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Requirements for Modelling Low-rise Buildings at Large-scales in the Wall of Wind

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Abstract

The problems associated with simulating hurricane force winds in facilities such as the Florida International University's Wall of Wind are discussed. One of these problems is the inability to model low frequency variations in both wind speed and direction. Data from the Silsoe Cube experiment is examined and shown to give similar results when processed in 10s records and 12 minute records. It is concluded that while turbulence of the same order of size as the building under test needs to be created anything larger than about 10 times the building size can probably be treated as a quasi-steady variation.

Introduction

Data compiled by Munich RE (2012) shows that in the period 1980-2011 six of the ten costliest insurance losses were associated with hurricanes, with Hurricane Katrina causing total losses of US$125bn and insured losses of US$62.2bn. While the damage caused by Katrina and other hurricanes often includes storm surge effects, a substantial amount of damage is caused by the direct action of the wind itself and most of this damage is associated with the many low-rise residential or industrial structures which are designed using wind loading codes of practice rather than with engineered high-rise structures.

Aly et al. (2011) note: "*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 (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. 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 suitable for experimentation and destructive testing of large-scale, low-rise structures 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."

FIU's new 12-fan WoW, shown in Figure 1, was officially unveiled in August 2012 and is the US's first university research facility capable of simulating Category 5 hurricane winds. It is a major research project of FIU's International Hurricane Research Center (IHRC). With 520 kW behind each 1.8m tall fan, the Wall of Wind can generate winds of up to 250 km/h. With a test section 4.5m high by 6m wide, the Wall of Wind allows researchers, businesses, government agencies and industry to test and analyse how structures and products perform in various hurricane conditions.

Figure 1. The Wall of Wind at Florida International University.

Wind Modelling Requirements

Unfortunately replicating the effects of hurricane force winds is not just a matter of having enough power to generate very high wind speeds, the flow must also reproduce the important features of the unsteady flow. In 1974, Tropical Cyclone Tracy devastated the City of Darwin in Australia's Northern Territory, Walker (1991) observes. "*It was clearly demonstrated in the investigation of Cyclone Tracey that the two major factors contributing to the wide-scale damage to housing were internal pressurization of buildings following failure of windward windows, generally due to windborne debris, and fatigue failure of cladding and metal connections under the fluctuating pressures.*" These comments allude to the importance of fluctuating winds in the failure of structures. Not only does the turbulence create unsteady loads, which under some circumstances can be more damaging than a sustained load of the same level, but it can also stimulate resonant responses in internal pressures or other systems. In addition the medium to small scale vortices in the flow are important in determining the curvature of the flow around a building or structure and hence can indirectly affect the wind loads. Regrettably it is almost impossible in any test facility to fully reproduce all of the features of strong winds and so it is necessary to investigate what features must be simulated and what are the consequences of not replicating others.

As noted on the FIU website ideally the FIU-WoW facility should have the following features:

- Holistic full-scale simulation of hurricane wind forces, turbulences and vortices.
- Coupling/hybridizing dynamic wind loading with nonlinear structural/material response.
- Monitoring performance levels and progressive damages for different wind force levels.
- Providing a controllable, programmable, and repeatable hurricane test environment.
- Eliminating scaling issues, and yielding realistic Reynolds and Strouhal numbers.
- Simultaneous testing for high wind forces and impinging rain.
- Simultaneous testing of high wind forces and wind-borne debris impact on components and the entire structure, including the effects of breach of envelope on internal pressure.

Experience with the smaller Wall of Wind projects and with model scale versions of the new large WoW have helped to provide some guidance. For example, Aly et al. (2011) have investigated techniques for generating wind profiles and how pressures on a building are affected by proximity to the fans, while Fu et al. (2012) have investigated techniques for dealing with the very large scale coherent fluctuations in real winds which totally engulf small buildings. However it is recognised by the authors that these studies are "*a first step in developing the proposed techniques*."

