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Wind profile management and blockage assessment for a new 12-fan Wall of Wind facility at FIU

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Abstract. Researchers at the International Hurricane Research Center (IHRC), Florida International University (FIU), are working in stages on the construction of a large state-of-the-art Wall of Wind (WoW) facility to support research in the area of Wind Engineering. In this paper, the challenges of simulating hurricane winds for the WoW are presented and investigated based on a scale model study. Three wind profiles were simulated using airfoils, and/or adjustable planks mechanism with and without grids. Evaluations of flow characteristics were performed in order to enhance the WoW's flow simulation capabilities. Characteristics of the simulated wind fields are compared to the results obtained from a study using computational fluid dynamics (CFD) and also validated via pressure measurements on small-scale models of the Silsoe cube building. Optimal scale of the test model and its optimal distance from the WoW contraction exit are determined – which are two important aspects for testing using an open jet facility such as the WoW. The main objective of this study is to further the understanding of the WoW capabilities and the characteristics of its test section by means of intensive tests and validations at small scale in order to apply this knowledge to the design of the full-scale WoW and for future wind engineering testing.

Keywords: Wall of Wind; atmospheric boundary layer; wind profile simulation; pressure coefficient; blockage.

1.Introduction

Hurricane winds compete with earthquakes as the dominant environmental loads for structures (Holmes 2001 Aly 2009). Globally, hurricanes cause enormous loss to life and property. The past decade has seen increased Atlantic hurricane activity and more than $150 billion of dollars in damage in 2004 and 2005 (Emanuel 2005, Pielke *et al*. 2008). There is a need for identifying more effective solutions for dealing with hurricane effects (National Science Board 2007). In addition to wind tunnel tests, full-scale testing and measurement of wind effects play an important role. In spite of recent advancements in computational fluid dynamics (CFD), wind tunnel simulation of scaled models is still the most common tool used to predict wind loading. To overcome scaling issues and enhance capabilities to conduct destructive testing under hurricane winds and rain, researchers at Florida International University (FIU) have developed a new open jet facility, the Wall of Wind

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(WoW). However, modeling proper hurricane wind characteristics for the facility is a big challenge. For example, unlike for flow in wind tunnels, the mean wind speed decreases along the flow direction. This requires testing the structures as close as possible to the fans exit. In addition, it is necessary to generate a wind flow with as large mean wind speed as possible to simulate destructive hurricane wind forces. For these reasons, wind field management for the facility requires techniques that are not necessarily similar to those in wind tunnels.

In 2003 the research team at the International Hurricane Research Center (IHRC) of FIU started planning a large-scale open jet type wind testing facility to produce an experimental data-base for better understanding of the effects of extreme winds on structures (Leatherman *et al*. 2007). The development of the WoW has been completed in stages, an incremental strategy that has enabled FIU researchers to gain experience in the development, testing, and operation of the facility, and helped reduce unnecessary expenses. With this vision, IHRC first developed a 2-fan WoW and then a 6-fan WoW (Fig. 1(a) shows the six-fan WoW) suitable for experimentation and destructive testing of large-scale, low-rise structures (Bitsuamlak *el al*. 2009, Gan Chowdhury *et al*. 2009, Gan Chowdhury *et al*. 2010). However, the maximum wind speed produced by the 2-fan and 6-fan WoW was lower than what is required for some destructive tests. To allow for a better understanding of hurricane-induced effects on residential buildings and other structures through large-scale and destructive testing, a more efficient and more powerful 12-fan WoW is under construction.

The 12-fan WoW comprises of an array of twelve electric fans (Fig. 1(b) shows the electric fans) controlled by Variable Frequency Drives (VFD); this phase, supported by the State of Florida and Department of Energy (DOE), is expected to be completed by the middle of 2011. This phase of WoW is designed to generate sustained wind speed up to 63 m/s (Category 4 wind speed being 59-69 m/s).

This paper focuses on a preliminary evaluation of the performance of the full-scale (or prototype) 12-fan WoW by using a properly designed small-scale replica and examining experimentally the potential flow characteristics and comparing pressure measurement results for a scaled model of the Silsoe cube building with those available in the literature. The major objectives of this research are, first, to develop flow management devices for the wind field simulation for the new 12-fan WoW facility; and, second, to determine the optimal scale of the test model and its optimal distance from the WoW contraction exit to facilitate future WoW testing.

