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Development of devices and methods for simulation of hurricane winds in a full-scale testing facility

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Abstract. The International Hurricane Research Center (IHRC) at Florida International University (FIU) is pursuing research to better understand hurricane-induced effects on residential buildings and other structures through full-scale aerodynamic and destructive testing. The full-scale 6-fan Wall of Wind (WoW) testing apparatus, measuring 4.9 m tall by 7.3 m wide, is capable of generating hurricane-force winds. To achieve windstorm simulation capabilities it is necessary to reproduce mean and turbulence characteristics of hurricane wind flows. Without devices and methods developed to achieve target wind flows, the full-scale WoW simulations were found to be unsatisfactory. To develop such devices and methods efficiently, a small-scale (1:8) model of the WoW was built, for which simulation devices were easier and faster to install and change, and running costs were greatly reduced. The application of such devices, and the use of quasiperiodic fluctuating waveforms to run the WoW fan engines, were found to greatly influence and improve the turbulence characteristics of the 1:8 scale WoW flow. Reasonable reproductions of wind flows with specified characteristics were then achieved by applying to the full-scale WoW the devices and methods found to be effective for the 1:8 scale WoW model.

Key words: Wall of Wind; full-scale testing; hurricane simulation; turbulence characteristics; fluctuating waveform; small-scale model.

1. Introduction

1.1. Hurricane losses

Hurricane-induced economic losses have increased steadily in the U.S., affecting the Gulf and East Coast from Maine to Texas during the past 50 years with estimated annual losses (in constant

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2006 dollars) averaging $1.3 billion from 1949-1989, $10.1 billion from 1990-1995, and $35.8 billion per year from 2001-2005 (National Science Board- NSB 2007).

Most coastal residential construction performs well under gravity loads, but significant damage has been observed after major wind events. During tropical storms and hurricanes, residential buildings and other low-rise structures experience most of the losses (Jones, *et al*. 1995). Damages during extreme wind events highlight the weaknesses inherent in current residential building construction and underscore the need for improving the structural performance of typical residential buildings. Also, there is great concern for the existing stock of old buildings that are not designed to an acceptable building code or not constructed to an acceptable quality.

1.2. Existing testing methods

A variety of experimental methods for research and development are available for determining wind effects and loadings on structures. These include wind-tunnel testing of small-scale models, full-scale field testing in the natural environment, and full-scale testing of components and structures to simulated wind-like forces generated by actuators and pressure chambers. To date, the experimental focus in wind engineering has been on the use of wind tunnels, mostly boundary-layer wind tunnels (Cermak 1995). Wind tunnel facilities have provided a wealth of data on the nature of wind loads for a wide range of structures.

As noted, e.g., by Levitan and Mehta (1992), effective studies of wind effects on full-scale buildings have been limited. Frequently, instrumentation, power sources, and recording devices fail in severe windstorms, leaving large uncertainties on the response. Nevertheless, field studies based on measurements conducted by, among others, Marshall (1977), Eaton and Mayne (1975), Kasperski, *et al*. (1996), Richardson, *et al.* (1997), Long, *et al.* (2005), and Datin, *et al.* (2006), have provided valuable findings and data, and contributed to the validation or otherwise of certain wind tunnel techniques. The Florida Coastal Monitoring Program (FCMP) is a unique joint venture focusing on full-scale experimental methods to quantify near-surface hurricane wind behavior and the resultant loads on residential structures. The purpose of one of its components is to collect hurricane-induced uplift pressure data on the roofs of real residential homes (http://fcmp.ce.ufl.edu/overview/house.htm).

Full-scale destructive tests on residential building models through pressure box or actuator loading are performed in facilities such as “Three Little Pigs” at the University of Western Ontario (http://www.eng.uwo.ca/research/ttlpp/default.htm) and the “Cyclone Testing Station” at James Cook University in Australia (http://www.eng.jcu.edu.au/csts/research.htm). In addition, the mobile “Wind Simulator” of the University of Florida, has been used to evaluate the performance of a variety of low-rise structures in Florida (http://news.ufl.edu/2007/08/29/hurricane-wind-machine/).

1.3. Wall of Wind full-scale testing approach

Much valuable information can be developed from current techniques. However, additional improvements could be made in construction practices if the performance of a building system could be evaluated in a full-scale turbulent flow field reasonably representative of a hurricane event. Full-scale testing on residential building models subjected to simulated hurricane-induced effects can lead to better understanding of hurricane-structure interaction and innovative design technologies that can mitigate hurricane wind damage. The International Hurricane Research Center (IHRC) at Florida International University (FIU) is developing a research approach that utilizes such full-scale testing, complemented by wind tunnel and existing full-scale methods and analytical tools. The goal is to perform economically a variety of wind-structure interaction studies of low-rise structures. Measuring 4.9 m high by 7.3 m wide, the 6-fan Wall of Wind (WoW) full-scale testing apparatus, funded by federal and state agencies and private industry, is currently capable of generating hurricane-force winds and wind-driven rain.

This full-scale research is envisioned to address two high priority investment categories for hurricane research, namely, 'Impacts and Interactions' and 'Preparedness and Building Resiliency,' as recommended by the National Science Board (NSB 2007). The research will facilitate the development of advanced mitigation techniques through the study in a controlled and repeatable environment of models of buildings or portions thereof under hurricane-induced wind and wind-driven rain.

The accuracy of the WoW full-scale testing will depend on the fundamental development of a wind field that reasonably replicates mean and turbulence characteristics of real hurricane winds. It was ascertained through testing that flows achieved by the full-scale WoW did not reproduce boundary-layer atmospheric flows unless specially developed flow modification devices and methods were used. To develop the target wind-flow generating devices and methods efficiently, a small-scale (1:8) model of the WoW was built, in which simulation devices such as airfoils, planks and grids were easier and faster to install and change. Wind characteristics obtained in the small scale WoW were analyzed for a variety of cases, and satisfactory wind fields were achieved. The corresponding devices and methods were then applied to the full-scale WoW, and it was determined that the full-scale flows so obtained were satisfactory.

The paper is organized as follows. Section 2 briefly describes tropical cyclone wind characteristics analyzed from near-surface wind data collected through the Florida Coastal Monitoring Program (FCMP) during hurricane passages. Such wind characteristics were then used as targets for simulating wind flows for the full-scale WoW facility. Section 3 describes preliminary design specifications pertaining to the WoW facility, compares the baseline flow characteristics to the target tropical cyclone wind parameters, and evaluates the WoW flow discrepancies which needed improvement. Section 4 describes a series of tests carried out in a small-scale WoW model to develop active and passive flow simulation devices and corresponding test results. Section 5 illustrates the application to the full-scale WoW of effective flow simulation techniques developed at small-scale. Section 6 describes the WoW research goals given the limitations of the apparatus. Section 7 presents a summary and conclusions.

2. Surface mean flow and turbulence structure in tropical cyclone winds

The effectiveness of the WoW full-scale testing will depend on the generation of wind fields that reasonably replicate near-surface Atmospheric Boundary Layer (ABL) profiles and turbulence occurring under real hurricane conditions. This section describes mean wind speed profiles and turbulence models that were used as targets for wind flow simulation in the full-scale WoW facility. Other wind target flows can be simulated as needed, e.g., flows with characteristics observed in individual storms, as opposed to flows with characteristics representing averages of characteristics observed in several storms, or flows with conventional characteristics specified in codes.

2.1. Tropical cyclone wind characteristics

The investigation of near-surface level hurricane wind behavior is aimed at providing information on hurricane wind characteristics required for the design of safe structures. Information on mean wind profiles, gust factors, turbulence intensity, integral scale, and turbulence spectra is essential for developing realistic models of wind pressure and wind loads on structures. Considerably fewer data and validated models are available for tropical cyclones than for extra-tropical storms.

Hurricanes are defined as tropical cyclones for which the maximum 1-minute sustained surface wind speeds exceed 33 m/s. Data obtained in the Florida Coastal Monitoring Program (FCMP) provide an opportunity to investigate tropical cyclone wind turbulence characteristics (Masters, *et al.* 2003; Masters 2004; Masters, *et al.* 2004; Masters, *et al.* 2005; Yu, *et al.* 2008). For the winds analyzed in this study the speeds were sufficiently high for neutral stratification to prevail. This assured that the characteristics of those winds were similar to those prevailing in hurricanes.

The wind data at 10 m height over flat open land were collected at three selected FCMP observation sites during two hurricane passages, namely Ivan (2004), and Lili (2002), the three measuring towers being referred to as Ivan-1, Ivan-2, and Lili. The time history of the Ivan-2 record is shown in Fig. 1a. It is emphasized that, while the entire time histories of the records used in this paper were non-stationary, each of the 1-hr segments selected for analysis satisfied the stationarity requirement. Segments with direction shifts larger than 10^o from the mean were not considered. Hourly record segments were evaluated for statistical stationarity by performing reverse arrangements tests at the level of significance $\alpha = 0.025$ to identify candidates for elimination (Bendat and Piersol 2000). Note that the 1-hour records used in this paper were also used in the paper by Yu, *et al*. (2008). Also, Powell, *et al*. (1996) referred explicitly to the use in their analyses of stationary hurricane records of at least 1 hour collected in Hurricane Bob.