In 2014 the author plans to spend 5 month on sabbatical leave at FIU where he will assist the FIU team with the development of equipment, testing techniques and analysis procedures. In particular the following aspects will be considered:

- What are the best approaches to dealing with large-scale low-frequency fluctuations? Do these need to be simulated or can they be treated as slow variations in the mean flow?
- How best to create medium to small scale turbulence and what are the consequences of any deficiencies?
- What are appropriate techniques for creating velocity profiles?
- What is the best scale to use in the facility? For some purposes full-scale testing may be essential but in other situations this may create excessive blockage and so a large-scale model may be more practical.

The Silsoe Cube

As an initial consideration of the first bullet point above, this paper will consider the low frequency pressure behaviour of four taps on the Silsoe Cube, depicted in Figure 2. It is generally accepted that the low frequency fluctuations in the natural wind are created by large scale turbulent structures which totally engulf a structure and its associated local flow field. Such slow fluctuations create conditions which are essentially equivalent to those which would occur if the same wind speed and direction remained unchanged. It is just that over an observation period there are a range of these situations which occur. It is also recognised that with facilities such as the WoW it is very difficult to replicate these low frequency fluctuation and so each test can at best represent conditions that in reality last for a short time.

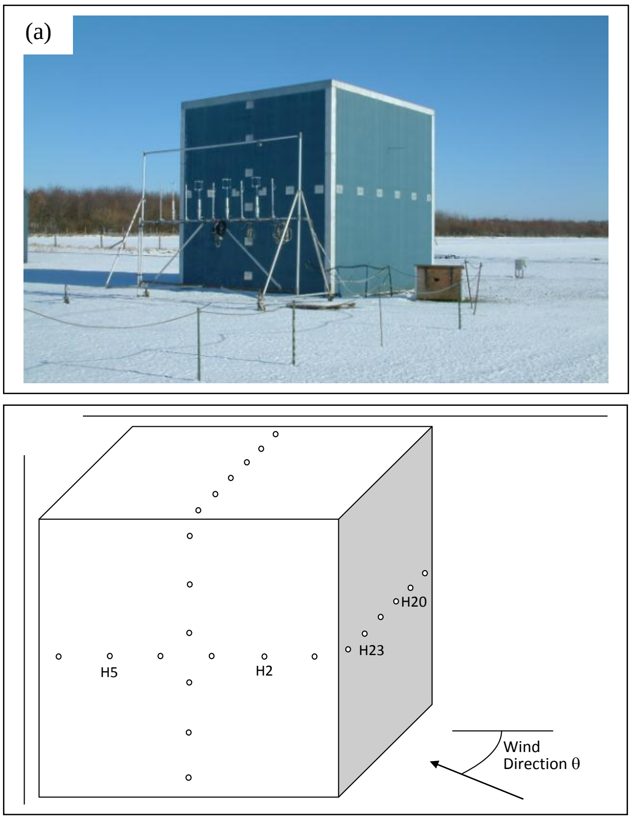

Figure 2. (a) The Silsoe 6 m Cube and (b) Pressure tap locations

Richard et al. (2007) discuss modelling the Silsoe Cube in a wind tunnel at a scale of 1:40, where some of these issues also occur. The conclusions of that study were: "*In order to compare wind-tunnel turbulence spectra with full-scale, normalising parameters that are independent of the turbulence should be used. One suitable form is to plot* $nS(n)/U(z)^2$ *against reduced frequency* $f = nz/U(z)$*, where the normalizing parameters are the mean wind speed (U(z)) and height (z) of the measuring point. Using turbulence dependant parameters, such as the variance and integral length scale, can easily mask differences.*

In situations where it is not possible to model the full turbulence spectra, such as the large scale modelling of low-rise buildings, care should be taken to correctly model the high frequency end of each spectrum. It is this turbulence that can directly interact with the local flow field and modify flow behaviour. This has been illustrated by studying data from tests conducted in a range of European wind-tunnels.

The approach taken at the University of Auckland in wind-tunnel modelling the Silsoe 6m Cube at a scale of 1:40, was to match the velocity profile and the high frequency turbulence as closely as possible. Similar mean pressure distributions were obtained as a result. Although the high frequency end of each spectrum was matched the size of the tunnel limited the low frequency end and so the longitudinal and transverse turbulence intensities were lower than in full-scale. This has the effect of reducing the standard deviation of wind directions and hence affects both the observed mean and peak pressures by reducing the band of wind directions occurring during a run centred on a particular mean direction.