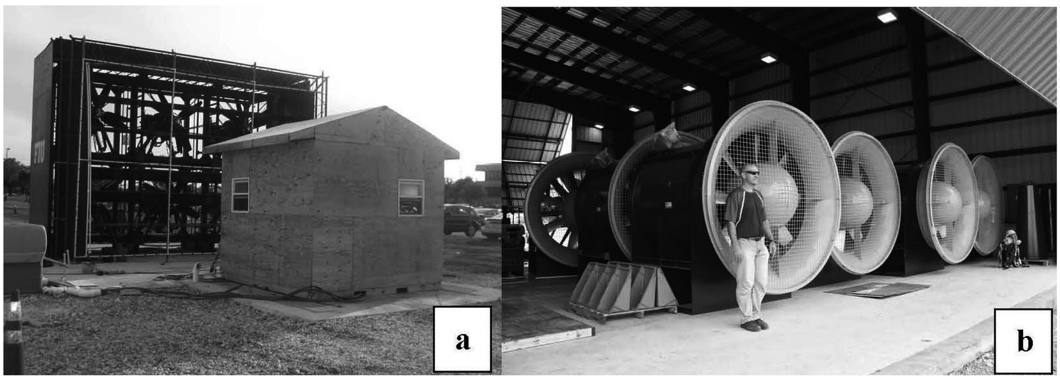


Fig. 1 (a) 6-fan WoW and (b) Fans for 12-fan WoW

2. Methodology

2.1 Computational fluid dynamics (CFD) simulations

Conceptual design of the new 12-WoW facility began with CFD modeling using the Large Eddy Simulation technique, performed in collaboration with RWDI, Inc (see Aly *et al*. 2011, 2010). The goals of the CFD study were to determine the number of fans required to produce the target wind speed (sustained wind speed up to 63 m/s), optimize the arrangement configuration of the fans, and develop the design of a contraction device capable of generating the target winds. The preliminary target air flow rate for the full-scale facility was determined to be 81552 m^3/min through the exit of the contraction, producing atmospheric boundary layer (ABL) type flows having sustained wind speed of approximately 63 m/s at a height of about 3 m above the test section floor. To achieve this target, twelve fans each having a flow rate of 6796 m^3/min were combined to generate an open jet WoW apparatus. Each fan will have a total pressure head of 3736 pascal (Pa) and will be driven by an electric motor of 522 kilowatt. Several arrangements of the fans, the contraction device, and flow straightening techniques were investigated:

a. Fan arrangement: 12 fans in a 3 high x 4 wide rectilinear arrangement; 12 fans in a 2 high x 6 wide rectilinear arrangement; 12 fans in a 2 high x 6 wide arc arrangement; 12 fans in a 2 high x 6 wide focused-arc arrangement;

b. Contraction device: a contraction with double-curvature geometry to minimize sharp corners; a short contraction with partial straight section;

c. Flow straightening techniques: vertical turning vanes having complex airfoil cross sections with uniform depths (dimension parallel to the streamlines); vertical turning vanes having thin plate cross sections with variable depths (depths gradually reducing from the edges to the center);

d. The height above the floor that the fans/contraction would be placed: Three heights were investigated – 0.6 m, 0.9 m, and 1.2 m. This height was to create some deficit in wind speed near the floor to simulate the near-surface wind speed retardation in ABL type flows due to surface roughness.

The CFD simulations were achieved with *OpenFOAM* (*OpenFOAM* 2010 used as a tool for mesh generation, solver, and post-process routines) and *ParaView* (*ParaView* 2010 used for mesh/boundary conditions verification, post-processing visualizations). The code is based on the finite volume method and supports any three-dimensional unstructured polyhedral mesh. Meshes can be generated directly by using available tools or can be imported from most other CFD software or mesh generators. The CFD domain including the WoW building (containing the 12-fan WoW) and the outside is shown in Fig. 2(a). All architectural and structural members of the WoW building, along with the hanging doors on both sides of the building, were simulated, making the simulations more aerodynamically consistent with the real-world facility. Fig. 2(b) shows the two different arrangements with vertical airfoils and turning vanes at the outlet of the contraction. More details are given in Aly *et al*. (2010). After various trials with the CFD simulations, an optimal arrangement of the 12-fan WoW facility was determined (shown in Figs. 2(c)-(d)), and consisted of the following: (a) 12 fans in a 2 high x 6 wide focused-arc arrangement; (b) a short contraction with partial straight section having final outlet dimensions of 3.6 m high x 6 m wide; (c) a set of variable depth full height thin-plate turning vanes; and (d) the outlet of the contraction positioned 0.6 m above the floor level.

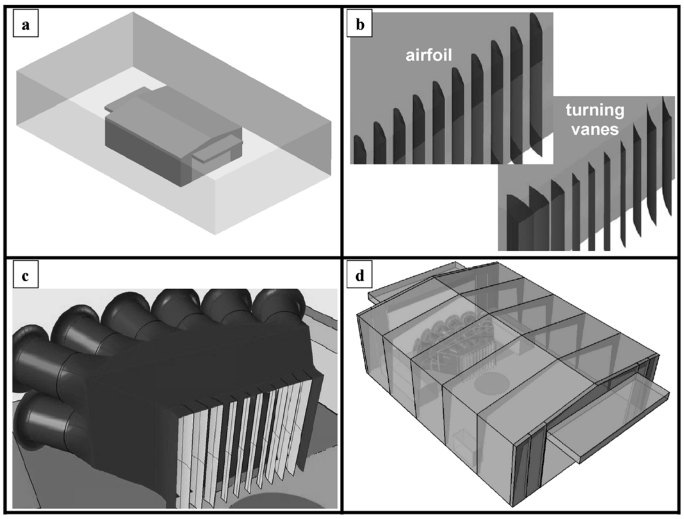
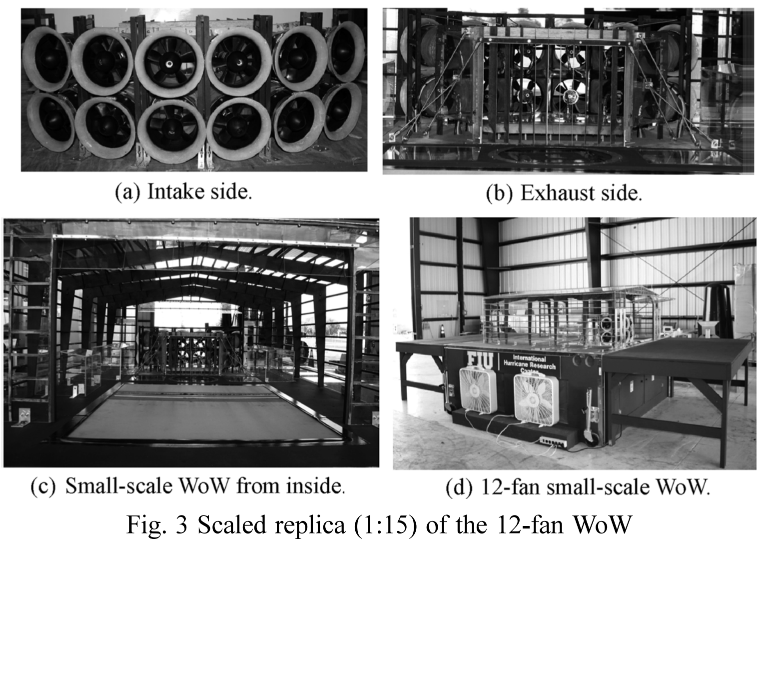