The work reported in this paper establishes the capability of reproducing in the WoW tropical cyclone wind flows measured at 10 m elevation over flat open land under neutral stratification conditions. The tropical cyclone flow characteristics were obtained from analyses of 1-hr long segments (see Yu 2007 and Yu, *et al*. 2008). The target flow whose simulation was sought was based on mean results obtained from analyses of records at three FCMP observation sites: Ivan-1, Ivan-2, and Lili. Specified target flow characteristics can alternatively be based on: analyses of, say, 5-min, 10-min, or 20-min long records; analyses of individual hurricane records; analyses of wind flows over terrains with various roughness characteristics (e.g., suburban terrain); or code specifications (e.g., some codes specify constant mean flow for buildings up to approximately 5 m height). The choices will depend on professional consensus or specific needs. One justification for developing simulations of atmospheric boundary layer flows over open terrain is that they allow comparisons of WoW measurements with full-scale measurements for, e.g., the Texas Tech building (Levitan and Mehta 1992) or the Silsoe cube (Richards, *et al*. 2001).

The observed normalized power spectra of longitudinal, lateral and vertical tropical cyclone wind components analyzed from FCMP data have significantly more energy at lower frequencies than is the case for non-hurricane winds. This is in agreement with results obtained for only one hurricane record by Schroeder and Smith (2003). The longitudinal power spectral densities for Ivan-1, Ivan-2, and Lili at 10 m height over open terrain, as well as the best fitting curve, are plotted in Fig. 1b (see details in Yu, *et al*. 2008). The longitudinal and vertical power spectral densities (PSD) ($S_u(n)$ and $S_w(n)$) of the FCMP are fitted as:

$$\frac{nS_u(n)}{u_*^2} = \frac{0.1628f^2 + 0.001173f + 6.714 * 10^{-8}}{f^3 + 0.08184f^2 + 4.553 * 10^{-4}f + 1.674 * 10^{-6}}, \quad f = \frac{nz}{U(z)} \tag{1}$$

$$\frac{nS_w(n)}{u_*^2} = \frac{0.0482f^2 + 0.03648f - 1.427 * 10^{-5}}{f^3 - 0.06981f^2 + 0.08011f + 0.002837} \tag{2}$$

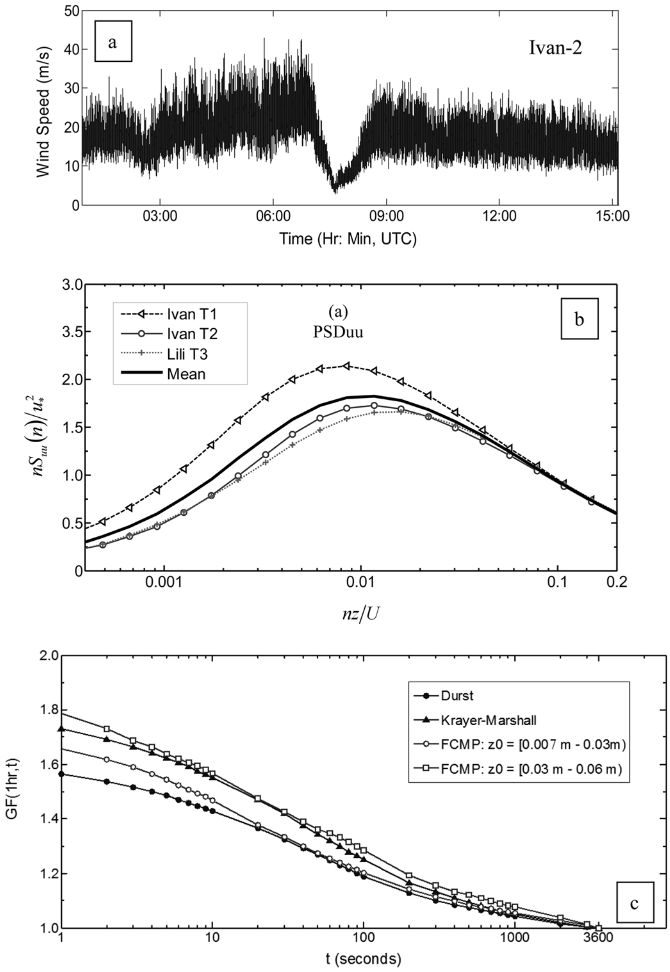

Fig. 1 Tropical Cyclone (TC) wind characteristics: (a) Sample time histories of wind speed records, (b) Normalized longitudinal power spectral densities, (c) Gust factor plots

where *n, z and U(z)* are the frequency, the height above the ground, and mean wind speed, respectively, and u_* is the friction velocity.

For FCMP, $u_*^2 = \sigma_u^2/\beta = \sigma_u^2/9.0$, where σ_u is the standard deviation of the fluctuating wind speed. For comparison, two power spectral density models (revised Kaimal model for longitudinal direction and Panofsky model for vertical direction) are given in Eqs. (3) and (4) (Simiu and Scanlan 1996):

$$\frac{nS_u(n)}{u_*^2} = \frac{200f}{(1+50f)^{5/3}} \tag{3}$$

$$\frac{nS_w(n)}{u_*^2} = \frac{3.36f}{1+10f^{5/3}} \tag{4}$$

where $u_*^2 = \sigma_u^2/6.0$.

The gust factor ($GF(T, t)$) is defined as

$$GF(T, t) = u_{\max}(T, t)/U(T) \tag{5}$$

where $u_{max}(T, t)$ is the largest of the mean wind speeds averaged over intervals of length t, and $U(T)$ is the mean wind speed averaged over the time period T. The $GF(T, t)$ in the ASCE 7 Standard is based on Figure C6-4 in ASCE 7-05 (2005), taken from Durst (1960). For open terrain with roughness $0.007 \text{ m} \le z_0 < 0.03 \text{ m}$ and at 10 m elevation, the estimated gust factor curve based on the in-situ FCMP wind measurement data closely matches the Durst curve for gust durations larger than 20 s. However, as shown in Fig. 1c, for gust durations of less than 20 s, the ordinates of the estimated gust factor curve are higher than those of the Durst curve. The estimated values of the gust factor from the FCMP wind measurements are lower than those obtained by Krayer and Marshall (1992), as shown in Fig. 1c. The 3-s gust factors based on the hourly mean wind speed are 1.52, 1.59 and 1.66 for Durst (1960), FCMP tropical cyclone winds ($0.007 \text{ m} \le z_0 < 0.03 \text{ m}$), and Krayer and Marshall (1992), respectively. Independent analyses by Masters (2004) of FCMP data obtained in 9 tropical cyclones for terrain exposure with 0.02-0.04 m roughness length led to similar conclusions.

2.2. Mean wind speed profile specifications in ASCE 7-05

According to ASCE 7-05, the hourly mean wind speed profile obeys the power law:

$$\frac{U_z}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{6}$$

where U_z is the mean wind speed at z (the height from ground), and U_{ref} is the mean wind speed at the reference height z_{ref}. The exponents α are 1/4.0 and 1/6.5 for suburban terrain (Exposure B) and open terrain (Exposure C), respectively (Note: The exponents α in this paper have the same meaning as the exponent $\bar{\alpha}$ in Table 6-2 of ASCE 7-05). The turbulence intensities for suburban terrain and open terrain under the height of 4.9 m are approximately 0.30 and 0.23, respectively. Note that the ASCE prescribes a 23% turbulence intensity for open terrain, which is approximately 30% higher than the turbulence intensity estimated from FCMP open terrain measurements (17.8%).

3. Preliminary full-scale Wall of Wind (WoW) configuration

3.1. Background of the full-scale testing facility

In 1999, the Idaho National Engineering and Environmental Laboratory (INEEL), through the U.S. Department of Energy (DOE), proposed a large-scale wind test facility (LSWTF) to study at full-scale the behavior of low-rise structures under simulated winds. The cost of this LSWTF was cited as \$70 to \$300 million (INEEL 1998; Philips 1999). At the request of the DOE Idaho Operations Office, the National Research Council (NRC) established a committee to review the potential value of the proposed LSWTF. The committee acknowledged that LSWTF could play a role in expanding knowledge and improving current practices, but concluded that the cost was unacceptably high and that the facility would be uneconomical and inappropriate to construct (NRC 1999).

Recognizing that full-scale testing will be advantageous but should not be an overly costly method of producing data, the research team at the IHRC (with contributions by Dr. Tim Reinhold, now at the Institute for Business and Home Safety - IBHS) started planning in 2003 to build a full-scale wind testing facility. With this full-scale testing facility, referred to as the Wall of Wind (WoW), full-sized structures such as site-built or manufactured housing, and half-sized small commercial and industrial buildings, could be tested under a range of storm conditions in a controlled and repeatable environment. WoW preliminary tests are described by Gan Chowdhury, *et al*. (2008). The goal of the WoW testing is to enable experimental identification of weaknesses in real structures and components subjected to hurricane-induced wind and rain. Through full-scale destructive testing, failure-mode investigation and better engineering, innovative mitigation techniques and products can be developed.