The reduced turbulence intensities also affect the peak to mean dynamic pressure ratio, which in the Auckland wind-tunnel was 1.91 in comparison with 2.78 in full-scale. However, since the missing turbulence is at low frequencies, the peak pressures appear to reduce in proportion. By expressing the peak pressure coefficient as the ratio of the extreme surface pressures to the *maximum dynamic pressure observed during the run, reasonable agreement is obtained. It is believed that the peak-peak ratio is a more reliable measure of peak pressures since it is less sensitive to spectral differences, measurement system response characteristics and analysis methods, provided the reference dynamic pressure and the surface pressures are measured and analysed in similar ways. It is also the peak-peak ratio that is used in most wind loading codes."*

The Silsoe cube has been used as one of the reference buildings in earlier studies for the Wall of Wind. Aly et al. (2011) used cubes of various sizes to assess blockage effects and Fu et al. (2012) used the Silsoe cube and the TTU building in a small scale model of the 12 fan WoW to compare pressure data obtained with constant fan speed and fluctuating fan speeds which produced almost the same peak dynamic pressure. Their results showed little difference between the two simulations, although they do not show whether either was correct.

The form of pressure coefficient recommended by Richards et al. (2007) has been adopted by Richards and Hoxey (2012a) as

$$C_{\bar{p}}(\bar{\theta})=\frac{\bar{p}}{\bar{q}},\quad C_{\tilde{p}}(\bar{\theta})=\frac{\sigma_p}{\sigma_q},$$

$$C_{\hat{p}}(\bar{\theta})=\frac{\hat{p}}{\hat{q}},\quad C_{\breve{p}}(\bar{\theta})=\frac{\breve{p}}{\hat{q}}. \qquad (1)$$

where p is the surface pressure at a tap location and q is the dynamic pressure at the reference anemometer which was at a height of 6 m, approximately 24 m upstream and 6m to the side of the centre of the cube. Data from symmetric taps such as H2, H5, H20 and H23 have been combined to produce results for one tap encompassing all directions. Figure 3 shows the resulting pressure coefficient variations with direction for Tap H2. Each data point is from a 12 minute run of 3000 samples and the graph includes data from the equivalent of 1700 runs.

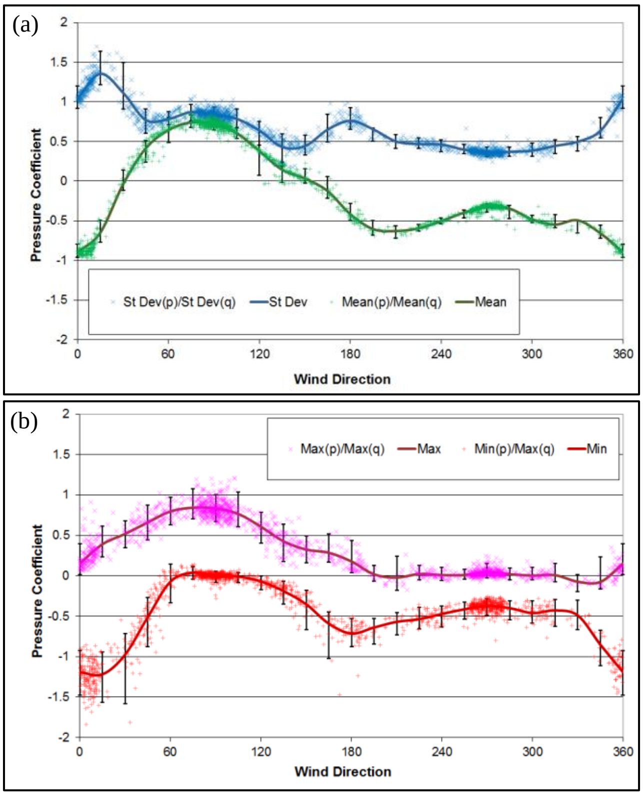

Figure 3. (a) Mean, Standard Deviation and (b) Maximum and Minimum pressure coefficients for Tap H2.

