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A physical modeler's view of Computational Wind Engineering

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ABSTRACT

A Panel Discussion was held at CWE2010 to promote a conversation on the topic of how Computational Wind Engineering (CWE) can become a commonplace tool in the various subdisciplines of wind engineering (structural loading, dispersion, sediment transport, ventilation and wind power) to complement, and eventually replace, physical modeling. Where may CWE be confidently used currently? What further development and validation, as opposed to calibration, of CWE is needed to result in its viable future? The authors have seen the slow merging of computational and physical modeling in recent years in hybrid practical applications. Physical modeling went through some decades of validation, focusing on full-scale pressures, loads and top-floor accelerations, to gain increased confidence in the small-scale modeling of buildings and structures in a boundary-layer wind tunnel. Such studies in the wind tunnel have their well-known and quantified discrepancies, but at least the practitioners know what is reasonably doable and what is not (some good examples may be found in Surry Ho and Kopp, 2003). Perhaps it is time for CWE to move down a similar path, using the experience of the physical modelers as a guide in its evolution. As with any advancement in technology, the economics and analytical rigor of CWE are what will determine its ultimate success.

1. Introduction

When the use of physical modeling first appeared as a wind engineering design and analysis tool considerable effort went into validating both the approach flow and the load/pressure data at small scales (say, 1:300 to 1:600) in the wind tunnel. Work in the 1950s focused on modeling the atmospheric boundary layer in the (then) new, long, boundary-layer wind tunnels (Cermak and Koloseus, 1954). By the 1960s small building models were placed in these scaled representations of the atmospheric boundary-layer. One of the first buildings to receive this new technology was the ground-breaking twin towers of the World Trade Center at the south end of Manhattan in 1964 (see Fig. 1, after Colorado State University, CSU, archives).

During the following three decades a series of major studies was performed by researchers all over the world to validate the model studies against full-scale data. As more confidence was gained through a coupled, iterative process of wind-tunnel technology refinement and validation, the eventual use of wind-tunnel studies became more commonplace. In fact, the technology was used to create the major wind-load codes and standards around the world from the 1970s onwards. As a consequence of the increased confidence in wind-tunnel studies, and their key contributions to the analytical design procedures, physical modeling in a boundary-layer wind tunnel became the only sanctioned means of superseding a code calculation in determining wind loads on buildings and structures. Not least, it is generally acknowledged that use of the wind tunnel can lead to less conservative, more economical, structural design compared with designing by code or standard.

This paper is intended to highlight the historical evolution of physical modeling and to suggest a similar path for CWE so that it may play a larger role in the wind-load assessment for the structural engineer. Economics and analytical rigor will be the driving parameters. Ultimately CWE is likely to replace the physical modeling of bluff bodies, but much more needs to be done before that eventuality is seen. These notes will point out

Abbreviations: ARPS, Advanced Regional Predictive System; BRE, Building Research Establishment (United Kingdom); BRI, Building Research Institute (Japan); CFD, computational fluid dynamics; CPP, Cermak Peterka Petersen Inc.; CSU, Colorado State University; CWE, Computational Wind Engineering; DAD, Design Assisted Database; DES, detached eddy simulation; DNS, direct numerical simulation; DRM, dynamic reconstruction model; FD, finite difference; FDS, Fire Dynamics Simulator; FE, finite element; FM, frequency modulated; FV, finite volume; HVAC, heating ventilation and air conditioning; JCU, James Cook University; LES, Large Eddy Simulations; NIST, National Institute of Standards and Technology; PIV, particle image velocimetry; RAMS, Regional Atmospheric Modeling System; RANS, Reynolds Averaged Navier–Stokes; RSFS, resolvable subfilter-scale stresses; RNG, re-normalization group; SGS, sub-grid scale; SPT, super pressure tap; TKE, turbulent kinetic energy; TTU, Texas Tech University; UWO, University of Western Ontario; WALE, wall adapting local eddy (viscosity); WRF, Weather Research and Forecasting (model)

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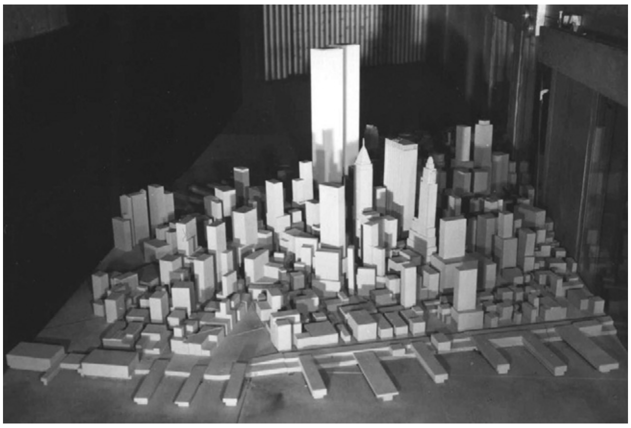

