Bridge, with inherent flexibility and a relatively poor aerodynamic cross-section. The instrumentation placed on the bridge to monitor it were as follows: 3 thermistor probes to measure air temperature, 6 tri-axis anemometers to monitor wind turbulence quantities, 6 pairs of single axis servo accelerometers to monitor the deck motion, and 3 accelerometers to measure the tower motion. The team found that the wind approach was from the southeast, with the average wind velocity of 22.3 m.p.h. This was in good agreement with the spectra of other models. Over a wide range of speeds, the energy tends to shift toward higher frequencies as the mean wind speed increases. A bridge, in general, exhibits periodic response at about 22 m.p.h. and random response which increases in amplitude as the wind speed increases. The bridge motion was observed to be primarily vertical and was rarely observed to vibrate in single mode. The bluff shape of the bridge was found to create a strong "local" or signature turbulence which plays a major role in its behavior. The six vertical modes of vibration were also identified in the study and compared well with the finite element analysis.

In "Numerical simulation of the unsteady flow around suspension bridge models using the discrete vortex method," Walther investigates to what extent the discrete vortex method (DVM) can be used to compute unsteady lift and drag forces on bridge section models. The bridge section studied is a conventional profile tested with and without snow-covered railings in smooth flow. The DVM approximates the vorticity field of the flow field using a large number of discrete vortices, each carrying a stiff vorticity core. This study adopted a Gaussian core shape. A solution algorithm and relevant equations are then explored in the paper. In a comparison with wind tunnel data, the main difference occurred for the "no snow railing" configuration at high angles of attack, where the DVM predicts too high of lift and drag forces. This was assumed to be caused by five factors: (1) insufficient total simulated time from which to calculate the time mean forces, (2) 3D effects not accounted for by the 2D numerical method, (3) the inability of the DVM to model turbulence, (4) not taking into account the last terms of Eq. (8) in the original report, and (5) ignoring the crach barrier on the experimental bridge model in the numerical simulation. The author went on to conclude that the lift and drag coefficients can be predicted within 10% for a bridge without snow-covered railings for negative angles of attack; however, for high positive angles, the lift and drag coefficients are overpredicted by a factor of 2. The study also concluded that the deficiencies mentioned are amplified in the simulation of flow around the suspension bridge section model for the "snow-covered railing" configuration. The difference between the measured and computed lift and drag coefficients were at best 50% for the lift and 5% for the drag at 0° angle of attack. In total, this method has proven to be effective in simulating flow around a suspension bridge for modest angles and a Reynolds number equal to 200.

13. Risk and damage assessment

The final topic of discussion is risk and damage assessment, which is of particular interest to insurance firms as well as engineers. Research in this area is primarily devoted to collecting post-disaster data, followed by the development of a model to assess the risk of failure of the constructed facilities and provide a quantitative measure to estimate the extent of damage under a particular intensity of wind storm. The work in which area has led to the development of computational schemes which can forecast the probability and severity of hazardous events, such as hurricanes, and the resulting losses, using various techniques, some of which are described below.

It is often the case that the contents of industrial and commercial buildings are worth several times the actual structure itself. In such cases, the content damage far exceeds the structural damage in the event of a hurricane. "Damage simulation model for building contents in a hurricane environment," by Stubbs and Boissonnade, suggests methods to simulate the damage of contents within a building during a hurricane. The study developed a model to predict the damage to the contents and then validates this methodology by simulating the content damage and comparing it with the observed content damage in an actual hurricane. First the contents of interest are identified and then the hazards threatening the contents, such as roofing and opening failure, are described and quantified. The resulting damage will then be related to the serverity of the hazard threatening the contents, producing damage ratios for the contents. The study then outlines the model to predict the damage, consisting of the following components: (1) the general model for predicting the damage growth to the building components, (2) relation of the damage to the building components and the Hurricane characteristics, (3) combination of the damage to the various components to provide general descriptions of the hazard to the contents, and (4) the relation of the damage to the various contents to the hazard level and probability of occurrence of the hazard. Once the model was designed, it was compared to an actual case study. First the example structure was described and the environmental setting was developed, as values were assigned to the matrices in the model. From this, damage ratios were predicted and compared to the actual observed damage ratios. The structure used in comparison by the paper was located one mile inland from the Atlantic Coast, in Miami, FL. The structure stood three stories high and covered 4500 square feet. During Hurricane Andrew, this structure was subjected to 110 m.p.h. winds, losing 75% of its roofing, and resulting in the failure of one window. The damage ratio to contents was observed to be 0.36 (meaning 36% of the replacement cost of contents were lost). The model designed by the team predicted a mean damage ratio for this event at 0.39, quite close to the actual observed ratio. This corresponds to heavy content damage with losses between 20 and 60% of the replacement cost of the contents. Thus, the model proved to be an efficient means to predict the impact of a hurricane on the building envelope given the hurricane environment.

