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From the field to the laboratory: Recent advancements in “full-scale” wind engineering

F.J. Masters[1]

[1]Department of Civil and Coastal Engineering, Engineering School for Sustainable Infrastructure & Environment
University of Florida, Gainesville, Florida, USA

Abstract

Field research and reconnaissance activities in tropical cyclones have steadily increased during the last two decades, which have led to new insights into the hurricane boundary layer and the wind loading of low-rise structures. Concurrently, wind engineers have developed new facilities capable of testing full-size structures or building systems under dynamic wind loading. This paper provides an overview of a selected number of these “full-scale” projects and demonstrates how they are interconnected.

Introduction

“Full-scale research” is the term of art in wind engineering that generally refers to

- field experiments conducted in tropical cyclones and other extreme wind events to characterize the nature of wind, wind-driven rain and wind loading
- laboratory experiments that attempt to simulate the dynamic nature of wind, wind-driven rain or wind loading at sufficient scale to evaluate the performance of a full-size test subject such as a building, signage or other infrastructure

The modern era of field research can be traced back to Hurricane Georges (1998), when Clemson University and Texas Tech University deployed prototype instrumentation in its path. Field research grew substantially during the early 2000s. Today, it is common for 50-100 observational assets to be deployed in a major hurricane by as many as ten research programs working in coordination. The types of measurement platforms have also diversified. For example, C-, X- and Ka-Band mobile Doppler radars, sodars, disdrometry and imaging probes, and pressure measurement systems are frequently deployed in conjunction with anemometric systems.

During this same timeframe, the capability of academic and private industry to simulate dynamic wind load conditions in a repeatable and highly realistic manner experienced unprecedented growth. The major significance is that prior to these developments, wind engineering did not have a reliable, full-scale destructive testing technology counterpart to the shake table or shock tube, which are the principal experimental tools of seismic and blast engineers, respectively. Currently, the largest such system is a 30 MW wind tunnel capable of testing a two-story building in a major hurricane, which is located at the Insurance Institute for Business & Home Safety (IBHS) Research Center in South Carolina. The facility complements a growing suite of research infrastructure designed to replicate boundary layer flows or dynamic pressure sequences on building component and cladding systems. Examples of other testing apparatuses include the Three Little Pigs project at Western University (Kopp et al., 2010), the Wall of Wind at Florida International University (Chowdhury et al., 2009), and several simulators at the University of Florida (Lopez et al., 2010; Shen et al., 2013). Kopp et al. (2012) addresses recent developments with regard to the study of residential building performance.

Full-scale research addresses basic and applied science issues. It is a critical validation tool to calibrate physics-based models that predict damage, insured loss and business interruption. Adroitly managing coastal risk and improving community resilience are critical issues for the public and private sector, especially with regard to anticipated changes in climate attributed with anthropogenic warming. Eventually, findings from full-scale research will play a role in decision-making that spans from setting rates for insurance premiums to issuing disaster declarations in advance of a tropical cyclone.

This paper gives a broad overview of major developments in full-scale research, followed by a short discussion on simulation of field observations in the laboratory for research and development for commercial purposes. Full-scale testing is beginning to be used by product manufacturers to test their systems in “real-world” conditions as a complement to the battery of standardized test procedures used in the product approval process. A general methodology is offered to reconstruct dynamic wind loads resulting from the passage of a real wind event.

Field Research

For more than four decades, wind engineers have conducted field research post-event to study damage causation. The shift toward performing experiments during storms followed Hurricanes Hugo and Andrew. Hurricane Hugo struck the South Carolina coast in 1989, causing widespread damage to the Charleston area. Three years later, Hurricane Andrew caused catastrophic damage to the Miami-Dade (formerly Dade) County, which was under the jurisdiction of what was believed to be the strongest “wind code” in the US, the South Florida Building Code.

The unexpected severity of damage in both storms prompted the development of new research directed at characterizing the surface wind field intensity at hurricane landfall and the resultant pressures on single-family homes. The Florida Coastal Monitoring Program (a consortium of universities) and Texas Tech University led two such projects. Both programs have extensively deployed weather stations in the path of Atlantic hurricanes. Between 1998-2013, data were collected in more than 30 different named storms along 4000 km of coastline. These programs spurred the formation of other projects such as Louisiana State University’s Scientific Towers Observing Regional Meteorology (STORM) and the SwirlNet program led by Natural Hazards Research Centre and the Cyclone Testing Station at James Cook University.