Fig. 1. Aeroelastic models of the World Trade Center, with surrounding Manhattan model, in one of the Colorado State University wind tunnels during the 1963/1964 studies.

where CWE currently is being used with confidence, how a hybrid CWE/wind-tunnel approach can be of value and what the authors believe needs to happen for CWE to mature to a fully reliable, bluff-body, architectural-aerodynamics tool.

2. Physical modeling in the wind tunnel

2.1. Introduction to physical modeling

The analysis of continuum mechanics was developed by a mixture of practitioners in mathematics and hydraulics, including Bernoulli, Euler, d'Alembert, Navier, Stokes, Cauchy, Poisson, Reynolds and Joukowski to mention a few (see Table 1). The most general formulation of the equations of motion is attributed to the French mathematician, Claude Louis Marie Henri Navier, and the British physicist, Sir George Gabriel Stokes. Analytical solutions to these equations are limited to simple geometries and well defined fluid properties. Examples of these flows may be found in many fluid dynamics texts (Yih, 1988; Karamcheti, 1980). Since, for most engineering applications, the ideal fluid solution was analytically unobtainable or apparently in conflict with common sense (d'Alembert's Paradox), many designers had to resort to physical testing.

A landmark innovator of physical testing is Alexandre Gustave Eiffel, who used the 320 m Parisian Eiffel Tower (which he was commissioned to design and construct in 1889 based on his extensive bridge building experience) as an outdoor laboratory for research in atmospheric science and aeronautics, leading to major advancements in these fields. Eiffel became an early pioneer of aeronautics and meteorology. In 1903 he measured bluff body drag coefficients by dropping test shapes from the second level of his famous tower onto the banks of the Seine River. Ironically, data from these experiments enabled by the height of the tower would have been useful in its design for wind loads. Instead, Eiffel resourcefully made wind load calculations for the structural design of the tower based on crude drag coefficient studies previously performed by others.

Eiffel's experimental data were later corroborated by the American aviation pioneer, Samuel Langley. His meteorological laboratory on the top level produced data that became the foundation of modern French meteorology. Once he developed this interest in aerodynamics he built a series of wind tunnels to study the new field (Barr, 1992).

> "…it drove a fan system providing a steady, controlled and turbulence free flow of air at speeds up to 70 km/hr. Airplane models were measured for overall aerodynamic balance, lift over wing surfaces and propeller efficiency….A larger and more powerful wind tunnel in the Paris suburb of Auteuil replaced the Tower facility. It provided an airflow of 110 km/hr in a 2 m wide tunnel, permitting Eiffel's continued experiments on lift characteristics".

Table 1
Major events in wind engineering.
Sources: Aynsley et al. (1977), Cermak (1975), Cook (1985), Glanz and Lipton (2003), Holmes (1982b), McWhirter (1986), Murakami (1992), Scruton (1960), Takagi (1992) and Timoshenko (1953).