As explained by Richards and Hoxey (2012a), short Fourier series have been fitted to the data sets. The data around this fitted curve has been analysed in order to estimate the error bars which have 5% of the data, in a 15° direction band, above and below the limits shown. It may be observed that with 12 minute records there is little scatter in the mean coefficients but rather more in the standard deviation, maximum and minimum coefficients.

Richards and Hoxey (2012b) discuss using the fitted Fourier series and the standard deviation of wind directions to estimate an instantaneous function, which when averaged over the range of wind directions would lead to the observed mean function. This instantaneous function has been obtained for tap H2 and then combined with the measured wind dynamic pressure and direction data to give expected quasi-steady time series for taps H2, H5, H20 and H23. Figure 4 shows examples of these for taps H5 and H23 from a later series of experiments where data was collected at 25 samples per second.

It appears from Figure 4 that both the windward face and side face pressures follow low frequency variations in a quasi-steady manner. Certainly fluctuations lasting about 100s are clearly reflected in both the measured time series and that expected from quasi-steady analysis. However it is not immediately apparent what is the shortest period that is responded to in this way.

Close inspection of the time series shows a consistent time delay between the quasi-steady series which is responding to the upstream anemometer and the measured time series which feel changes in wind pressure a short time later. Cross-correlation analysis showed a typical time delay of a few seconds which was allowed for in later analysis.

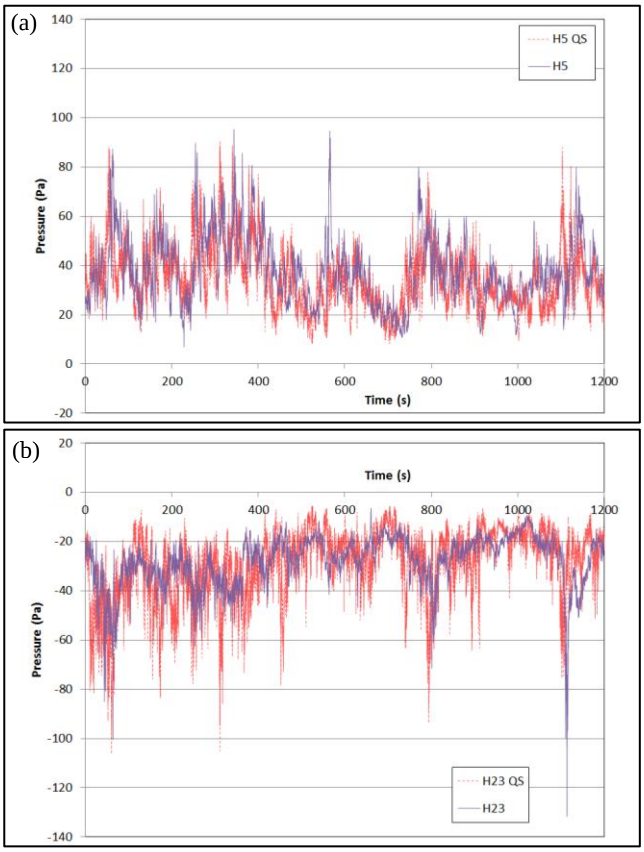

Figure 4. Pressure time histories for (a) tap H5 and (b) tap H23 over a 20 minute period during which the mean wind direction was 106° and mean dynamic pressure at 6 m was 47 Pa. Also included are the quasi-steady expectations based on the reference wind dynamic pressure and direction.

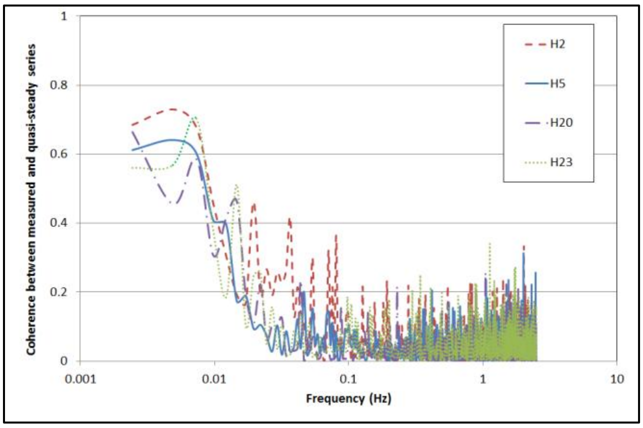

Figure 5. Coherence functions for the four featured taps.