The Florida Coastal Monitoring Program (FCMP) is a collaborative effort between the University of Florida, Clemson University, Florida International University, Florida Institute of Technology (FIT) and IBHS. Balderrama et al. (2011) gives a comprehensive description of the program. The FCMP operates four 10-m and two 15-m portable weather stations designed to withstand gust loading and debris generated by a strong Category 5 hurricane (Figures 1 and 2). The data acquisition system measures 3D wind speed and direction at multiple levels and collects temperature, barometric pressure, and relative humidity data at the tower's base. The towers resist sliding and overturning through 2700 kg of self weight, and an outrigger system which places supports 6 m from the tower base, and earth screws at the end of the outriggers that resist uplift. The structural lattice structure can withstand a factored wind load computed from a 90 m/s gust.

Figure 1. FCMP 10 m Portable Weather Station

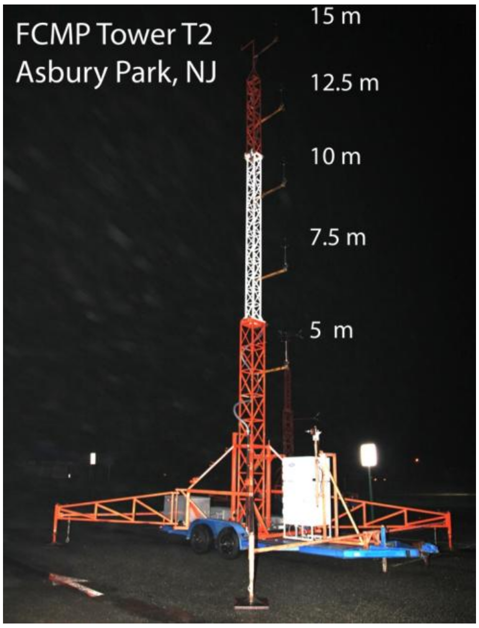

Figure 2. FCMP 15 m Portable Weather Station

The FCMP also conduct experiments to measure wind-induced pressures on single-family homes (Figure 3). Forty-one instrumented homes in Florida, South Carolina, and North Carolina are prewired for rapid installation of 25-30 absolute pressure sensors that record data at 100 Hz. UF and FIT have also developed wireless and GPS-synchronized modular sensors, respectively, that are in the initial stages of prototyping and validation. The goal of this component is to compare full-scale pressure loads with those measured on a scale model of the subject houses in a boundary layer wind tunnel in order to provide a basis for evaluating wind load provisions in coastal regions. Liu et al. (2009) presents the results one such comparative study using data collected on a residence during Hurricane Ivan in 2004. An NSF sponsored study (CMMI 0928563) is now underway to compare the results from multiple wind tunnel facilities of two of the FCMP homes that experienced hurricane wind loads during Hurricane Ivan.

Figure 3. Installation of a FCMP house pressure measurement system

Texas Tech University (TTU) has led multiple efforts to characterize surface winds and storm structure in landfalling hurricanes. During 1998-2005, TTU deployed two Wind Engineering Mobile Instrument Tower Experiment (WEMITE) platforms (Figure 4). Wind speed measurements were taken at five levels ranging from 3.1 to 10.7 m using RM Young Gill anemometers. Schroeder and Smith (2003) describes the platform in greater detail. In 2005, TTU expanded its observational assets to include a large suite of 2.5 m observational platforms collectively called StickNet (Figure 5). The probes were designed for quick deployment time, ease of transport and low cost, thus it is possible for TTU to cast a wide net in the landfall area and in locations with a high risk of storm surge. TTU added two Ka-band mobile Doppler radars to its infrastructure in 2009 (Figure 6). In contrast to longer wavelength radars, these fully coherent, pulse compression systems have a 12 m gate spacing, which is ideal for capturing high-resolution motion.

In the past, a common goal of both programs was the characterization of gust factors, i.e. the ratio of a short duration peak gust to the mean value of the record. Gust factors are used to convert wind speed and gust velocity pressure values from one set of observational metadata (height, duration, terrain) to another set of conditions. Prior research had relied extensively on extratropical (e.g., fronts) weather events to calibrate theoretical models (e.g., Durst, 1960). Krayer and Marshall (1992) analysed anemographs from civilian and military weather stations in four Atlantic basin hurricanes and determined that an upward adjustment of gust factors was warranted in hurricane-prone areas. Today the research has shifted to several related but distinct study areas, including the role of large-scale motions aloft in the modulation of the surface wind field below (Kosiba et al., 2013), estimation of surface wind fields from multi-Doppler radar synthesis, characterization of raindrop size distribution, and coherent structures in the roughness sublayer wind field.