1643	Torricelli invents barometer
1687	Newton discovers viscosity, laws of motion, calculus, *Principia*
1738	Bernoulli defines conservation of energy applied to fluids, *Hydrodynamica*
1755	Euler forms inviscid equations of fluid motion
1806	Beaufort defines Beaufort Scale of wind speed in terms of its visible effects
1836	**Collapse of Brighton Chain Pier by oscillatory motion**
1845	Stokes formulates the Navier–Stokes equations of fluid motion
1846	Robinson invents cup anemometer
1879	**Collapse of Tay Bridge in Scotland**
1883	Reynolds develops dimensionless parameter to investigate the onset of turbulence
1888	Dines invents pressure tube anemometer
1904	Prandtl develops boundary layer concept
1912	von Kármán identifies vortex shedding in wakes
1914	King gives equation for cooling hot-wires
1928	Fisher and Tippet develop theory of extreme values
1934	**Record maximum 10 m wind gust (370 km/h) recorded at Mt. Washington, USA**
1935	Taylor develops statistical theory of turbulence
1940	Rathbun collected data on the full-scale Empire State Building
1940	**Collapse of Tacoma Narrows Bridge by oscillatory motion**
1954	Cermak builds first large boundary-layer wind tunnel
1954	Jensen formulates model scaling laws
1957	Van der Hoven compiles wide frequency range spectrum of winds
1958	Cermak describes Reynolds number independence for modeling the atmospheric boundary layer
1961	Davenport illustrates application of statistical concepts to wind loading
1963	**First international conference on wind effects on buildings**
1964	Cermak and Davenport make first design oriented test of a major building in a boundary-layer wind tunnel; World Trade Center (New York City)
1965	**Collapse of three cooling towers at Ferrybridge**
1970	**Term "wind engineering" coined**
1974	Eaton and Mayne report on Aylesbury House; full-scale low-rise study in Great Britain
1975	Marshall studies full-scale pressures on the Malmstrom homes
1976	Deaves and Harris develop mathematical model of strong winds
1984	Holmes defines wind-tunnel pressure tubing response characteristics
1986	**Amarube Tekkyo rail bridge disaster in Japan**
1987	**Construction of the TTU Experimental Building**
1988	Silsoe Structures Building is constructed in Great Britain
1992	Murakami hosts the first CWE symposium in Tokyo
1996	**New record maximum 10 m wind gust (408 km/h) recorded at Barrow Island, Australia**

Eiffel's wind load calculations used in designing the Paris Exposition Tower, based on crude drag coefficients, and his subsequent experiments in bluff body aerodynamics after construction of the tower were some of the earliest attempts to understand static wind loading. Prior to this some bluff body building studies had been attempted by Kernot (1893) and Irminger (1894).

However, the application of wind-tunnel testing to ground based structures took six more decades to become a useful engineering tool. In fact, the term "wind engineering" was not coined until the early 1970s, leading to the first United States National Conference on Wind Engineering Research in 1975 (Solari, 2004). Prior to this development the field was treated as a subset of the larger topic of "Industrial Aerodynamics" (Scruton, 1960; Cermak and Peterka, 1978). Initially studies were performed in a uniform flow that produced spurious results. Probably the most quoted examples are papers by Bailey (1935) and Jensen (1958). A very readable historical discussion of this period is given by Surry (1999), including the amusing details of Jensen's full-scale internal pressure experiment. By the 1950s atmospheric studies of the Earth's turbulent boundary layer had led to a greater understanding of its structure and complexity, and ultimately to the establishment of a better set of modeling criteria. Cermak (1958) demonstrated the criteria for Reynolds number independence when modeling an atmospheric boundary layer flow at a reduced scale. Building studies were performed frequently by the 1960s, and the theoretical justification for such work was contained in papers by Cermak (1971, 1981) and Cermak and Peterka (1966). In brief, it had been observed that the Reynolds number drag dependence for bluff, sharp edged bodies (and the boundary layer itself) was small when performed above a critical Reynolds number. Thus, a major similarity requirement could be waived and the test results would remain valid. Other similarity requirements include equating the Rossby, Richardson, Prandtl and Eckert numbers between model and prototype. The significance of these non-dimensional quantities depends on the situation being modeled. However, the insensitive nature of load and pressure coefficients to Reynolds number meant that boundary-layer wind-tunnel modeling was viable at moderate, readily achievable wind speeds.

Concurrent studies into the effects of turbulence and how to measure it had been progressing from as early as Schubauer and Dryden (1935) to more recent work by Van der Hoven (1957), Monin and Obukhov (1954) and Davenport (1965). Knowledge of the turbulent spectrum of the natural wind and incorporation of its scaled representation in the wind tunnel led to the growth of modeling from static building studies to dynamic investigations. The description of the energy content of the wind via the turbulence spectrum by Davenport (1965) was an essential concept that pushed wind engineering from static to dynamic studies. During the 1940s and 1950s dynamic wind-tunnel studies were generally limited to flexible, long-span bridge structures, catalyzed by the dramatic failure of the Tacoma Narrows Bridge. The transition from studies of bridge dynamics to studies of building dynamics was principally motivated by the decision to build the twin towers (Glanz and Lipton, 2003) of the World Trade Center in New York (Davenport, 1988). Designs of a challenging height and/or form have resulted in a rapid evolution of wind-tunnel testing for the dynamic aspects of high-rise buildings.