Fig. 2 Rendering of the 12-fan WoW testing facility: (a) Computational domain for CFD analysis, (b) Outlet of the contraction with two options of airfoils and turning vanes, (c) Close-up view of the contraction with turning vanes and (d) WoW building schematic.

2.2 Experimental scale model of the 12-fan WoW and instrumentation

Following the development of the basic configuration of the 12-fan WoW based on the CFD simulations, a small-scale replica (1:15) of the 12-fan facility with planks mechanism was built for developing flow management devices to generate target wind profiles and to determine the optimal scale of the test model and its optimal distance from the WoW contraction exit. By using the small-scale model, it was easier and faster to install and change the simulation devices and the cost of experiments was greatly reduced. The small scale model of 12-fan WoW is shown in Fig. 3.



(a) Intake side. (b) Exhaust side.

(c) Small-scale WoW from inside. (d) 12-fan small-scale WoW.

Fig. 3 Scaled replica (1:15) of the 12-fan WoW

Based on the CFD study, the replica model consists basically of 12-fans (selected based on scaling laws) arranged in an arc to produce a concentrated flow. The wind speed is further enhanced using a contraction device with vertical turning vanes at the outlet. A movable carriage (traverse system) helps to secure the wind speed measuring probes and measure wind speeds in grid-patterns across various planes from the contraction exit.

The carriage is powered by two electrical motors through two spur gear reduction mechanisms (gear ratio = 1:3) and two toothed belt drives. The small-scale 12-fan WoW is housed inside a 1:15 scale model building that replicates the full-scale building constructed for housing the prototype 12-fan WoW and protecting from environmental conditions (e.g., sun and rain). The building model was constructed using wood beams covered by polystyrene transparent sheets.

2.2.1 An easily adjustable planks mechanism

The mechanism consists basically of an external frame where horizontal steel planks are supported by hinges for ease of adjustment (Fig. 4). Two vertical threaded steel guides are used to help keep in place the planks at a certain pitch angle, and to help prevent across-wind oscillations. The pitch angle of each plank can be adjusted through the hinged supports and the vertical steel guides to simulate a wide range of atmospheric boundary layer (ABL) profiles. A total number of six steel planks were used. The number of planks as well as the distance between each two successive planks were determined based on achieving two purposes: reduce the deviations of the mean wind speed data points about the target profiles, keep the blockage produced by the planks as low as possible.

2.2.2 Cobra probes

The Cobra probe (from Turbulent Flow Instrumentation Pty Ltd, or TFI) has the capability to measure unsteady 3D velocity. The multi-hole pressure probe can capture the velocity variation within a high range of frequencies. The probe has a frequency response of up to 5000 Hz. In comparison to hot-wires, Cobra probe is robust and withstands moderate knocks and contaminated flow. Furthermore, the Cobra probe can provide flow mapping in test sections and around test objects.

Four Cobra probes arranged vertically as shown in Fig. 5 were used for wind velocity assessment.