The preliminary 6-fan WoW configuration (Fig. 2a) was constructed on the FIU Engineering campus. The 6-fan WoW system consisted of a 2×3 array of Chevy 502 big block carburetor engines turning Airboat Drive Units CH3 2:1 propeller drives, providing a wind stream approximately 4.9 m high by 7.3 m wide. Each engine, driving a pair of counter-rotating propellers of approximately 2.3 m in diameter, was mounted in a steel frame "engine section" measuring 2.44 m by 2.44 m. The engine section was equipped with wedges in each corner to direct flow into the propellers. Each engine section was connected to a "propeller section" housing the propellers. Each propeller section was connected to a "diffuser section" that makes transition from an octagon to a square section, helping the proper stacking of the six fan array. WoW is capable of variation of fan engine speed by

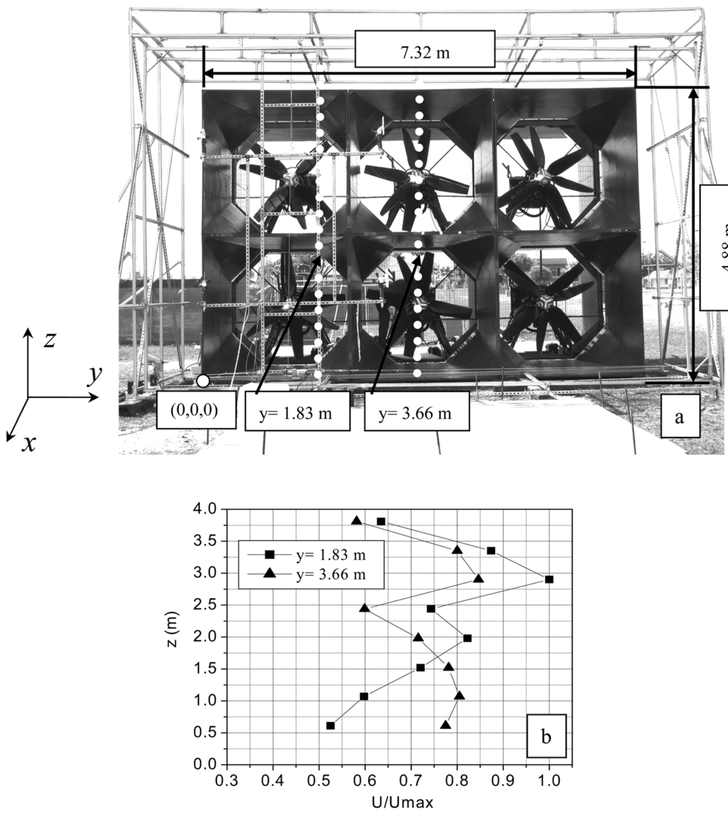

Fig. 2 (a) Preliminary WoW configuration and coordinate system, (b) Non-dimensional velocity profiles at y = 1.83 m and y = 3.66 m servo control mechanisms aided by arbitrary waveform generation. The engine rpm (revolutions per minute) values are related to the test wind speeds exiting the WoW through pre-determined calibration curves.

3.2. Wind field for preliminary WoW configuration

The 6-fan WoW is capable of generating a maximum sustained wind speed of approximately 56.1 m/s with all engines running at 4500 rpm. But in addition to high wind speed, it is also important to generate realistic mean and turbulence characteristics in the wind field. To evaluate wind field characteristics for the preliminary configuration of the 6-fan WoW, RM Young (05103V) and Gill propeller anemometers were used to measure the fluctuating wind speed for WoW. To evaluate free undisturbed flow conditions, wind speeds were measured at a 10 Hz sampling rate without the test structure in place. The wind monitors, within ranges of 0-100 m/s, recorded wind speeds in the longitudinal, lateral and vertical directions. A program was developed and tested to systematically analyze WoW data and estimate the mean and turbulence characteristics of the flow field.

Each of the six fans was operated through the application to each engine of a single flat rpm waveform signal, so that all engines ran steadily at a constant rpm. The wind speed measurements were performed at a distance of x = 2.7 m from the exit of the fans (refer to the coordinate axes system of Fig. 2a), corresponding to the location of the test models' leading edge. The record length (T) was 60 s for each point, and the sampling frequency was 10 Hz. The non-dimensional velocity profile was found to be similar for runs using various flat rpm waveforms. The non-dimensional mean velocity profiles at y = 1.83 and 3.66 m are shown in Fig. 2b. From the figure it follows that a reduction in wind speed occurred near the horizontal plane between the top and bottom fans corresponding to z = 2.44 m.

Wind speed time histories corresponding to the average roof eave height for typical low-rise residential buildings (typically 3.0 m to 3.4 m) were recorded to evaluate the turbulence characteristics. Fig. 3a presents the recorded WoW longitudinal wind speed time history at 4,000 rpm (at z = 3.35 m of center line). Fig. 3b presents the corresponding power spectral density (PSD) of the longitudinal velocity fluctuations, and a comparison with the power spectral density obtained from FCMP tropical cyclone wind measurements over flat open land (see Section 2.1). The mean wind speed, corresponding turbulence intensity, longitudinal integral length scale (L_u^x), and gust factors for the WoW, and their counterparts obtained from FCMP data are listed in Table 1.

From Table 1 and Fig. 3, the following deficiencies in the WoW generated wind field for the preliminary configuration could be noted:

- For the WoW generated flow, the highest wind speeds occurred at the center part of each fan. Near the top and bottom edges of each fan the wind speeds decreased rapidly. The mean wind speed profile did not match an Atmospheric Boundary Layer (ABL) profile as given in ASCE 7-05.
- The gust factor (GF(6min, 3sec) = 1.09) and the longitudinal turbulence intensity (6.0% turbulence intensity) for the WoW-generated wind field were lower than the FCMP and ASCE values.
- The longitudinal integral length scale (L_u^x = 59.6 m) for the WoW-generated wind field was lower than that obtained from the FCMP (L_u^x = 98.7 m).
- The power spectral density plots showed that, for the WoW flow, higher frequency spectral ordinates were comparable to, although somewhat higher than, those of the FCMP. The fact that

the spectral ordinates in the WoW flow were lower in the region of highest energy than in FCMP explained why the turbulence intensity was less in the full-scale WoW flow than in FCMP.

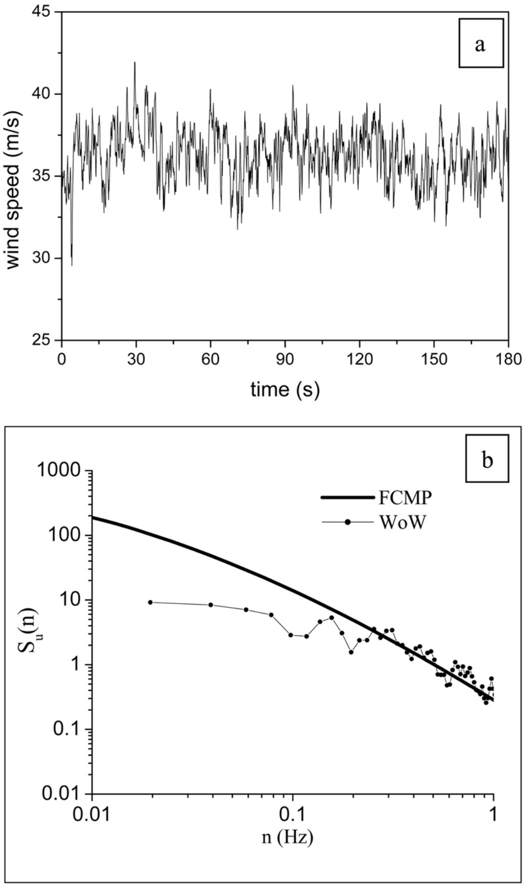

Fig. 3 Wind characteristics for preliminary WoW configuration: (a) Wind speed time history, (b) Comparison of power spectral density plots (WoW vs FCMP)

Table 1 Wind Characteristics of Preliminary WoW at 4,000 rpm and Comparison with Real Tropical Cyclone Winds

Case	Mean wind speed (m/s)	Turbulence Intensity (TI_u) (%)	Gust Factor GF(T,t)	Integral Length Scale, L_u^x (m)
Preliminary WoW	36.3 (1-min mean speed)	6.0	GF(6min, 3sec) = 1.09	59.6
FCMP*	17.8 (1-hr mean speed) 22.3 (1-min mean speed)	17.8	GF(1hr, 3sec) = 1.59 GF(6min, 3sec) = 1.43	98.7

*Mean results of three observation sites (Ivan- 1, Ivan- 2, and Lili), at which data were collected by Florida Coastal Monitoring Program (FCMP). Individual values for Ivan-1, Ivan-2, and Lili may be obtained from Yu (2007).

3.3. Scope of study for development of flow simulation devices and methods

In the preliminary configuration no flow simulation devices were used. For this reason the WoW flow features differed from their ASCE-7 and FCMP counterparts. This fact established the need to develop such devices. The next sections describe research performed to design devices and methods for generating full-scale WoW flows that closely match atmospheric boundary layer profiles and tropical cyclone winds parameters. The approach adopted for this purpose was to design those devices through tests in a small scale (1:8) WoW (Section 4), and then test the effectiveness of those devices in the full-scale WoW (Section 5).

4. Development of devices and methods for flow simulation using a small-scale Wall of Wind(WoW)

In view of the deficiencies of the preliminary WoW system an investigation was undertaken using a small-scale (1:8) WoW model to develop the target wind flow generating devices and methods efficiently. Several methods and their effects on the wind flows (such as the application of diffusers, flaring configuration of fans, grids, raising of fans above the ground, variation of rpm values for fans) were studied at the small-scale WoW system. By using the small-scale WoW, it was easier and faster to install and change the simulation devices and the cost of experiments was greatly reduced.

The Dantec Dynamics Hot-Wire system was used for the measurement of wind speeds, which consisted of a data acquisition (DAQ) system, two miniature 55P11 wire-probes, and a hot-wire calibrator. The Dantec Dynamics Hot-Wire Calibrator is a simple but accurate device for 2-point calibrations of most hot-wire probes used with Constant Temperature Anemometers, and is valid for the entire velocity range from 0.5 m/s to 60 m/s. The measurement section of the wind speeds was set at 740 mm from the exit of the fans.

The following subsections describe in some detail the process that led to a satisfactory simulation of the target flow. It is felt that it is important to record, for the benefit of future modelers, not only the successful phases of this process, but also those found not to be fruitful in the empirical search for appropriate devices and methods. Additional details can be found in Liu (2008).