Instrumental in the development of dynamic studies was the ability to observe the passing turbulence structure using hot–wire anemometry. The initial analysis, based on the correlation between flow rate and heat transfer, was performed by King (1914), but the technique was severely limited by practical electronic considerations for two more decades (Dryden and Kuethe, 1920). The work of Schubauer and Klebanoff (1946) showed the high frequency responses achievable with an advanced electronic system and its practical value in measuring the high frequencies inherent in turbulent flows. The technique evolved into two approaches: the constant-current and constant-temperature procedures. Both incorporate the use of a Wheatstone Bridge.[1] A brief discussion of this topic is given by Hinze (1975), Bradshaw (1971) and a far more detailed synopsis by Sandborn (1972, 1981).

2.2. Early validation of the boundary-wind tunnel: low-rise buildings

In an effort to improve the codified pressure data for low-rise structures and, of course, to confirm the wind-tunnel procedure, the Aylesbury House Experiment was undertaken in Great Britain. Eaton and Mayne (1975) describe an extensive full-scale experiment on several two storey homes in Aylesbury, 65 km northwest of London, England. The principal contribution to wind engineering resulting from this project was an experimental building with a variable pitch roof. Most of the pressure data were collected on this building and some on three downwind dwellings. Subsequently many laboratories around the world have tested models of the Aylesbury House (Holmes, 1982a). The Aylesbury experimental building was built upwind (relative to the prevailing winds) of a suburban area with a fairly open exposure; a range of $50 < z_o < 150$ mm is reported. In this way the data from the exposed experimental building upwind could be compared with that collected in the complex environment of the downwind housing estate. The reference pressure was taken from a common in-ground pit located between the isolated house and the estate downwind. The site of a reference pit and its design are frequently problems associated with full-scale measurements (Levitan, 1992) and the Aylesbury house was no exception. Eaton and Mayne believe that there was a slight under-reading of the actual ambient pressure by the pit design that was used, about 8% of the stagnation (dynamic) pressure at a standard 10 m height.

The pressure data were collected on FM tape and later digitized at a rate of 32 Hz to produce mean, peak, standard deviation and frequency domain data. This early experiment in low-rise structures produced copious quantities of data and plenty of discussion over the next decade (e.g. some believed that the upstream hedges were significant flow modifiers; others did not). One feature that came from the study is shown in Fig. 2. As the roof pitch was increased from 10° to 22.5° the uplift produced by the corner vortices diminished appreciably. Eaton and Mayne make no reference to flow visualization or the presence of corner vortices, but the mean pressure contour pattern for the 10° case in Fig. 2 shows a strong resemblance to the data from the cornering winds on the Texas Tech University building in the 1990s. However, Newbury and Eaton (1974) show a sketch of corner vortices and so some flow visualization was actually performed. In any case, the steeper pitches seem to progressively weaken the vortex, perhaps by distorting and "squashing" it onto the roof surface. This consistency with the speed ratio data was collected over various roof pitches by Cermak et al. (1991).

Holmes (1982a) discusses some of the full-scale results from the Aylesbury building and the subsequent international model study. The full-scale turbulence intensity at eaves height ranged between 22% and 27% for the southwest to south wind and Holmes is of the view that turbulence intensity is an "important parameter to be scaled correctly in the wind-tunnel test", while the longitudinal integral length scale similarity "does not seem to be a parameter of the greatest importance". A summary of the

[1] It is interesting to note that the Wheatstone Bridge was actually invented by the mathematician Christie. Charles Wheatstone, Professor of Experimental Philosophy at Kings College, London (1834), simply popularized its use (Thomas, 1991).