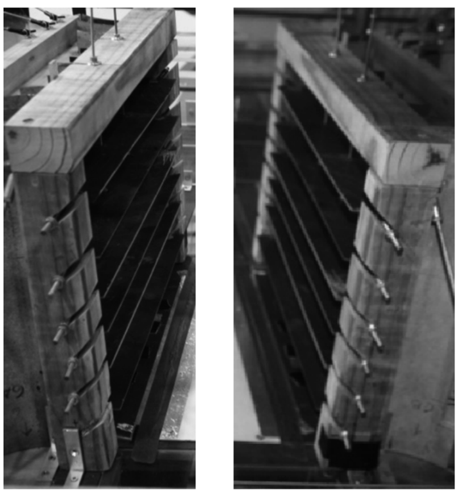


Fig. 4 Adjustable planks mechanism

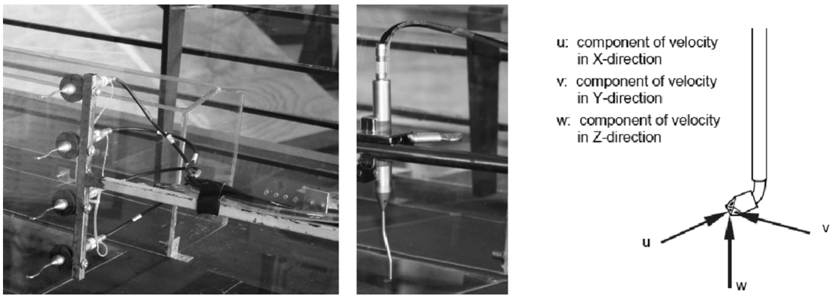


Fig. 5 Cobra probes for measurements of wind velocity components

The assessment provided insight into the wind field generated with and without the flow management devices and explored mean wind speed as well as turbulence characteristics. The probes were mounted on a steel bar which was fixed by means of two vertical steel rods secured to the movable carriage (traverse system).

Wind speeds were measured at a sampling rate of 1750 Hz. Such high frequency of acquisition was very important for capturing significant content of the signal and hence accurately estimating the turbulence characteristics (such as turbulence intensities and spectra). Each test was performed for a time period of 1 minute. This time period was sufficient to have a wind speed record with a stationary mean value for each individual test.

2.3 Test models for pressure measurements

Four models of the Silsoe cube building (6 m cube) (Richards *et al*. 2001, Murakami and Mochida 1990) were used for pressure measurements and validation. The models had different scales and were referred to as 0.25 H, 0.33 H, 0.50 H, and 0.75 H, with roof height being 25%, 33%, 50%, and 75% of the total wind field height (H) at the exit of WoW contraction, respectively. Table 1 Dimensions and corresponding tunnel blockage of the Silsoe cube models. Table 1 lists the scale and the dimensions of each model along with the corresponding tunnel blockage if the models were tested in a wind tunnel with the same flow cross-section area as the exit of the WoW. A 16-channel pressure scanner from Scanivalve Corporation was used for model surface pressure measurements on a vertical centerline section of each building model. Fig. 6 shows pressure taps layout on the outer surface of a test model along with the wind direction.

At the location of any pressure tap, the time history of the pressure coefficient $Cp(t)$ was obtained from the time history of the measured differential pressure, $p(t)$, as

$$Cp(t) = \frac{p(t)}{\frac{1}{2}\rho U^2} \tag{1}$$

where ρ is the air density at the time of the test (assumed to be 1.2 kg/m^3) and U is the mean wind speed measured at the windward eave height of each test model over a time period of 1 minute.

Referring to the data vector of the pressure coefficients over the sampling time period as Cp, the mean value of the pressure coefficients at any tap location, Cp_{mean}, is defined as

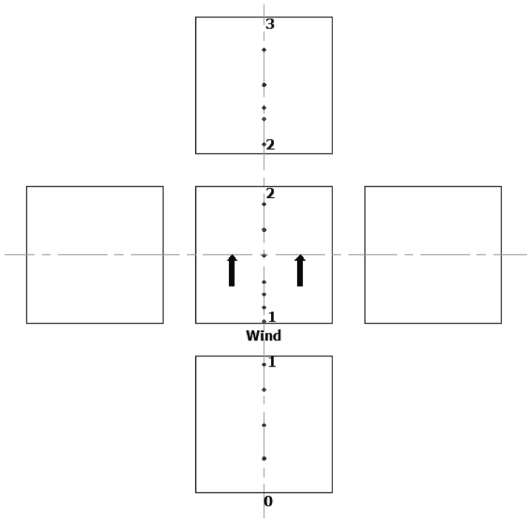


Fig. 6 Pressure tap layout for Silsoe cube models

$$Cp_{mean} = \frac{1}{n}\sum_{i=1}^{n} Cp_i \tag{2}$$

where n is the number of elements in the sample.

3. Wind field management

3.1 Uniform profile generation using Configuration I

In this configuration, the WoW model flow was produced with vertical turning vanes and without

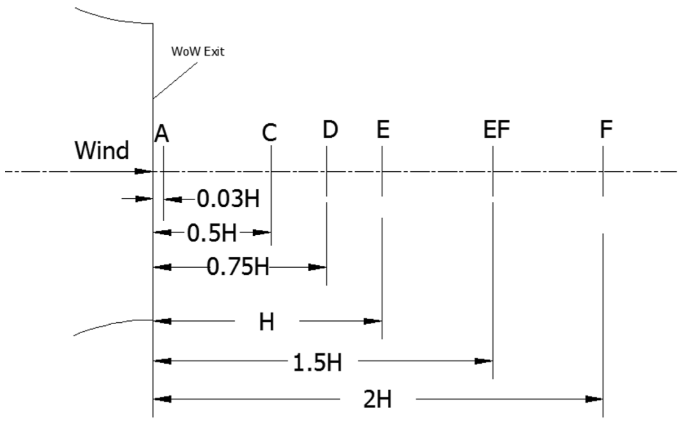


Fig. 7 Wind profile measurement locations

any planks or mesh. Three locations were considered for wind speed measurements. The measuring locations considered are *A*, *C*, and *E*, as indicated in Fig. 7 (where *H* is as defined earlier). Measurements were conducted for two different wind speeds and referred to as 15% and 35%,