4.1. Initial Testing

The first case tested was a small-scale (1:8) WoW model with diffusers (Fig. 4a), which replicated the preliminary full-scale WoW configuration and was used as the preliminary baseline case for the small-scale WoW. All six fans were running steadily at 25% of full throttle power during the test. Mean wind speed profiles were measured at various locations defined by the coordinate y. Sixteen measurement points in the vertical direction (i.e. the z-direction) were used. For mean wind speed profiles, each measurement was performed for 45 s, and the sampling frequency was 30 Hz. The non-dimensional mean velocity profiles at 1:8 scale model dimensions $y = 0.229$ and 0.457 m (corresponding to prototype dimensions 1.83 m and 3.66 m) are shown in Fig. 4b. Fig. 4b showed reductions in wind speeds near the horizontal plane between the top and bottom fans at $z = 0.305$ m, corresponding to $z = 2.44$ m in the preliminary full-scale WoW configuration, for which similar wind speed deficits were observed (see Fig. 2b). Also, the velocity profiles differed between $y = 0.457$ m and $y = 0.229$ m; similar differences were observed in the preliminary full-scale WoW configuration (see Fig. 2b).

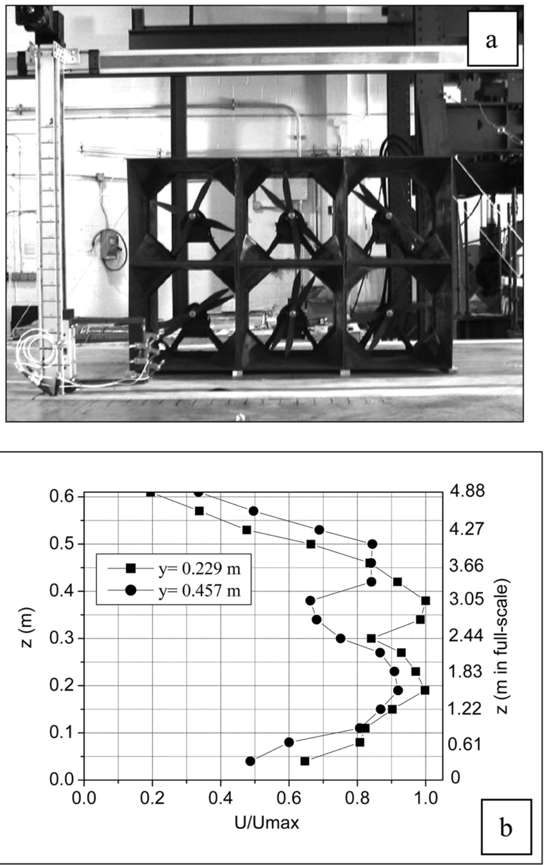

Fig. 4 Preliminary small-scale (1:8) WoW: (a) Preliminary baseline configuration, (b) Non-dimensional velocity profiles at y = 0.229 m and y = 0.457 m

Fig. 4b suggested the following problems: (1) diffusers were creating compartmentalization of the flow causing velocity deficit between top and bottom diffusers; (2) an ABL profile was not generated, as higher wind speeds occurred at the mid-levels of the top and bottom fans. To address these issues, a new model was built, replacing the six diffusers with a single contraction all around the 6-fan system. To enhance the air intake by the WoW fan system, an outer frame was installed outside the WoW model. The outer frame maintained a uniform gap (0.051 m) all around the fan propellers. These modifications reduced the variations between wind profiles measured at different locations in the wind field but resulted in lower wind speeds close to the contraction walls. To increase the wind speed at the sides, differential rpm was tested for the middle and side fans, and improved results were achieved by running the left and right side fans at 27% and middle two fans at 25% of full throttle power.

4.2. Application of inclined horizontal plates to improve the mean wind speed profile

The fans were raised by h = 0.051 m with respect to the ground level to create flow deficiency closer to the ground surface. This allowed producing a speed gradient at the bottom of the model, simulating an ABL-like flow. Phillips, *et al.* (1999) applied an array of differentially-spaced flat

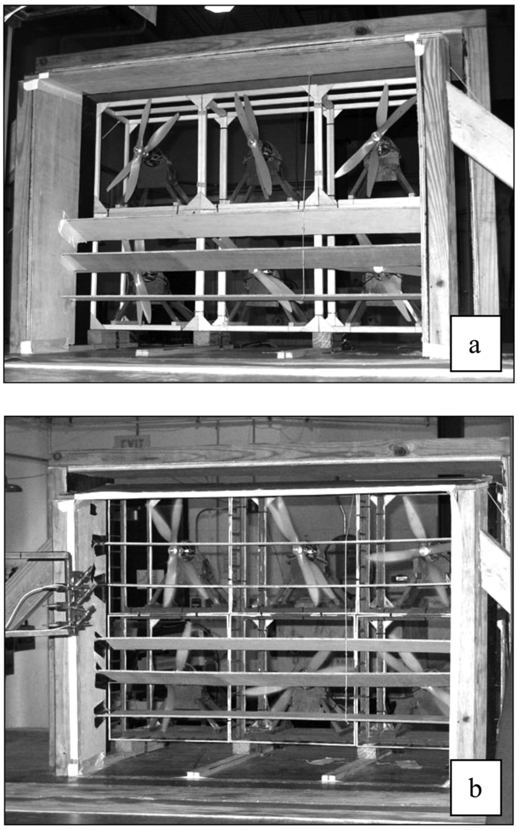

Fig. 5 Revised baselines of small-scale WoW: (a) *Revised baseline 1* with three plates, (b) *Revised baseline 2* with five plates

plates (at zero incidence) to modify a uniform wind tunnel velocity field to a specific velocity profile. For the current testing, flat plates were used for ABL generation, but instead of zero incidences different inclinations were tested. To increase the wind speed with increasing height and generate an ABL-like flow, 3 horizontal plates (Fig. 5a), each measuring 0.114 m wide, were used to redirect the flow from the bottom fans to the top. A series of experiments were carried out to optimize the locations and inclinations of the plates. The optimal configuration was determined when the plates were located at the heights of 0.127, 0.221 and 0.297 m, with the inclinations of -0.5^o (pointing down), 17^o (pointing up) and 17^o (pointing up), respectively. The above-mentioned configuration is called the *revised baseline 1* (Fig. 5a). The best fitting exponents α at lines of $y = 0.229$ and 0.457 m were 1/4.63 and 1/3.28, respectively.

To further improve the flow, two additional plates were installed in the upper area. A series of combinations of plate locations and angles were tried to produce the target flow. The configuration with 5 planks (-0.5^o, 17^o, 17^o, 0^o and 0^o inclination with centers at $z = 0.127$, 0.221, 0.297, 0.434 and 0.531 m) was referred as the *revised baseline 2* (Fig. 5b). The non-dimensional mean velocity profiles and the best fitting profiles of the *revised baseline 2* are shown in Fig. 6. The fitting exponents α at lines $y = 0.229$ and 0.457 m were 1/3.89 and 1/3.35, respectively, being close to the suburban terrain value of 1/4.0 as given in ASCE 7-05 (see Section 2.2).

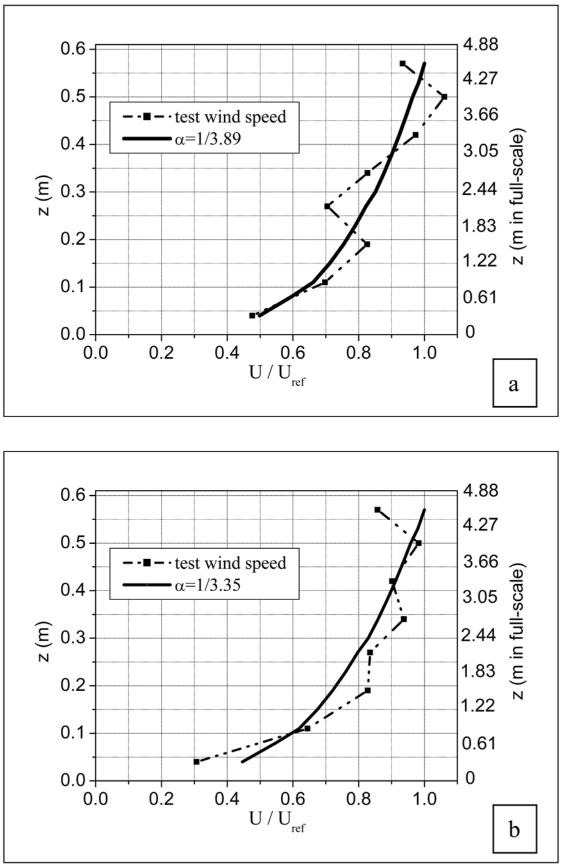

Fig. 6. Non-dimensional velocity profiles of small-scale WoW (*Revised baseline 2*): (a) Profile at y = 0.229 m, (b) Profile at y = 0.457 m

4.3. Influence of other parameters

Grid generated turbulence characteristics were discussed by Mikhailova, *et al*. (2001). For the small-scale WoW, turbulence intensities were measured at several heights. The turbulence intensities measured at a height equivalent to the full-scale roof eave height of a single story building were lower than those given in ASCE7-05 for open and suburban terrains. To increase the turbulence, especially close to the height equivalent to the full-scale roof height of a single story building, two grids were installed separately and tested: (1) a 0.003 m diameter plastic bi-directional grid with 0.031 m opening; (2) a 0.006 m diameter wood dowel vertical grid with 0.032 m opening. Installing the grids did not enhance the turbulence characteristics at the equivalent full-scale roof eave height.