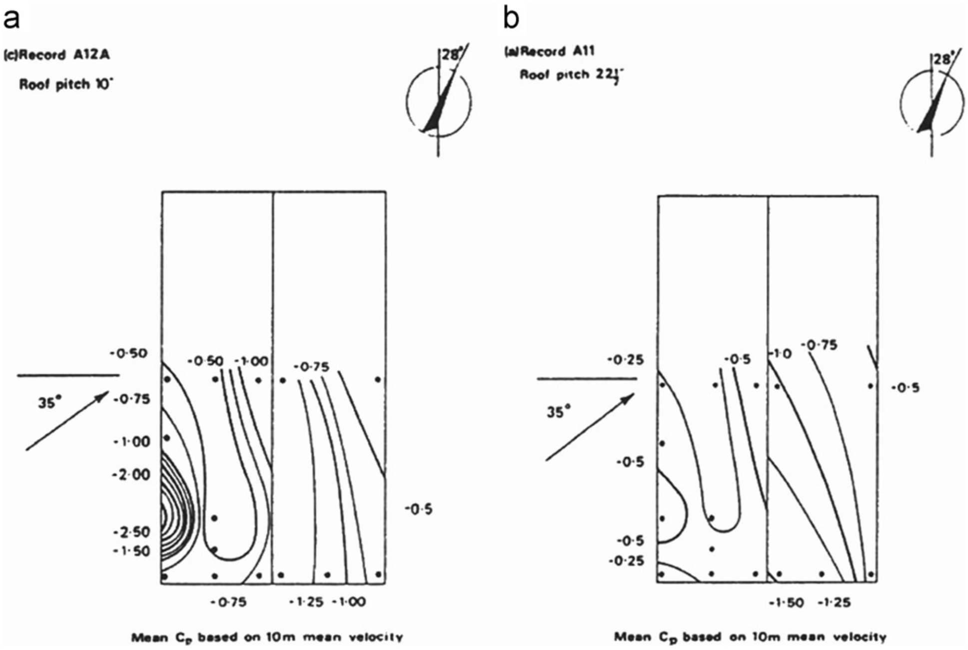

Fig. 2. Mean, full-scale pressure contours for cornering winds on two roof slopes (10° and 22.5°) of the Aylesbury House in Great Britain in the 1970s (after Eaton and Mayne, 1975).

international comparative study of the 1:100 model of the Aylesbury House is given by Sill and Cook (1989).

The Silsoe Structure Building is described by Richardson et al., (1989) and then later by Hoxey and Richards (1995). It was a portal framed, low-rise structure that featured two types of eave cladding detail. The approaching wind has a clear open country fetch (except for some hedge windbreaks) from the southwest to the northeast in a clockwise arc. The Silsoe z_o varied from 10 to 43 mm over the duration of the project. The longitudinal turbulence intensity at 10 m elevation was in the range 20–23% and the transverse turbulence intensity ranged from 17 to 18%.

The wind-tunnel studies performed by the Building Research Establishment (BRE) on the Silsoe Building were taken with a sample rate of 200 Hz and the total number of samples taken per run was 16,000. The ridge-level, wind-tunnel speed was 10 m/s. The models were then retested at the University of Western Ontario (UWO) at a higher sampling rate (500 Hz) and with more data points (30,000). The roof pressure coefficient data taken on the full-scale Silsoe Structure fell in between that measured at BRE (smaller by up to 30%) and UWO (larger by as much as 50%) for some locations on the roof. It should be noted that the shapes of the pressure plots were all very similar; the data were simply displaced vertically on those plots. The Silsoe positive pressure coefficients on the windward wall had generally good agreement between all investigators (as an aside, the peak positive pressure data on the windward wall also form the more recent area of agreement between CWE and full-scale pressure results—as will be discussed later). The data published for Silsoe were only for a centreline section of taps across the building with the wind impinging on the long side; no azimuth dependencies were shown.

A full-scale study performed on residential homes at the Malmstrom Air Force Base in Montana is reported by Marshall (1975), as well as a second study on full-scale mobile homes (Marshall, 1977). In the former, the mean data were in reasonable agreement between the model and full scale, although some correction was required for the siting of the static pressure source. However, the serious mismatch of turbulence intensity resulted in peak pressure coefficients that were consistently deficient in the model studies. The full-scale turbulence intensities ranged from 27% to 38%, while the wind-tunnel flows varied from 6% to 31%. This connection between the peak pressures recorded and the approach turbulence intensity has been demonstrated by others more recently (Okada and Ha, 1991). However during this period, immediately after Marshall's experiments, Surry (1982) expanded on the important impact of a mismatched scale and turbulence structure in the wind tunnel. Marshall (1975) writes,

> "The consistently low fluctuating pressure coefficients obtained from the wind-tunnel model are attributed to improper simulation of the lower portion of the atmospheric boundary layer"

Reardon and Holmes (1981) give a synopsis of their research on low-rise structures performed at James Cook University (JCU). The authors discuss trends noted in the JCU boundary-layer wind tunnel in a variety of flows and model geometries. Some of their pressure related conclusions include:

- For flows perpendicular to a wall, a more turbulent environment resulted in closer reattachment, more free streamline curvature and lower pressure coefficients.
- For quartering flows the action of the vortices was enhanced by roof overhangs.

Of particular relevance to physical (and CWE) modeling is their commentary on the siting of the extreme roof suctions.