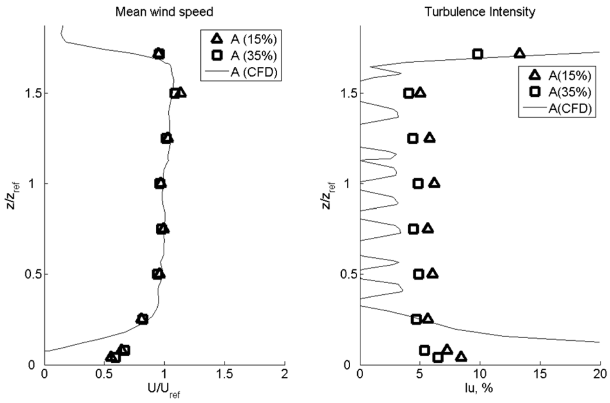


Fig. 8 Mean wind speed and turbulence intensity profiles at location *A* (for Configuration I)

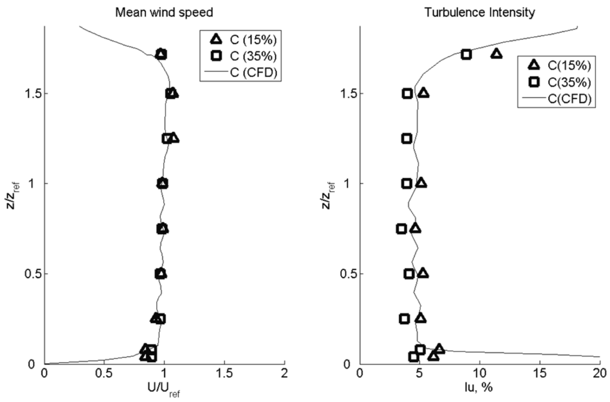


Fig. 9 Mean wind speed and turbulence intensity profiles at location *C* (for Configuration I)

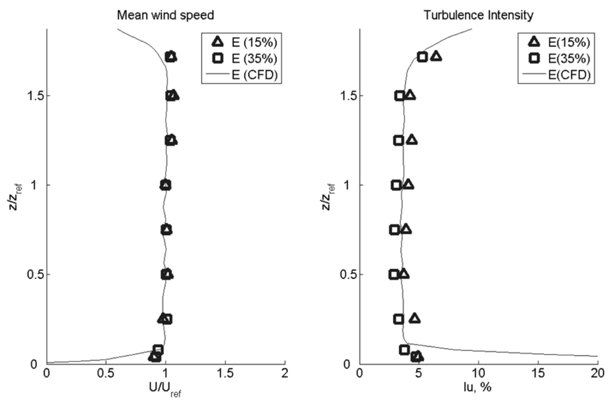


Fig. 10 Mean wind speed and turbulence intensity profiles at location *E* (for Configuration I)

which are actually related to the percentages of the power (throttle ratio) given to the fan motors that generally can generate mean wind speeds (U_{ref}) of about 20 m/s and 40 m/s, respectively, at the reference height z_{ref} of 163 mm at location *E*.

The measured profiles are compared to those predicted by the CFD study. Figs. 8-10 show mean wind speed (non-dimensional) and turbulence intensity profiles at the three measuring locations. Results show that there is good agreement between the mean wind speed and turbulence intensity profiles measured and those predicted by the CFD study for the two throttle ratios, at locations *C* and *E*. The measured mean wind speeds are almost uniform along the height; except for some wind speed retardation near the ground for location *A*. Turbulence predicted by the CFD at location *A* is lower than that in the experiment. Overall turbulence is generally low and a mechanism was designed to achieve the target mean wind speed profiles with higher turbulence intensities.

3.2 Suburban terrain profile generation using Configuration II

The aim of this configuration is to generate a wind field with a power law profile typical of suburban terrain (power law exponent α = 0.25). This configuration was set up by adjusting the planks' pitch angles as follows (starting from the lowest plank): 8.5°, 13°, 15°, 8.5°, 3.5° and 1.5°

(a) Configuration II. **(b) Configuration III.**

Fig. 11 ABL generating configurations

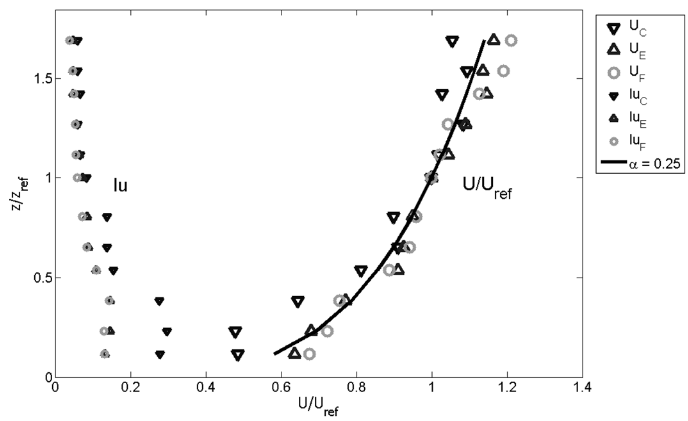


Fig. 12 Wind profiles for Configuration II (suburban terrain)

(Fig. 11(a)). In addition, a piece of wood with a length of 394 mm, a width of 25 mm, and a height of 16 mm was placed on the floor under the lowest plank to produce some blockage in the lower part of the boundary layer (see Fig. 11(a)).