As stated earlier, the fans were raised above the ground to create a flow deficiency closer to the ground, which made it possible to produce a wind speed gradient at the bottom of the model similar to an ABL-like flow. In addition to testing with $h = 0.051$ m, two other cases were tested in which the fans were raised by $h = 0.025$ m and $h = 0.013$ m, respectively, where h denotes the raised height of the fans with respect to the ground. Comparing the results it was determined that the best configuration to achieve an ABL-like flow field as well as horizontal uniformity was $h = 0.051$ m.

Variation of rpm between the top set and the bottom set of fans could influence the shear layer and the α values. Experiments were performed to study the influence of differential rpm (between top and bottom sets of fans) on α values. The wind field was measured when the top 3 fans were running steadily at 27%, 25% and 27% and the bottom 3 fans at 29%, 27% and 29% of full throttle power, respectively. Compared to the case with all side and middle fans running at 27% and 25% of full power, respectively, the trial test with the bottom 3 fans running at higher rpm than the top 3 fans deteriorated the fitting α-s of the mean speed profiles. Therefore, the variation of rpm between top and bottom fans was not deemed to be suitable.

4.4. Application of quasi-periodic waveform signals

Based on the above mentioned test results, the two configurations, *revised baselines 1 and 2* ($h = 0.051$ m, side and middle fans running at 27% and 25% of full power, respectively, and no grids), were selected as the optimal configurations for generating reasonable ABL-like mean wind speed profiles. Fig. 7 presents the longitudinal power spectral density plots for the FCMP flow and the scaled small-scale WoW flow at the height $z = 0.419$ m and $y = 0.457$ m.

As shown by Table 1 and Fig. 3, the turbulent intensities and gust factors for the small-scale and full-scale WoW were lower than those for the FCMP. According to Figs. 3 and 7, the WoW system, while generating reasonable high frequency longitudinal velocity fluctuations, did not generate components with frequencies of less than approximately 0.2 Hz. Thus an alternative technique, different from the mere application of passive flow simulation devices (such as grids), was required to simulate turbulence parameters of tropical cyclone winds, including turbulence intensity, power spectral density, and gust factor.

Transient flow field characteristics have been simulated actively in small-scale laboratory experiments by utilizing multiple-fan array systems driven by AC servomotors, each fan being individually computer controlled to generate flow features that can be easily modified and adjusted (Ozono, *et al.* 2006). In these multiple-fan systems sharp changes in gust magnitudes were successfully simulated. Methods already proven for gust and turbulence generation for other small scale experiments could be applied for the generation of turbulence and gust effects for the WoW. Variation of the fan engine speed achieved by servo-control through multiple sinusoidal control

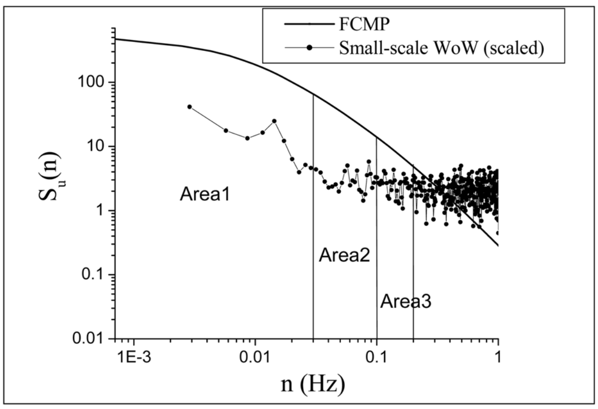

Fig. 7 Longitudinal power spectral density plots (FCMP vs small-scale WoW)

functions would help to simulate turbulence by adding low frequency fluctuations. To apply this concept, combinations of low-frequency quasi-periodic waveform signals were designed based on real tropical cyclone data (FCMP). The signals were used to control the rotational speed of the fans in the small-scale WoW and thus improve the turbulence intensities, the power spectral densities, and the gust factors.

4.4.1. Design of quasi-periodic waveform signals

According to Rice (1954), an approximate representation of a Gaussian process $G(t)$ with zero mean, unit variance, and one-sided spectral density $\Phi(\omega)$ is

$$G_N(t) = \sum_{k=1}^{N} a_k \cos(\omega_k t + \theta_k) \quad (7)$$

$$a_k = [2\Phi(\omega_k)\Delta\omega/(2\pi)]^{1/2} \quad (8)$$

where a_k is the amplitude, θ_k are random uniformly distributed phase angles over the interval $[0, 2\pi]$, $\omega_k = k\,\Delta\omega$, $\Delta\omega = \omega_{cut}/N$, and ω_{cut} is the cutoff frequency beyond which the ordinates Φ of the spectrum is neglected. Note that the spectrum $\Phi(\omega)$ is defined so that its integral over ω equals the variance of the signal, and that the circular frequency is $\omega = 2\pi n$. Eq. (7) is used to design the waveform signals.

A MatLab program was developed to generate the waveform signals. The inputs for the program were a target power spectral density, number of sinusoidal signals to be generated, and the frequency intervals within the power spectral density plot up to a cutoff frequency. The program outputs were the frequencies, amplitudes and random phase angles for the sinusoidal signals. The summation of individual sinusoidal signals resulted in the quasi-periodic waveform used to generate by servo control non-uniform rotational speeds of the fans. The goal was to develop a flow which possessed low-frequency fluctuations approximately matching the area under the target power spectral density up to the cutoff frequency.

In this simulation, the cutoff frequency for the target FCMP power spectral density was set as 0.2 Hz. The power spectral density was divided into three areas having intervals 0-0.03 Hz, 0.03-0.1 Hz, and 0.1-0.2 Hz, respectively (see Fig. 7). Three sinusoidal signals were generated with frequencies of 0.015, 0.065, and 0.15 Hz, corresponding to the mid-point frequency for each area. After obtaining the area for each interval, the MatLab program derived the amplitude a_k of the corresponding sinusoidal fluctuation by using Eq. (8). The amplitude ratio was equal to a_k divided by the FCMP mean wind speed. The three amplitude ratios thus obtained were used to generate the fluctuating signals to be applied to the small-scale WoW. The mean values of the fluctuating signals for the side fans and the middle fans were also set as 27% and 25% of full throttle power, respectively. Two fluctuating waveforms were created and used in the small-scale WoW. The waveforms W1 and W2 were created by only using one sinusoidal signal and by combining three sinusoidal signals, respectively (see Table 2).

4.4.2. Results of using fluctuating waveforms

The tests were carried out using the small-scale WoW configuration *revised baseline 2* (see Fig. 5b). Profiles were measured at various horizontal distances from the edge. The elevations of the measurement points were 0.038, 0.114, 0.191, …, and 0.572 m. The record length was 180 s for each point, and the sampling frequency was 100 Hz.

Table 2 Waveforms in Small-Scale WoW

Waveform case	FCMP frequency (to be simulated)	Frequency in small-scale WoW $C_f = 3.4{:}1$	Amplitude ratio	Start phase
W1	$n_1 = 0.015$ Hz	0.051 Hz	28.6%	0°
W2	$n_1 = 0.015$ Hz	0.051 Hz	28.6%	160.1°
	$n_2 = 0.065$ Hz	0.221 Hz	18.4%	221.6°
	$n_3 = 0.150$ Hz	0.510 Hz	11.7%	285.1°

The use of sinusoidal and quasi-periodic waveform signals resulted in the small-scale WoW flow characteristics (including longitudinal turbulence intensities (TI_u), gust factors (GF), power spectra (PSD), and integral length scale (L_u^x)) shown in Fig. 8 and Table 3 for z = 0.42 m of the center line. Fig. 8 and Table 3 show that the application of waveforms consisting of quasi-periodic sums of sinusoidal signals could significantly influence and improve the turbulence characteristics. The turbulence intensity values for W1 (sinusoidal signal) and W2 (quasi-periodic signal) were 28.3% and 34.3%, respectively, significantly higher than the flat waveform value of 14.1%. Also, the gust factors GF (3 min, 3-sec) for W1 and W2 were 1.34 and 1.41, respectively, significantly higher than value of 1.08 for the flat waveform, and comparable to the gust factors GF (3 min, 3-sec) of 1.33 and 1.37 for ASCE and FCMP, respectively.

After observing the potential gains obtained with the waveform approach, investigations were made to achieve reasonable flow characteristics using the quasi-periodic waveforms without the application of the inclined horizontal plates. Though reasonable turbulence characteristics were still achieved, the mean wind profile was disrupted. This suggested the use of the inclined horizontal plates for simulating profiles reasonably representing the atmospheric boundary layer.

The next section describes how the knowledge gained from the small-scale WoW was used to enhance the mean and turbulence characteristics of the full-scale WoW wind field parameters. *Revised baseline 2* with quasi-periodic waveform signals was chosen for the modifications, since it resulted in reasonable ABL-like flows with (a) more horizontal uniformity than *revised baseline 1*, and (b) reasonable turbulence parameters. Studies of the vertical turbulence at the full-scale WoW were also performed.

5. Full-scale Wall of Wind (WoW)

Based on the test results for the small-scale WoW, passive devices (e.g., outer frame, contraction, and inclined horizontal plates), and active control (quasi-periodic sums of sinusoidal signals designed on the basis of real tropical cyclone data analyses), were used to improve the mean and turbulence characteristics of the full-scale WoW flow. All the devices as well as the quasi-periodic waveforms were designed using the scaling parameters between the small-scale and full-scale WoW. The full-scale 6-fan WoW was raised 0.41 m above the ground. The diffusers were replaced with the contraction and outer frame. Five plates (-0.5°, 17°, 17°, 0° and 0° inclination) were placed inside the contraction, replicating the *revised baseline 2* configuration for the small-scale WoW. The revised configuration of the full-scale WoW is shown in Fig. 9. All the tests were carried out with the rpm ratio of side fans to middle fans of 1.08 (i.e., 27%/25%).