> "The worst mean roof suctions, independent of direction, occur along the edges near the windward corner, but not at the corner itself"

2.3. Later validation of the boundary-wind tunnel: low-rise buildings

The CSU/TTU Cooperative Program on Wind Engineering contributed to wind-tunnel validation in the 1990s, and one prime focus was on the model and full-scale pressure coefficient data comparison on the TTU Building. There was excellent agreement for all mean pressure coefficients between the 1:100 model and the full scale (Cochran, 1992). This matching of mean coefficients was regardless of the tap location and approaching wind azimuth. Other model-scale/full-scale comparisons in the literature generally do not demonstrate this most basic feature since the azimuthal mean pressure coefficient dependence is usually not published for both the model and full-scale data. The emphasis has usually been placed on the flows normal to the test building.

Two early studies of the TTU Building should be noted. Surry (1989) reported on wind-tunnel studies performed at UWO prior to any full-scale data being available and Okada and Ha (1991) presented data collected at the Building Research Institute in Japan.

The study by Okada gave good mean pressure coefficient agreement with the full scale, but the magnitude of the peak and standard deviation data were significantly less than were reported on the Lubbock full-scale building. The data were reported for normal flow orientations only. Okada attributes the mismatch in peak and standard deviation data to a combination of two modeling limitations. His turbulence intensity was only 75% of that recorded in the field and, as noted above, this is an important parameter for peak pressure measurements in the wind tunnel. In addition, the long tubing system and Scanivalve used to collect the data required a low-pass filtering at 50 Hz. When combined with a modest sample rate of 100 Hz, the collection of reduced peak and standard deviation pressure coefficients can be expected (Rofail and Kwok, 1991).

The data reported by Surry (1989) were collected "in advance of the full scale data" so as to "partly provide an 'unbiased' set of pressures for comparison". Surry's motivation for this procedure was to avoid the subtle, but real, observation that "model experiments are often a matching process, where wind-tunnel simulations are varied until reasonable agreement is obtained, rather than being truly independent simulations". *CWE validations need to avoid this temptation as well.* The 1:100 model tested at UWO was exposed to two flow regimes. The flow designated "exposure #2" most closely matched that seen at the TTU field site and the freestream flow velocity used in the tunnel was 14 m/s. The tubing system was of modest length (610 mm) and included a Scanivalve. Consequently low-pass filtering at 100 Hz was employed. At a relatively high sample rate of 500 Hz this tubing system was probably adequate to capture all the peak pressure coefficient data available in the wind-tunnel flow. In fact, a tubing system with an improved frequency response did not alter the peaks greatly (Surry, 1991). All the pressure coefficient data (mean and peak) from the 90° flow case of Surry's study are in good agreement with the TTU full-scale data. However, the data presented for the "near 60°" flow direction show significant disagreement over the centerline taps. The peak suctions on the model were about 40% less than the values at full scale. This was an early indication of the mismatch of peak pressure coefficients that occurs when the dominant flow mechanism is the roof corner vortex. For building surfaces not under the influence of the corner vortices the agreement between the model and full-scale peak coefficients is good.

2.4. Validation of the boundary-wind tunnel: high-rise buildings

Comparative studies between full-scale structures and wind-tunnel models have been reported for a few high-rise buildings and towers. Davenport (1988) reanalyzed the data collected by Rathbun (1940) on the Empire State Building and found reasonable agreement with a high-frequency force balance model study. No local pressure data were used in the comparison. Similarly, the dynamic characteristics of Sydney Tower (Kwok, 1983) agreed well with those observed in the wind tunnel.

However, cladding pressure data are relatively scarce on high-rise structures. One contributing reason is the difficulty in establishing a reliable reference pressure. One useful study was performed on the Commerce Court Tower (239 m tall) in Toronto and was reported by Dalgliesh (1975). The reference pressure was "a common internal reference pressure, that of the recording room on the 33rd floor". In summary, the mean data agreed well with the wind-tunnel results, but the author had less confidence in the standard deviation data.

Holmes (1976) discusses the full-scale spectra and cross-spectra of pressures on the 43-m Menzies Building at Monash University. In this investigation of these frequency dependent properties, an assessment of the alongwind gust factor method is presented for the rectangular structure as a whole. Neither the specific mean and peak pressure coefficients, nor a wind-tunnel comparison is the principal focus of this paper (the original dissertation may contain this information). However, the non-linear relationship between a Gaussian upwind velocity field and the non-Gaussian pressure response on the structure is noted as important for the higher turbulence intensities found close to the ground. This topic is elegantly expanded upon (with some experimental data) a few years later (Holmes, 1981).