Fig. 12 shows the mean wind speed (*U*) and turbulence intensity (I_u) profiles measured at locations *C*, *E*, and *F* (see Fig. 7) using Configuration II. It is shown that mean wind speed profiles at *E* and *F* are matching well with the target profile for suburban terrain. However, the mean wind speed profile at *C* shows some irregularities at the lower part of the boundary layer (the scatter of the measured data at *C* is the highest among all of the locations considered). This is due to the fact that location *C* is closer to the flow exit from planks where the wind speed was subjected to sudden changes with less homogeneity and had not the enough time to be properly mixed as was the case at *E* and *F*.

3.3 Open terrain profile generation using Configuration III

The target of this configuration is to produce a wind field with a power law wind profile typical of flow over open terrain ($\alpha = 0.15$). This configuration was achieved by adjusting the planks' pitch angles as follows (starting from the lowest plank): 0°, 6°, 6°, 5.5°, 0°, and 0° (Fig. 11(b)). In addition, a steel mesh was placed at the lower part of the planks mechanism to produce some blockage for the lower part of the boundary layer (see Fig. 11(b)).

Fig. 13 shows mean wind speed and turbulence intensity profiles measured at locations *C*, *D*, *E*, *EF*, and *F* of Fig. 7 Wind profile measurement locations. under Configuration III. It is seen that mean wind speed profiles at all of the five measuring locations are matching well with the target open terrain profile. It is also shown that mean wind speed profiles show less irregularity when compared to the profiles obtained from Configuration II. This is mainly attributed to the fact that the planks pitch angles are generally lower than those of Configuration II. The reduction in the mean wind speed at the top of the profile is natural since this region represents the end of the oncoming wind stream (upper envelope of the jet). Thus the usable boundary layer height can be defined as the height up to which there is a reasonable replication of the target *ABL*.

3.4 Wind spectra

A quasi-periodic wave form (designed on the basis of analyses of tropical cyclone wind data, see

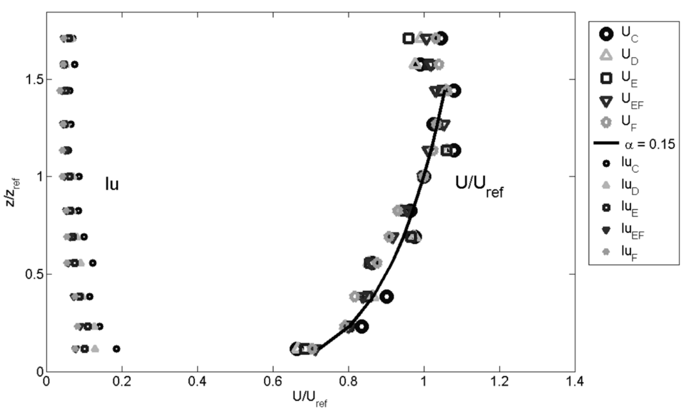


Fig. 13 Wind profiles for Configuration III (open terrain)

Huang *et al*. 2009) controlling the fans rpm is under consideration for actively producing low-frequency turbulence. This method has been already proved through 6-fan WoW experiments (Huang *et al*. 2009). The variation of the fan rotational speeds has no significant effects on the mean wind speed profiles. The flow generated by the fans at constant RPM is referred to as flat flow and the actively controlled flow is referred to as quasi-periodic flow (QP flow). Fig. 14 shows the dimensional spectra for both flows for the small-scale 12-fan WoW. For comparison purposes the figure also shows the spectrum proposed by Yu (2007) and Yu *et al*. (2008) for hurricane wind data in open terrain exposure, obtained within the framework of the Florida Coastal Monitoring Program (FCMP) (Masters 2004). Because of the limitations of the small scale WoW fan's performance, it was possible to obtain spectra covering only the dimensional interval n = 0.03 Hz to n = 10 Hz. However, the turbulence intensities achieved in the experiments increased from 6% in the absence of low-frequency fan rotations to 26% when quasi-periodic fan rotations were activated. The 26% longitudinal turbulence intensity is between the prescribed turbulence intensities for open and suburban terrains as given by ASCE 7 (ASCE 7-05, 2005).

4. Wind field validation using pressure measurements on Silsoe cube

Pressure measurements on the Silsoe cube models are used for validating the wind fields generated. Mean pressure coefficient data from the Silsoe cube models are compared with published wind tunnel data from Murakami and Mochida (1990) as well as full-scale results from Richards *et al*. (2001).

For each model, the tests were carried out at five locations using open terrain *ABL* simulation. The windward wall of each model was kept perpendicular to the main wind direction at distances of 0.5 H, 0.75 H, and H, 1.5 H, and 2 H (where H is as defined earlier), which are referred to by *C*, *D*, *E*, *EF*, and *F*, respectively, as shown in Fig. 15. Figs. 16-19 show mean surface pressure coefficients at the vertical centerline of the four cube models (named as 0.25 H, 0.33 H, 0.50 H, and 0.75 H as defined earlier) at the five different locations.

It is shown in Fig. 16 that pressure coefficients for the 0.25 H cube are generally in good agreement with the values provided in the literature for a scaled 1:65 wind-tunnel model (Murakami and Mochida 1990) and a full-scale prototype (Richards *et al*. 2001).