For the revised configuration, mean velocity profiles were measured at various locations defined

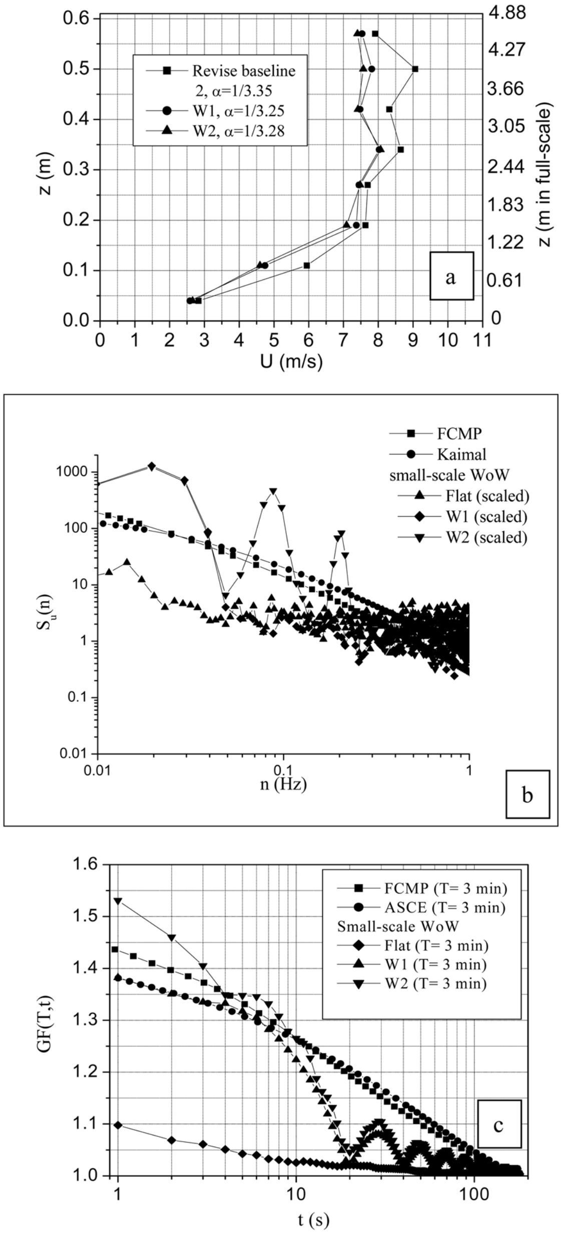

Fig. 8 Wind characteristics for revised small-scale WoW (*Revised baseline 2*): (a) Mean velocity profile; (b) PSD at z = 0.42 m; (c) GF at z = 0.42 m

by their y values. The non-dimensional mean velocity profiles at y = 1.22, 3.66, and 4.27 m, and the best fitting profiles are shown in Fig. 10. For the revised configuration, the fitting exponents α at lines of y = 1.22, 3.66, and 4.27 m were 1/3.30, 1/3.97 and 1/3.50, respectively, being close to the suburban terrain value of 1/4.0 as given in ASCE 7-05. As indicated by Figs. 2b and 10, the profiles generated with the revised WoW configuration show significant improvements over those generated by the preliminary configuration with respect to the uniformity of the flow field and the

Table 3 Small-Scale WoW Characteristics

Waveform	Mean wind speed (m/s)	Turbulence Intensity (TI_u) (%)	Gust Factor GF(T,t)	Integral Length Scale, L_u^x (m)
Flat	8.3	14.1	*GF*(7.5min, 3sec) = 1.08	1.3
W1	7.7	28.3	*GF*(3min, 3sec) = 1.34	16.7
W2	7.5	34.3	*GF*(3min, 3sec) = 1.41	12.4

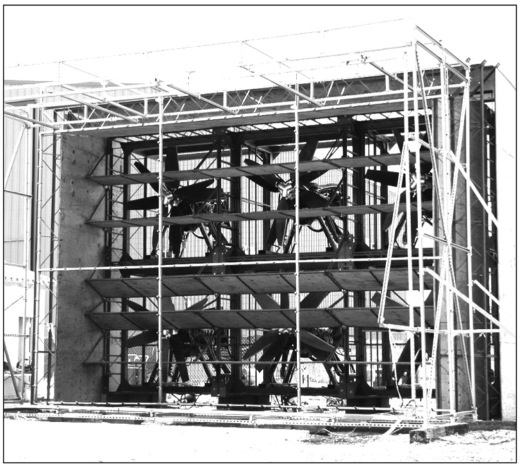

Fig. 9 Full-scale 6-fan WoW (Revised configuration)

ABL-like flow profiles.

To add low-frequency quasi-periodic components to the WoW flow, the fluctuating waveform signals were applied to the fans through servo control mechanisms. Based on the approach described in Section 4.4, two new waveforms W3 (sinusoidal signal) and W4 (quasi-periodic signal) for full-scale WoW were created using scaling parameters. The mean rpm of the side fans was set as 3,500 for waveform W3 and 2,855 for waveform W4, respectively. This was done for safety reasons to prevent the peak rpm of the fans from exceeding 4,000 following the application of quasi-periodic waveforms to WoW engines. The 4000 rpm limit of the fans' rpm (as opposed to 4500 rpm for uniform fan rotation) was warranted because quasi-periodic fan rotations affected the engines more severely than uniform rotations did. Three waveforms were tested – flat waveform (4000 rpm), W3, and W4 – and wind data was collected for various locations (i.e., for various y values). For each location, the measurement points were located at heights z = 1.07, 1.52, 1.98, …, and 4.27 m. All the tests were carried out with a 1.08 rpm ratio of side fans to middle fans. The record length was 360 s at each point, and the sampling frequency was 10 Hz.

For the revised WoW configuration, the mean wind speed and peak 3-sec gust, and the corresponding longitudinal turbulence intensity (TI_u), longitudinal integral length scale (L_u^x) and gust factor (GF) at the center line (y = 3.66 m) and height 3.35 m (close to the average roof eave for typical low-rise residential buildings), are listed in Table 4. Comparisons with FCMP and preliminary WoW values are also presented in Table 4. The comparisons clearly show that significant improvements were achieved by the revised WoW configuration with W4 (quasi-

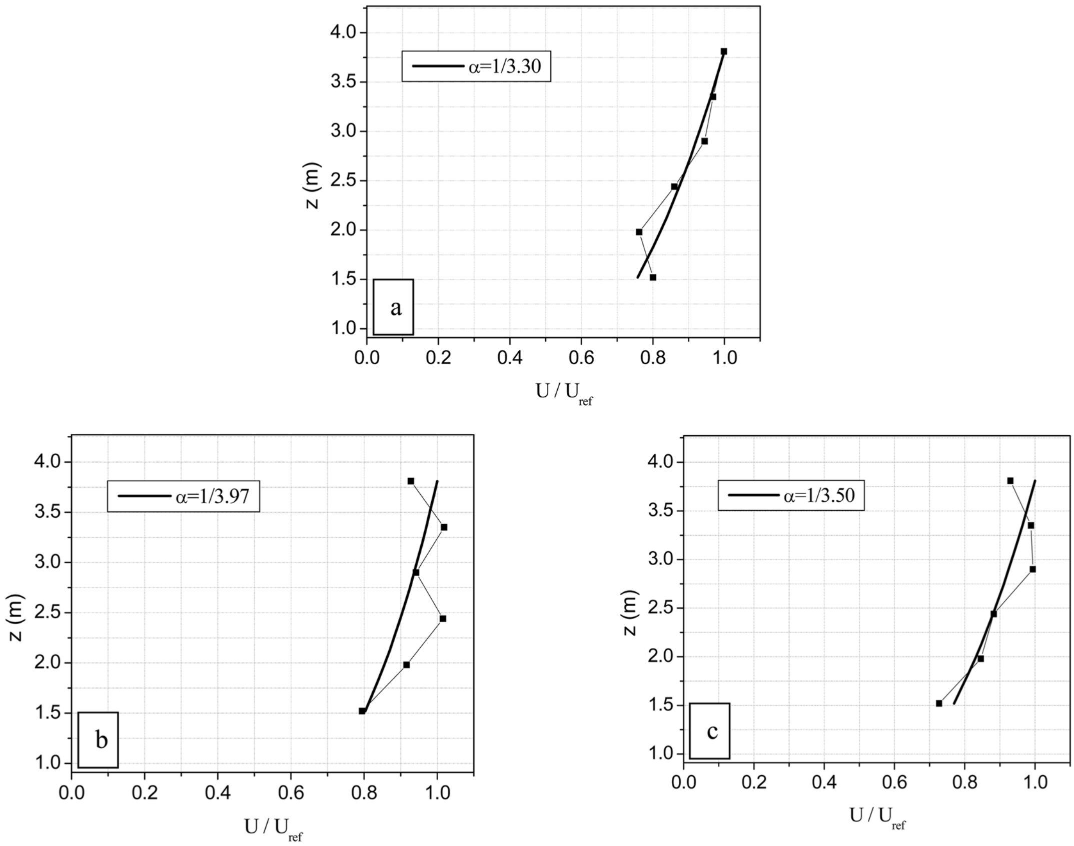

Fig. 10 Non-dimensional mean velocity profiles (Revised full-scale WoW): (a) at y = 1.22 m, (b) at y = 3.66 m, (c) at y = 4.27 m

periodic) waveform with respect to the turbulence intensity, gust factor, and integral length scale, whose values were comparable with the FCMP tropical cyclone wind values. As the mean rpm for a fluctuating waveform was lower than that for the flat waveform, the mean wind speed was reduced when using W3 and W4 waveforms as compared to the case of the flat waveform. However, the peak 3-sec gusts for the flat (4000 rpm), W3, and W4 waveforms were 38.2 m/s, 41.8 m/s, and 38.3 m/s, respectively (Table 4), that is, they were comparable in the three cases.