2.5. Summary statements on validation of the boundary-wind tunnel

In summary, the difficulty in obtaining good stationary pressure coefficient data in the field is routinely demonstrated by all of the full-scale studies. When comparisons are made with wind-tunnel coefficient data the full-scale data are almost always more scattered—even when the full-scale data are selected for stationarity. This is, in part, caused by difficulty in presenting single extreme peak samples in a random process. Fig. 3 shows a comparison between the full and model-scale pressure coefficient data for a central wall tap on the TTU Building. The agreement is reasonably good, even noting the full-scale scatter that occurs after stationarity tests have been satisfied.

However, the same cannot be said for the roof corner (Fig. 4), particularly when under the influence of the roof corner vortices. This mismatch is caused by at least two mechanisms: (i) a Reynolds number mismatch of the tight vortices (Fig. 5) and

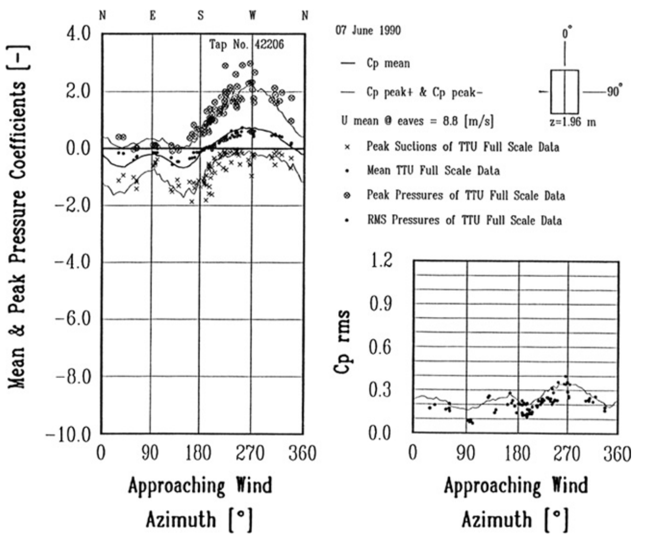

Fig. 3. Full-scale and model-scale (1:100) pressure coefficient data for the Texas Tech Building for a tap located at the center of the long wall (after Cochran, 1992).

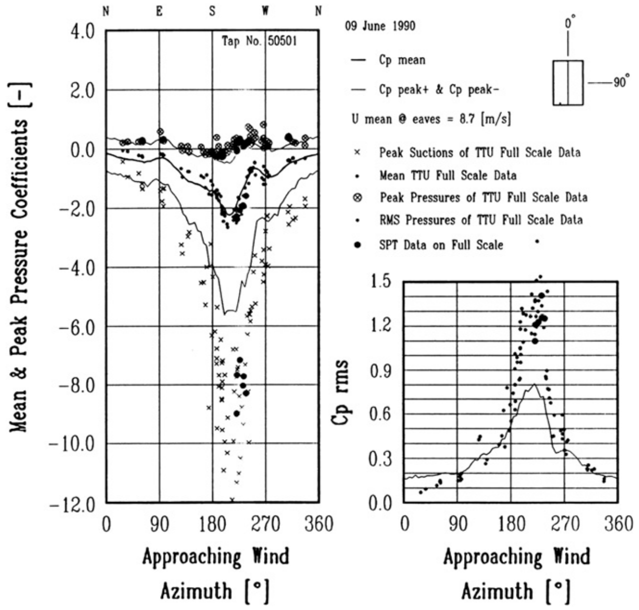

Fig. 4. Quartering winds at the roof corners produce roof-corner vortices. Wind-tunnel data do not capture the same magnitude of peak coefficients due to the relative tap size (see SPT data) and Reynolds number influences discussed below (after Cochran, 1992).