In order to determine the limits of quasi-steady type response the data was averaged over 5 samples and then a 150 minute record was subdivided into 28 blocks and a coherence analysis carried out. The resulting coherence functions, in Figure 5, show high coherence values for frequencies less than 0.01 Hz (100 s periods) which decreases steadily until above 0.1 Hz (10s period) the values are simply noise.

Although it is pushing the indicated limits the data from the later series of experiments has been analysed in 10 s records. Although not all wind directions were recorded the use of symmetry has meant that many wind directions were covered. The results are shown in Figure 6 where the solid lines are curves fitted to this set of data, whereas the dashed lines are those fitted to the 12 minute record data in Figure 3. It is perhaps surprising that the curves are so similar although obviously the scatter is significantly greater with the short duration records. It is also interesting to note that the maximum and minimum curves are closer to each other in the 0 - 150° range since each record is less likely to include data from angles well away from the mean.

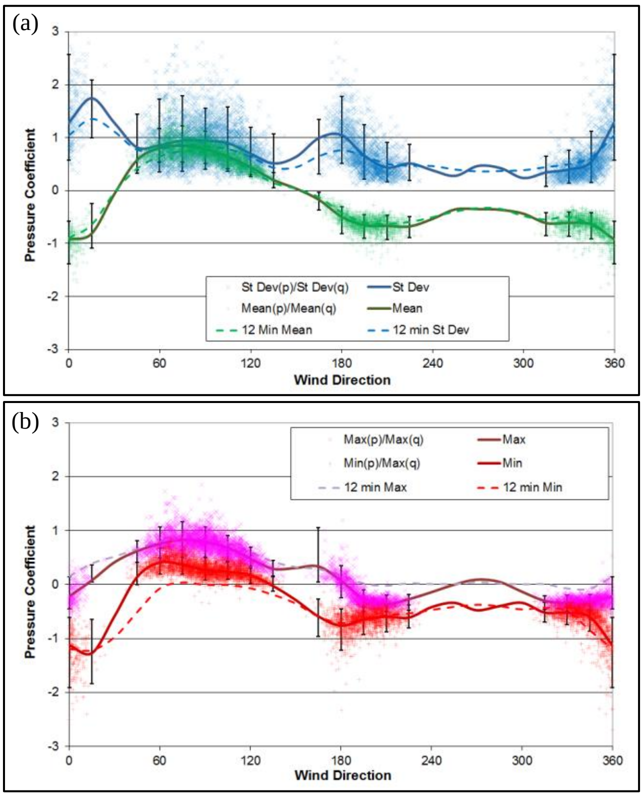

Figure 6. (a) Mean, Standard Deviation and (b) Maximum and Minimum pressure coefficients for Tap H2 based on 10s sample lengths.

Implications for the Wall of Wind

The analysis above suggests that reasonable results can be obtained from multiple short duration runs. It suggests that fluctuations in the wind that occur over periods longer than about 10 times the building size divided by the mean wind speed could possibly be treated as quasi-steady variations. However it is recognised that in modelling such flows it is important that turbulence of the same order of size as the structure itself needs to be correctly simulated. This not only means that the along wind fluctuations need to occur but representative vortical structures need to exist. Such turbulence not only affects flow separation and reattachment but also stimulates dynamic response in separated flows and in flow structures such as the delta-wing type vortices found on flat roofs.

If the high frequency end of the spectrum is correctly modelled then it is suggested that results obtained in high speed facilities such as the Wall of Wind can reproduce the situations that occur during a moderately short duration gust in a real storm.

Conclusions

Pressure data from the Silsoe Cube has shown that analysis using only 10s records is very similar to that obtained previously with much longer 12 minute records. This suggests that facilities such as the Wall of Wind do not need to model turbulence with length scale larger than about 10 times the building size.

Acknowledgments

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