The Saffir-Simpson scale is defined in the Commentary to the ASCE 7-05 Standard in terms of sustained (1-min) speeds over water. According to Simiu, *et al.* (2007), Category 1 hurricanes on the Saffir-Simpson scale correspond to approximately 1.07×33.1 m/s $= 35.4$ m/s peak 3-s gust speed at 10 m above open terrain. Thus, for all the current testing with the revised full-scale WoW configuration, the wind speeds corresponded to Category 1 hurricane conditions. To produce more severe hurricanes, additional research is currently being performed. The goal is to achieve the requisite turbulence generation in the WoW while maintaining the mean rpm between 4,000 to 4,500 by redesigning the fan engines.

Longitudinal and vertical turbulence intensities (TI_u and TI_w, respectively) with flat and fluctuating waveforms at the revised WoW configuration center line (y = 3.66 m) are plotted in Fig. 11. In the longitudinal direction, the turbulence intensity values increased significantly with the application of

Table 4 Comparison of Wind characteristics of Full-Scale WoW (Revised Configuration)

Case (Waveform; mean rpm)	Wind speed (m/s)	TI_u (%)	TI_w (%)	GF(T,t)	L_u^x (m)
Revised WoW (Flat waveform; 4,000)	36.7 (1-min mean speed) 38.2 (3-sec peak gust)	4.6	5.4	*GF*(6min, 3sec) = 1.06 *GF*(1min, 3sec) = 1.04	36.6
Revised WoW (W3 sinusoidal waveform; 3,500)	33.7 (1-min mean speed) 41.8 (3-sec peak gust)	19.9	6.7	*GF*(6min, 3sec) = 1.33 *GF*(1min, 3sec) = 1.24	134.7
Revised WoW (W4 quasi-periodic waveform; 2,855)	28.8 (1-min mean speed) 38.3 (3-sec peak gust)	23.8	7.1	*GF*(6min, 3sec) = 1.42 *GF*(1min, 3sec) = 1.33	89.9
Preliminary WoW (Flat waveform; 4,000)	36.3 (1-min mean speed) 38.5 (3-sec peak gust)	6.0	-	*GF*(6min, 3sec) = 1.09 *GF*(1min, 3sec) = 1.06	59.6
FCMP*	22.3 (1-min mean speed) 28.3 (3-sec peak gust)	17.8	7.0	*GF*(1min, 3sec) = 1.27 *GF*(6min, 3sec) = 1.43 *GF*(1*hr*, 3sec) = 1.59	98.7

* Mean results of three observation sites (Ivan- 1, Ivan- 2, and Lili) at which data were collected by Florida Coastal Monitoring Program (FCMP).

the fluctuating waveform W4. The estimated turbulence intensity value at 3.0 m height (the average roof eave height for typical low-rise residential buildings) was approximately 23.0%, comparable to the FCMP turbulence intensity value of 17.8% (Table 4) and significantly higher than $TI_u = 6.0\%$ measured for the preliminary WoW configuration (Table 4). In the authors' opinion, the fact that the longitudinal turbulence intensity exceeds the FCMP value for open terrain is an indication that the turbulence achieved in the WoW is representative of flow over terrain that is somewhat rougher than typical open terrain. For the revised WoW configuration, the vertical turbulence intensity of 7.1% matches very well the value of 7.0% measured for FCMP (Yu 2007).

For the revised WoW configuration, the longitudinal and vertical power spectral densities at y = 3.66 m and z = 3.35 m, and a comparison with the FCMP, the revised Kaimal, and the Panofsky models are shown in Fig. 12. Fig. 12a shows that the non-uniform rotational speeds of the fans induced by servo control resulted in a flow for which the low-frequency fluctuations and the area under the spectral curve were approximately equal to those of the target FCMP spectral curve. The spectral distribution of the low-frequency fluctuating components in the flow differs, however, from the monotonically decreasing spectral curve of the FCMP flow. This difference can be reduced by using non-uniform rotational speeds of the fans that, instead of consisting of a superposition of a three-component quasi-periodic signal, contain more than three harmonic components. The objective of the tests reported in this paper was limited to showing that the application of quasi-periodic waveforms can significantly influence and improve the turbulence characteristics.

Also, although the fluctuating waveforms were primarily designed to influence the longitudinal

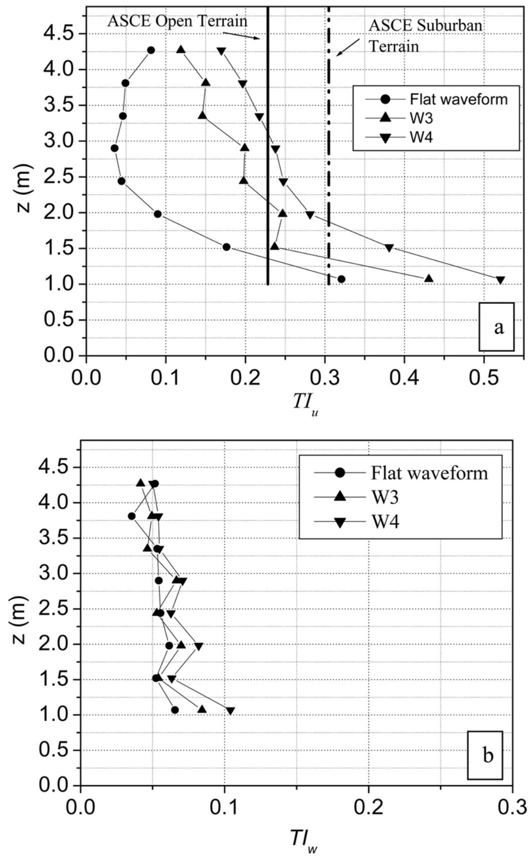

Fig. 11 Turbulence intensity profiles (Revised full-scale WoW) at y = 3.66 m: (a) Longitudinal turbulence intensity (TI_u), (b) Vertical turbulence intensity (TI_w)

turbulence in the WoW, such waveforms enhanced the vertical turbulence spectra by adding missing low-frequency as well as high frequency content. Fig. 12b shows that, compared to the flat waveform, W4 achieved reasonable simulation of the FCMP vertical fluctuations. This increased the vertical turbulence intensity, which compares well with the 7.0% value measured for FCMP (Yu 2007). If further improvement is deemed necessary regarding the modeling of vertical turbulence, future research will consider the design of oscillating horizontal airfoils as used in wind tunnel applications (Nishi, *et al.* 1997).

Fig. 13 presents the gust factors for the revised WoW (at y = 3.66 m, z = 3.35 m) and a comparison with FCMP and ASCE (Durst 1960) models plotted for T= 6 min. The 3-sec gust factor values for WoW were GF (6 min, 3-sec) = 1.33 and 1.42 for W3 and W4, respectively. These values were significantly higher than the preliminary WoW value of GF (6 min, 3-sec) = 1.09 and were comparable to the corresponding GF (6 min, 3-sec) values of 1.39 and 1.43 for ASCE and FCMP, respectively. Thus the W4 waveform achieved realistic gust effects close to those for real tropical cyclone winds.

It is emphasized that the above results are viewed as only a first step toward achieving better flow simulations. The results suggest, however, that flow simulation techniques applied to the full-scale WoW promise to achieve realistic tropical cyclone wind characteristics, although additional work is in our opinion required to develop additional devices and methodologies for a variety of applications.

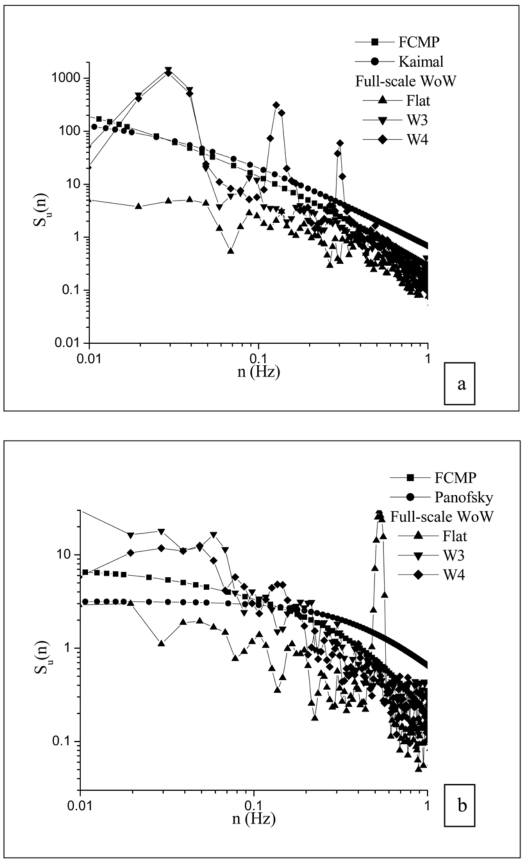

Fig. 12 Power spectral densities for revised full-scale WoW (z = 3.35 m, y = 3.66 m): (a) Longitudinal power spectral density plots, (b) Vertical power spectral density plots

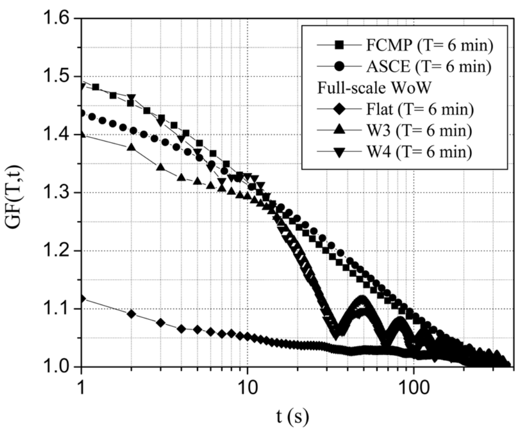

Fig. 13 Gust factors for revised full-scale WoW (z = 3.35 m, y = 3.66 m)

Such research and development work is currently being pursued at the WoW facility. Also, further research needs to be performed toward multi-plane flow characterization and control at various distances away from the fans. A multi-plane study is necessary to evaluate the characteristics of the flow surrounding the test structure. Such characterization is necessary for, among other purposes, flow separation and reattachment studies. An initial computational fluid dynamics study has been performed to evaluate the wind field size of the WoW required to achieve reasonable test results for models of various sizes (Bitsuamlak, *et al*. 2008). The study will be expanded to help better understand the wind field size and depth requirements, and will guide future research to characterize and control the WoW flow.