With the 0.33H cube at locations *C* and *D*, Fig. 17 shows that there is general agreement with respect to the roof and leeward pressure among the measured, wind-tunnel, and full-scale results.

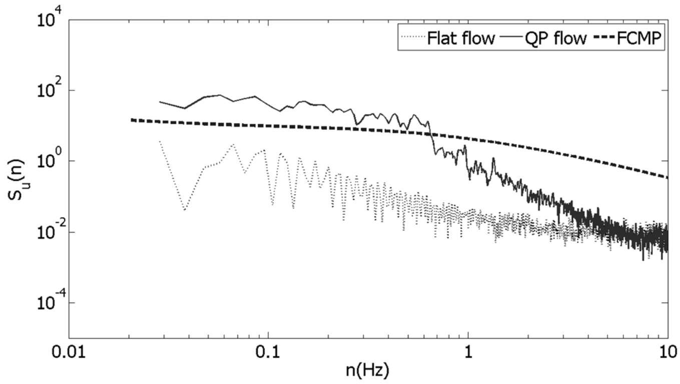


Fig. 14 Dimensional spectra of longitudinal wind flow fluctuations

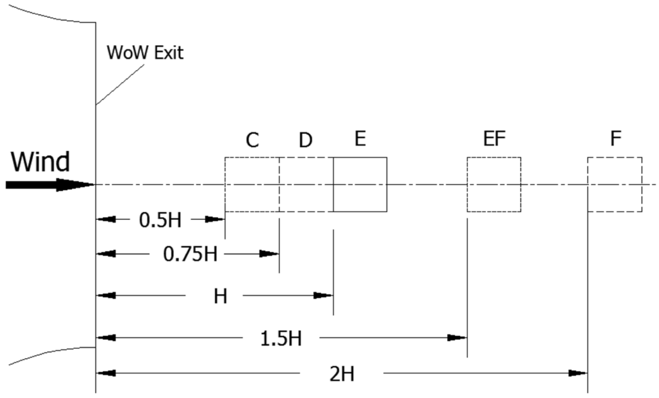


Fig. 15 Test locations for Silsoe cube models

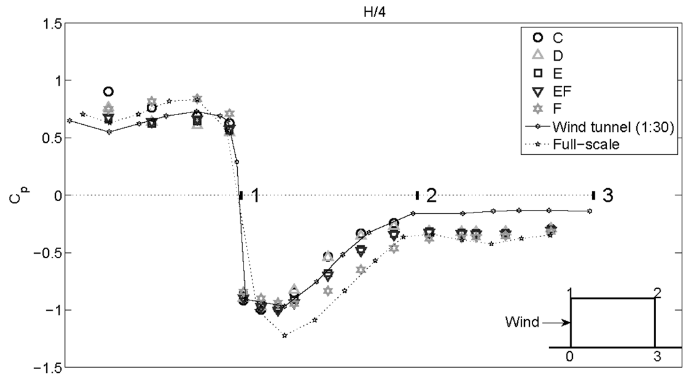


Fig. 16 Mean pressure coefficients for the 0.25 H cube model

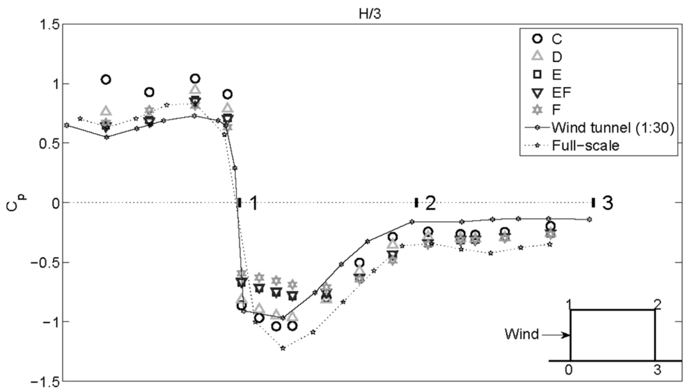


Fig. 17 Mean pressure coefficients for the 0.33 H cube model

However, windward pressures for location *C* appear to be sensitive to approach flow conditions (this may be also due to some possible blockage effects at this location). Although pressures for locations *E*, *EF*, and *F* have trends similar to those reported in the literature, roof pressures near the windward edge are deviating.