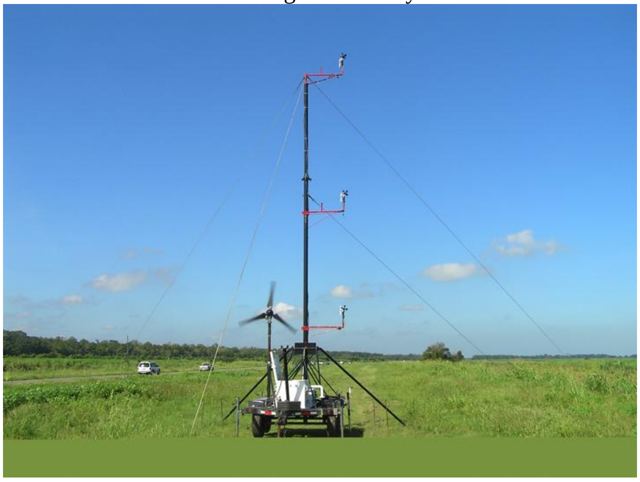

Figure 4. Texas Tech University Wind Engineering Mobile Instrument Tower Experiment (WEMITE) program. Photo courtesy of John Schroeder

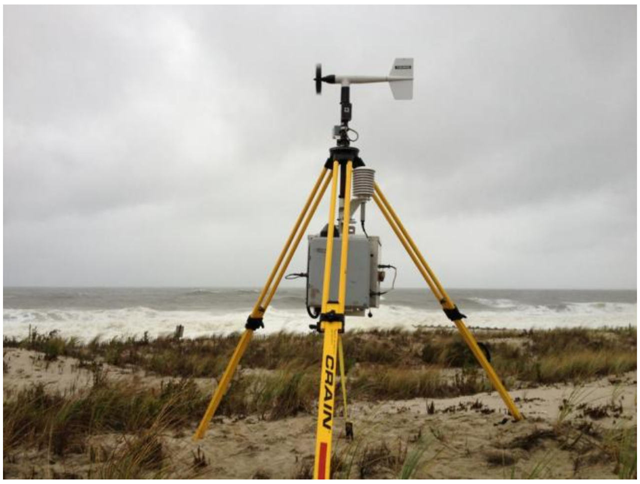

Figure 5. Texas Tech University Wind Engineering Stick-Net. Photo courtesy of John Schroeder

Figure 6. Texas Tech University Mobile Ka-Band Doppler Radars. Photo courtesy of John Schroeder

From the Field to Laboratory

Dynamic loading of full-scale structures is generally performed one of two ways. A partial turbulent boundary layer can be generated using a large fan array and control measures to impart the desired mean velocity and turbulence characteristics. This 'Wall of Wind' concept originates from work by Dr. Timothy Reinhold at Clemson University that demonstrated proof-of-concept for development of a larger facility at Idaho National Laboratory (Kennedy, 1999). The concept did not ultimately become a reality, and the Wall of Wind project went dormant until 2004, when the author reinitiated the project at Florida International University (FIU) with support from the reinsurance industry and the National Science Foundation. FIU developed its Wall of Wind in several phases, moving from modified airboat systems and to a bank of industrial vaneaxial fans. In 2006, Reinhold initiated the development of the largest controlled fan boundary layer wind tunnel (Figure 7). The 30 MW full-scale test facility opened in 2011, and has successfully been used to study a wide range of topics including water ingress through roof sheathing, hail damage and the asphalt shingle roof performance.

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Figure 7. IBHS Research Center. Photo courtesy of IBHS

Dynamic wind pressure waveforms can also be applied directly to the test subject. Cook et al. (1988) led the first effort with the development of the Building Research Establishment Real-time Wind Uniform Load Follower (BRERWULF), which was a closed-loop control system that modulated the air exchange between a fan, the free atmosphere and a pressure chamber with an integrated, interchangeable test article. Kopp et al. (2010) developed its predecessor, the pressure loading actuator (PLA). Inspired by this work, the author developed a 'High Airflow' Pressure Loading Actuator (HAPLA) shown in Figure 8. A second system (Figure 9) was later developed to test larger buildings systems (up to 40 m^2) at higher loads and air leakage (Shen et al., 2013). Collectively, these systems can apply loads up +/- 23 kPa with waveform frequencies ranging from 2-7 Hz. The major difference between the systems is the size of the specimen and the amount of air leakage that can be accommodated without sacrificing controllability or reducing the achievable peak load. The next section describes how to reconstruct representative loading conditions from an extreme wind event using a dynamic pressure loading actuator.