6. Wall of Wind (WoW) research goals

Wall of Wind (WoW) full-scale testing consistent with the capabilities of the apparatus, complemented by wind tunnel and existing full-scale methods and analytical/numerical tools, will provide data needed to perform wind-structure interaction studies and to develop damage mitigation techniques for low-rise structures. Research work performed using the WoW included rooftop equipment damage mitigation, vortex suppression testing, and secondary water barrier evaluation. These tests, as described below, were mostly governed by the flow around the windward corner or edge of the roof, with little influence due to the depth of the flow field. However, research will be further pursued on the development of flows with spatial characteristics allowing the realistic simulation of wind-structure interactions for typical residential homes.

Rooftop equipment failures pose significant threats during tropical cyclones because: (1) detached equipment may result in puncturing of the roof membrane, thus weakening the roof; (2) disconnected rooftop equipment may leave large openings in the roof, allowing the possibility of water infiltration; and (3) detached rooftop equipment can pose considerable threats as high momentum windborne debris (Reinhold 2006). WoW experiments were performed to measure the wind loads exerted on full scale rooftop equipment specimens, and to develop mitigation techniques that would alleviate severe rooftop equipment wind loads (Gan Chowdhury and Erwin 2008). A test building was outfitted with air conditioning condenser units at the edge of the roof (Fig. 14a), which were instrumented with force transducers to measure the aerodynamic loading effects. Wind screens placed around the rooftop equipment were found to effectively alleviate the aerodynamic loading effects. The results demonstrated the effectiveness of wind screens as a retrofit method to reduce the damage of roof top equipment and secondary losses.

Widespread damage to roofs in hurricanes and other high wind events has highlighted the need for improving the wind performance of roofs, including both new construction and retrofit on existing buildings. Effective and economical methods to mitigate wind effects on roof components are sought to reduce accumulated losses from frequently recurring low- and moderate-intensity events. An experimental study was carried out in the 6-fan WoW to assess the effectiveness of aerodynamic edge devices at full scale in reducing wind effects over the roof corner and edge regions (Lin, *et al.* 2008). Two sets of tests, roof gravel scour testing (Fig. 14b) and pressure testing, were carried out to visualize the development of edge vortices and compare roof uplift pressures with and without aerodynamic edge shapes. The tests allowed the estimation of the effects of such shapes in alleviating wind damage of roofing material as well as high uplift pressures on roofs. The research demonstrated the potential for substantial reduction of roof uplift pressures through the development and application of mitigation techniques to lessen or prevent hurricane-induced damage to new and existing roofs.

The WoW apparatus was used to develop a full-scale wind-driven rain test methodology allowing the assessment of roof secondary water barrier effectiveness in preventing wind-driven rain intrusions (Sambare,

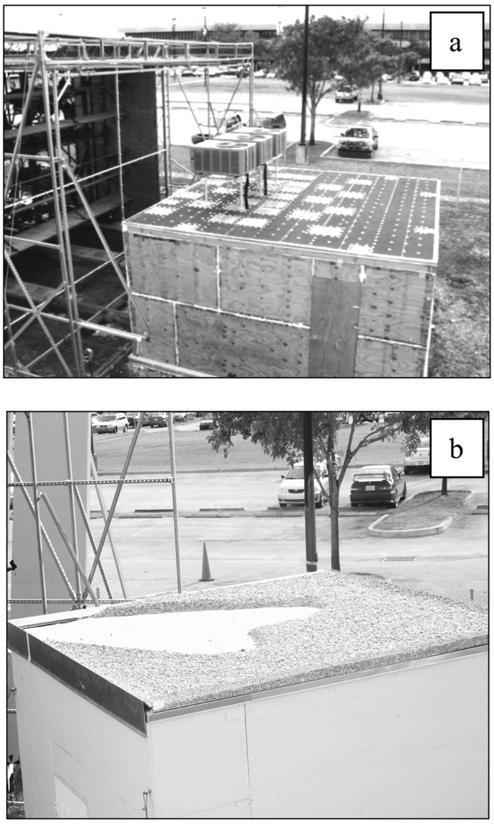

Fig. 14 Testing with full-scale WoW: (a) Rooftop equipment testing, (b) Gravel scour with standard fascia

et al. 2008). Six different secondary water barriers for roofs were investigated. Amounts of water intruded through secondary water barriers were measured and used as an index to their respective performances. More water intrusion was noticed for light water barriers than for heavy ones, for which the amount of water intrusion was low. No water intrusion was observed for self-adhering heavy secondary water barriers. The tests showed that the amount of water intrusion was reduced as the roof slope increased.

Further research on hurricane damage study and mitigation techniques will be performed based on the capabilities and limitations of the WoW apparatus as evaluated through multi-plane flow characterization at various distances away from the fans. The limitations of the apparatus include the limited spatial extent of the flow, which will not permit simulation of realistic wind-structure interaction for structures with large horizontal dimensions.

This limitation means that realistic debris trajectories such as occur in actual hurricanes cannot be produced by the WoW flows. However, effects of debris impact in strong winds and rain can be simulated by using a debris-propelling gun in conjunction with WoW wind flow and artificial rain. Studies by Holmes (2004), Lin, *et al.* (2007) will help to determine parameters for debris impact simulations.

7. Summary and conclusions

Catastrophic loss due to hurricanes is the largest and most pervasive risk faced by the Atlantic and

Gulf Coast states in the U.S. The economic viability of the state of Florida and other Atlantic and Gulf Coast states depends upon hurricane damage mitigation. Wall of Wind (WoW) full-scale testing, complemented by wind tunnel and existing full-scale methods and analytical tools, is anticipated to perform a wide range of wind-structure interaction studies within the capabilities of the apparatus. This will help in the development of damage mitigation techniques for low-rise structures within an economic budget.

The accuracy of the WoW full-scale testing facility and its success in helping to understand wind-structure interaction and mitigating hurricane effects will depend on the generation of wind fields with mean and turbulence characteristics that reasonably resemble those of real tropical cyclone and hurricane winds. The preliminary full-scale WoW configuration was capable of generating high wind speeds but could not generate reasonable mean and turbulence characteristics at those speeds.

In view of the deficiencies of the preliminary WoW system an investigation was undertaken using a small-scale (1:8) WoW model to develop the target wind flow generating devices and methods efficiently. The mean and turbulence characteristics of the flow were improved markedly through the application of passive devices and of active controls designed on the basis of analyses of tropical cyclone wind data. The knowledge gained from the small-scale WoW was used to enhance the full-scale WoW wind field parameters.

In the revised full-scale WoW configuration, it was possible to generate reasonable mean wind speed profiles and turbulence characteristics for winds with peak 3-sec gusts corresponding to Category 1 hurricanes. To produce more severe hurricanes, additional research is currently being performed on redesigning the WoW fan engines, so that high mean rpm be maintained while adequate turbulence generation is achieved.

Just as in the small-scale WoW, the results in full-scale WoW show that the application of fluctuating waveforms can greatly influence and improve the turbulence characteristics. Application of quasi-periodic sums of sinusoidal signals, designed on the basis of real tropical cyclone wind data analyses, succeeded in adding low-frequency quasi-periodic components to the WoW flow and improving the longitudinal power spectral densities, turbulence intensities, integral length scales, and gust factors. The application of quasi-periodic signals also improved the vertical turbulence for the revised full-scale WoW configuration. If further improvement is deemed necessary regarding the modeling of vertical turbulence, future research will consider the design of oscillating horizontal airfoils as used in wind tunnel applications.

The success achieved in enhancing full-scale WoW performance on the basis of results obtained in the small-scale WoW shows that the use of the small-scale model for this research can be warranted. It is emphasized that the research work and the results reported in this paper are viewed as only a first, but important step toward achieving a wide range of flow simulations. The results show that flow simulation techniques as applied to the full-scale WoW can achieve realistic tropical cyclone wind characteristics. Additional improvements in flow simulation techniques are nevertheless required. FIU is currently engaged in a vigorous research and development effort aimed at achieving further progress in generating realistic flow simulations for various applications.

Further research on hurricane damage study and mitigation techniques will be performed by accounting for the capabilities and limitations of the WoW apparatus. The limitations of the apparatus include the finite wind field size, which will determine restrictions on model sizes. Multi-plane flow characterization and control will be performed for various distances away from the fans. Current research activities will be further pursued to achieve such multi-plane flow characterization and control.

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