The rapid acceleration of coastal developments and population shifts to coastal regions place millions of dollars of property and lives at risk to tropical storm damage. Research is required to determine the probability of occurrence of damaging storm winds and wave action in such regions in order to predict interests in these regions. Furthermore, as a result of global warming trends, there is also expected to be an increase in the sea level and an increase in the intensity and wind speed of hurricanes. Accordingly, the need for a such a model to relate the characteristics of the geophysical environment and the hurricane with the resulting damage is discussed in "Integrated risk assessment for coastal regions subjected to tropical storms/global climate change" by Kareem, et al. The study suggests that the hazard may be estimated by determining the probability model best describing the occurrence and severity of extreme winds and storm surge/waves at a specific site. The procedure typically used requires the use of phenomenological models and historical records combined with the Monte Carlo simulation procedures to predict hurricane wind speeds. Such a model, however, assumes independence of the variables and may lead to an unrealistic simulation of the storm. Another method mentioned is the extended bootstrapping technique, empirical simulation, which assumes that historical occurrences, are equiprobable in the future, and then interpolates and extrapolates parameter sets for storms with historical data compilations. The extended bootstrap population provides non-parametric and relatively non-subjective information on storm occurrences incorporating joint probability among problem variables. The paper then discusses the numerical models used to compute sea surface elevations and currents due to mesoscale processes like tides and hurricane storm surge. This method incorporates a wide range of scales of motion in a numerically discrete form of the governing equations, utilizing finite element method and grid refinement as the landward boundary is reached. The vulnerability to damage may then be found using a damage probability matrix (DPM); however, it is difficult to define all the term in the DPM. The study cites that often reliability-based mathematical models of load effects and resistance, along with experience, offer algorithmic means of ascertaining the DPM. The DPM can be based on such approaches as the fault and event tree analyses computed using a link between the structural analysis programs and structural reliability program PROBAN. For non-engineered structures, the study suggests that the development of the DPM be based on the typical extreme loading patterns and pressure coefficients, basic damage scenarios, component resistance, joint and connection capacities, and structural system analysis. The study states that the integration of the probabilistic hazard model at a site with damage potential derived from the DPM provides a measure of the risk to facilities due to tropical stroms. Regression models developed to predict wind, waves, storm surge, and tides are used to evaluate the storm effects at a desired site for a large number of storm characteristic parameters, using a data base derived by Monte Carlo or extended empirical simulations. This will result in a large number of storm effects used to estimate the extreme value statistics and associated mean recurrence intervals. The study thus concludes that a methodology for assessing risk for constructed facilities of tropical storm-prone areas must be developed. The study contributes to this by discussing a development framework for computational capability for integrated risk assessment of constructed facilities under tropical storms.

Hurricane Hugo caused $1 billion in damage to buildings, infastructure, and crops in Louisiana, leading to 8 deaths and 104 injuries. An assessment of the damage in Louisiana as a result of this category 3 hurricane is presented in "Damage assessment of Hurricane Andrew in Louisiana" by Levitan, et al. The study notes that the ANSI/ASCE 7-88 standard fastest mile design wind speed for this region of Louisiana was 100 m.p.h., while winds in certain towns like Berwick exceeded this value. Maximum winds of 126 m.p.h. were gauged as the hurricane swept across the coastline, spawning 14 tornadoes in its wake. The hurricane resulted in a loss of power for the area and litter deposits in streams that contaminated the water supply and caused losses of $266 million in the finishing industry. Typically, most structures suffered only roofing and glazing losses. Most pre-engineered structures had partial structural failures and notable effects of increased internal pressure. Schools were found to perform the worst of all structures with roof and glazing failure, resulting in extensive water damage, with many gymnasiums losing their roofs as they sheltered hurricane victims. As for site-built homes, the study found that they remained relatively intact, with older homes suffering damage due to poor wall-to-roof connections. Gable roofs were found to perform worse on apartment buildings than homes, probably due to the increased height and size of apartment complexes. The worst damage befell manufactured homes and mobile homes, in which 1/3 were damaged due to poor anchorage connections. The tornados in the aftermath of the storm resulted in the destruction of 45 site-built homes and 10 mobile homes, one death, and numerous injuries near the town of Laplace. The study also noted two types of glass breakage in the storm: detachment due to poor structural design and missile impact.

Insurance companies have an understandable concern for the probable maximum losses (PML) for structures they insure, an estimation of which is profiled in "Estimation of probable maximum loss from hurricane for an insured portfolio of risks" by Wiggins. The PML derived in the study, which targeted coastal areas in North and South Carolina, was based on category 1–5 hurricanes with expected wind velocities of 74 m.p.h. and above. The PML was defined by the study as the loss associated with 475 yr return period event for wind speeds of 125 m.p.h. The study encompassed 518 structures valued at a total of $295 million, ranging from 1 to 6 stories, constructed between 1961 and 1987, at 248 sites. The average value of each structure was $0.57 million. The study incorporated wind data and hurricane characteristics from hurricanes recorded since 1871 and computed the probability of hurricane occurrence for any one point along the South and North Carolina coastline. It was noted that only 46 hurricanes had occurred in this region in the last 120 yr, with 47% striking perpendicular to the coastline, 36% striking oblique to the coastline, and 17% striking tangentially. The PML developed by the study also included provisions for a Fugita 3 tornado with average velocity of 182 m.p.h. The probability of this tornado to strike at any location in the designated area was found to be 6/1000 per year. The study notes that only 13 Fugita 4 and 1 Fugita 5 tornados have struck the region between 1930 and 1974. From all the data collected, a damage algorithm was developed. Hurricane Hugo was then utilized by the team as a case study. Hugo was recorded as a category 4 hurricane which impacted South Carolina in 1989. Only 2 hurricanes of this magnitude have stuck the region in the last 120 yr. During Hurricane Hugo, 6.8% of construction was damaged by winds at 110 m.p.h., with only 5.4% of the structures built after 1980 suffering damage, while 17.8% of the structures built before 1980 were damaged. Thus, the study found marked improvement in construction techniques since 1980. The study predicted that Hugo caused $3.6 million in losses, 57% of which may be attributed to wind damage and the rest attributed to flood damage. Hugo actually caused $3.5 million, so while the study slightly overestimated this amount, it underestimated the vulnerability of construction and failed to include the likelihood of high tide occurring at the same time as the storm surge. These areas will be in need of improvement in future work.

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