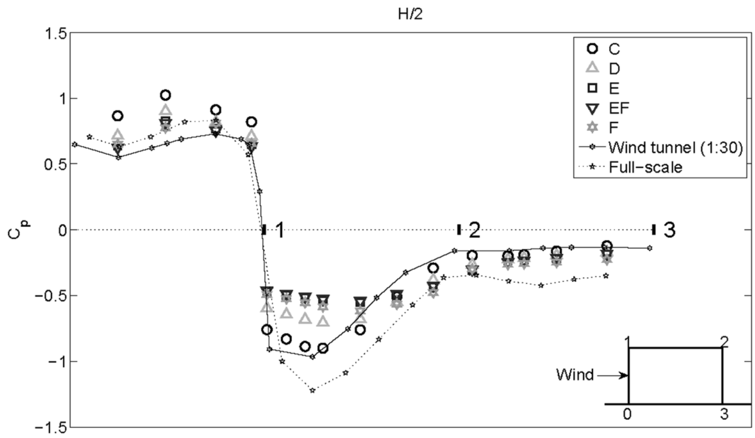


Fig. 18 Mean pressure coefficients for the 0.5 H cube model

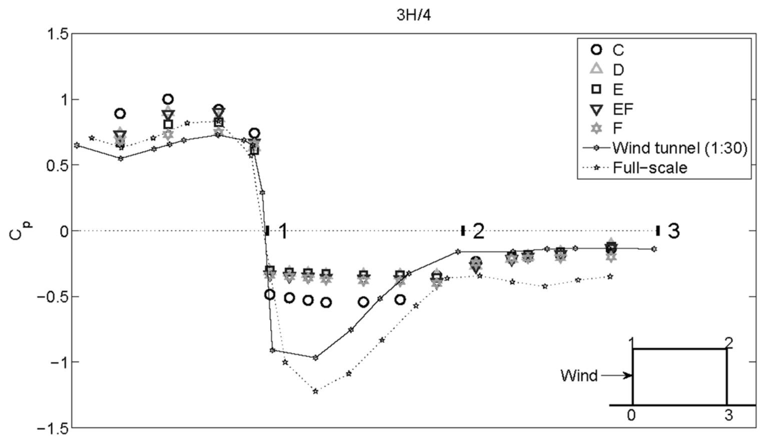


Fig. 19 Mean pressure coefficients for the 0.75 H cube model

Figs. 18 and 19 show that as the test model dimensions are increased further, the roof pressures are deviating from the values reported in the literature. This phenomenon could be due to the blockage effect produced by large models placed in front of open jet flow. The wind flow diffuses to the surroundings upon hitting such large models and the inadequate flow structure near the model roof edge precludes the formation of realistic separation bubble, thus hindering the generation of realistic roof pressures near the edge. Thus it is necessary to minimize such blockage effects by not using very large models. However, for the 0.50 H cube model tested at location *C* there is good agreement between the measured roof pressures and pressures reported in the literature. The corresponding wind tunnel blockage of this model (Table 1) is about 16%. The maximum allowable blockage in a wind-tunnel, to avoid results corrections, should not exceed 5% (Holmes 2001). This indicates the capability of open jet tests such as WoW tests to achieve reasonable roof pressures under relatively high blockage ratios.

In conclusion, the 0.33 H cube model, the height of which is one third of the wind field height at the WoW exit, had an optimal size when it was tested at a distance that is about 0.75 H (75% of the wind field height at the WoW exit). Such conclusion is in agreement with a *CFD* study published in

Table 1 Dimensions and corresponding tunnel blockage of the Silsoe cube models.

scale	model name	height (mm)	width (mm)	depth (mm)	corresponding tunnel's blockage (%)
1:94.5	0.25H	63.5	63.5	63.5	3.56
1:67.5	0.33H	89	89	89	7.00
1:45.0	0.50H	134	134	134	15.87
1:31.5	0.75H	190	190	190	31.90

Bitsuamlak *et al*. (2010).

5. Discussion

Wind profiles obtained with Configuration I (without planks) are useful for performing aeroelastic study using section models of long-span cable-stayed or suspended-span bridges (Gan Chowdhury and Sarkar 2003). Furthermore, this configuration may be potentially useful for high wind speed, low-turbulence aeronautical applications.

WoW simulation is sufficiently flexible to generate commonly used mean wind velocity and turbulence intensity profiles. The mean and turbulence characteristics of the target flow were achieved through the application of passive devices (planks) and of active controls designed on the basis of analyses of tropical cyclone wind data obtained through Florida Coastal Monitoring Program (FCMP) (Master 2004, Yu *et al*. 2008). The knowledge gained from the small-scale 12-fan WoW will be used for flow simulation and pressure validation purposes in the prototype 12-fan WoW (Fu *et al*. 2011).

The wind profiles simulated in this study provide a tool for future large-scale model tests at the prototype 12-fan WoW facility. In addition to the possibility of providing a low turbulence test section that can be used for bridge testing, the 12-fan WoW will allow, through large-scale and destructive testing, a better understanding of Category 1 to 4 hurricane effects on residential buildings and other structures.

6. Conclusions

Wind fields assessed experimentally at the small-scale 12-fan WoW facility are in a general agreement with the CFD results. However, turbulence intensities predicted by the CFD at the exit of the WoW are lower than in the experiments. The adjustable planks mechanism proposed in this research allows for generating different mean wind speed profiles. Suburban terrain (α = 0.25) and open terrain (α = 0.15) are achieved with Configuration II and Configuration III, respectively. Under the simulated open terrain winds (α = 0.15), roof pressure measurements on a cube with a height of about 33% to 50% of the wind field height are in good agreement with values reported in the literature, while the corresponding tunnel blockage ratio is about 7% to 16%, respectively. This indicates the capability of open jet tests to achieve reasonable roof pressures for low-rise buildings under relatively high corresponding tunnel blockage ratios. Based on the recent experiments, the optimal distance between the WoW exit and the models' windward wall, for profile development and pressure validation, is shown to be 75% of the wind field height at the exit.

The Wall of Wind testing technology combined with possible different wind profiles offers great advantages for future-oriented applications involving bridges, buildings, wind-induced rain, and destructive testing at large scales. This is important for the improvement of code provisions, innovative hurricane mitigation development, and for producing solutions which bridge the disciplines of wind engineering and structural engineering.

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