Figure 8. High Airflow Pressure Loading Actuator, University of Florida

Figure 9. Dynamic Pressure Simulator, University of Florida

Reconstructing Wind Loading Effects from an Extreme Wind Event

Methods to specify dynamic wind loading requirements for full-scale tests vary (e.g. Lopez et al., 2011; Morrison and Kopp, 2012; Henderson et al., 2012). An established, universal approach does not exist. Jancauskas et al. (1994) describes one of the earliest attempts to develop such a method from boundary layer wind tunnel modeling and an arbitrary "design" tropical cyclone, which was based on Cyclone Winifred (1986). Although this method was developed for computational analysis, its framework easily adapts to experimental research. Letchford and Norville (1994) developed a similar approach for wall cladding using pressure data collected on the Texas Tech University Wind Engineering Research Field Laboratory. Both methods reduce the dynamic load sequence to sinusoidal loading functions. Jancauskas et al. (1994) applied a rainflow-counting algorithm. Letchford and Norville (1994) used a level crossing method.

The approach that follows is based on direct simulation of a sequence of pressure time series for the specific case of reconstructing an event. It is intended for simulating pressure in an isolated region but can be applied to simulate spatially varying conditions (e.g., Smith et al., 2010; Morrison et al., 2012) by sending different inputs to multiple control devices. The method requires synchronized sequences of wind speed, direction and horizontal rainfall intensity at a given location, which can either be taken from field measurements (such as those described earlier) or a worst-case envelope of historical records and wind tunnel modeling data.

1. Obtain historical records of extreme wind events of interest and define the "episode." Specifically, determine the interval of time within the storm event that is of interest and create a contiguous non-overlapping record of wind speed and direction. The interval should be selected based on a minimum wind speed threshold and the reasonable change in direction. Figure 10 contains two representative sequences derived from notable Atlantic hurricanes. The 3 s gust velocity at the coastal crossing point taken from the NOAA Hurricane Research Division H*Wind surface wind field analyses are plotted.

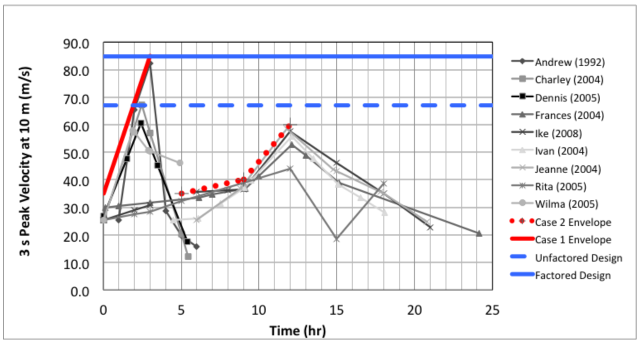

Figure 10. Peak 3 s gust wind speed envelopes obtained from H*Wind analysis for nine Atlantic Hurricanes occurring during 1992-2005. Each storm's time axis is shifted to group the storms in a common time frame reference. The velocities are plotted as peak 3 s values at 10 m in open exposure conditions, which is equivalent to the basic wind speed in ASCE 7 (2010). The two red lines are the enveloped sequences. The solid red line depicts the envelope for the compact, fast-moving design level event (Case 1), and the dotted red line depicts the envelope for the broad, slow-moving, non-design level event (Case 2). Both cases represent ~90 degree change in wind direction, which is ideal for testing in either positive or negative pressure. For comparison, the blue lines depict design level wind speeds for Miami-Dade County (pre-ASCE 7-10)

2. Obtain and process high-resolution pressure data acquired from a boundary layer wind tunnel modeling study or alternatively, from a full-scale experiment (e.g., Liu et al., 2009). The purpose of this step is to convert this data to its full-scale counterpart. This record also serves as the command signal for the simulation device. The pressure sequences should be chosen with consideration of the following factors:

   - Directionality. Pressure sequences must be extracted for each wind sector. A general recommendation is to choose the sequence such that most intense wind speed record aligns with the most severe pressure case.
   - Load character. It may be more appropriate to choose the sequence with the largest peak pressure, the largest peak pressure obtained from an extreme value analysis (e.g., Leiblin, 1974) or the largest cycling rate. If the water penetration resistance of the specimen is being evaluated, the sequence with the largest mean pressure will produce the most conservative results (Lopez et al., 2011)
   - Spatial averaging. If the test specimen is of any significant size (say > 3 m^2), pressure data from multiple locations should be averaged using weighting factors computed from the tributary areas normalized to the gross area

3. Construct command signals for each interval in the storm record, which should be divided into contiguous, non-overlapping segments (say 10-15 minutes). The mean velocity or the peak gust of each segment is used to convert

pressure measured in the wind tunnel. Pressure data are normally saved as non-dimensional pressure coefficients

$$C_p(t) = \frac{p(t) - p_{ref}}{\frac{1}{2}\rho U_{ref}^2} \tag{1}$$

where *p(t)* is the pressure measured at a specified location on the model surface, p_{ref} is the pressure measured at a specified reference location, ρ is the density of air and U_{ref} is the velocity measured at the same location. The reference height most often corresponds to several meters above the wind tunnel floor and outside of the influence of the roughness element grid, thus C_p values must be re-referenced to elevation of the storm record. If the mean velocity is to be used, the referencing is performed using the logarithmic law

$$C_{ph}(t) = C_p(t)\left[\frac{ln(z_{ref}/z_0)}{ln(h/z_0)}\right]^2 \tag{2}$$

where z_0 is the roughness length (m), z_{ref} is the reference height of the instrument at full (model) scale and h is the reference height of the storm record at full (model) scale). If re-referencing to a shorter duration gust or average, a second referencing factor must be applied:

$$GC_{ph}(t) = C_{ph}(t)\left[\frac{1}{GF}\right]^2 \tag{3}$$

where GC_{ph} corresponds to gust velocity pressure (e.g. 3-sec for ASCE 7) and GF is the gust factor, which is computed based on the upwind terrain conditions, reference height and gust duration. See Masters et al. (2010) for a suitable method to compute the GF. For further information on the overall conversion process, see St. Pierre et al. (2005).

4. Convert the model-scale time increment (dt) to its full-scale counterpart for each basic wind speed value from the reduced frequency relationship:

$$\left(\frac{fL}{U}\right)_{fs} = \left(\frac{fL}{U}\right)_m \tag{4}$$

   where f_{fs} is the sampling frequency of the pressure scanning system, L_m/L_{fs} is the model building scale, U_m corresponds to the re-referenced wind velocity shown in either Eq. 2 or 3, U_{fs} is the user specified wind speed at full-scale and f_{fs} is the frequency at full-scale. The full-scale time increment is equal to the inverse of f_{fs}.

5. Low-pass filter and resample the data for the pressure loading actuator. To improve controllability and reduce time to tune the control loop (PID), low-pass filter the pressure sequences with a cutoff frequency that matches the maximum waveform frequency the pressure loading actuator can achieve. Lastly, resample the data to a reasonable instruction rate (e.g., 50 Hz) if a digital to analog conversion is required.

Implications for Research and Development

Industry relies primarily on testing procedures intended for product approvals (e.g., ASTM E330-02, 2010; FBC, 2010a; FBC, 2010a) to evaluate the performance of products. These methods, while highly repeatable, have some shortcomings. For example, the rainflow analysis used in cyclic (fatigue loading) sequences is based on a linear damage accumulation model, which is idealistic and not necessarily representative of how real building systems undergo progressive damage. Second, these tests are often administered in nearly perfect settings and without consideration of the installation/interface. In contrast, full-scale tests are performed on systems that are nearly identical to field construction. Loads are applied at sufficient scale to recreate equilibrium and compatibility conditions at the boundary conditions.

The approach described above provides a complementary means to recreate environmental loads with sufficient realism to evaluate building system performance. The major tradeoffs are the cost and time to set up experiments. It is highly unlikely that full-scale tests will be performed as Bernoulli trials for vulnerability modeling, however, used in conjunction with conventional tests to model constitutive behavior of components, it is a highly valuable tool to refine and validate computational engineering models (i.e. finite element analysis). The author anticipates full-scale testing apparatuses, calibrated to field measurements, will play a vital role in industrial research and development for many years to come.

Conclusions

State, federal and private sponsors have directed significant resources to developing customized suites of instrumentation to study wind hazards *in-situ* as well as dedicated facilities to recreate severe weather conditions in a controlled laboratory environment. This paper presented information on a select number of these programs, and demonstrated how they are interconnected activities.

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