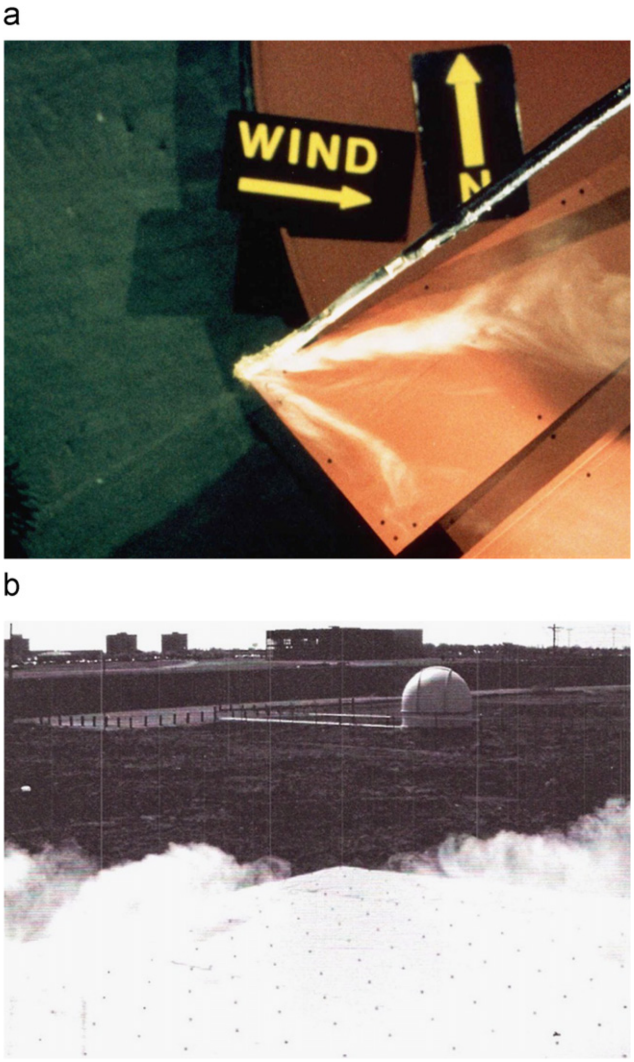

Fig. 5. Roof-corner vortices on a wind-tunnel model (top) and on the TTU Building (bottom).

Fig. 6. 1:10 TTU Building model in the large Monash University wind tunnel (after John Holmes).

(ii) a need for an equivalently-scaled pressure tap size between the model and prototype, particularly when the tap is a comparable size to the flow mechanism causing the peak pressure. A study of a 1:10 model (Fig. 6) of the TTU Building in the large Monash University wind tunnel by Cheung, Holmes, Melbourne, Lakshmanan and Bowditch (1997) indicates that (i) is a partial reason, and the full-scale experiment using a "super pressure tap" (SPT, in Fig. 7 and the large dots in Fig. 4) at the TTU Building (Cochran et al., 1993) confirmed the impact of (ii). The apparent shortcoming of modeling vortex flows in a wind tunnel, at small scales, to obtain design cladding pressures is offset by the application of these peak pressures over full-scale areas much larger than the tap on the model (e.g. a pane of glass at the sharp top corner of a building). The impact of progressively larger tributary areas is well established in many wind-loading codes and sources like Hosoya et al. (1999). Thus, the designer is getting useful design data (due to the inherent area averaging of peak pressures at full scale) but, perhaps, for the wrong reasons.

Some more recent wind-tunnel studies of the Texas Tech Building by Endo et al. (2006) have shown better agreement with the full-scale data under the corner vortices (Fig. 8 shows tap 50501, as in Fig. 4 too) when a series of ergodic, repeated data-collection runs (up to 150 for each azimuth in this 2006 study) is used to define the peak pressure coefficient range (labeled "peak-max", "peak-ave" and "peak-min" in Fig. 8). This type of distribution for peak pressure statistics is discussed by Holmes and Cochran (2003) and the use of this concept has resulted in better agreement with the full scale than the single-event, largest peak pressure coefficient from the wind-tunnel study shown in Figs. 3 and 4. Both the 1992 and 2006 studies had very similar modeling parameters (open-country, boundary-layer, approach profiles, although the 2006 study had an improved incident turbulence structure), test procedures (five-degree azimuth increments) and frequency response characteristics (tubing response flat to over 200 Hz and sample rates over 1000 Hz). Thus, the principal impact on wind-tunnel modeling is the use of multiple runs to explore the range of statistically likely peaks. Directly under the roof-corner vortices (approximately 200–250° in the case shown in Fig. 8) there is still some mismatch, but this statistical approach is clearly an improvement (since the full-scale data may be considered a collection of multiple runs too) and this should be considered by CWE practitioners validating cladding pressures in the future. It seems likely that any remaining mismatch of peak cladding pressures between the wind tunnel and the full scale is due to the Reynolds number influence at model scale under the tight vortices, and relative tap sizes, discussed earlier.

Before leaving the topic of rooftop corner vortices it is probably worth mentioning some studies that have shown ways

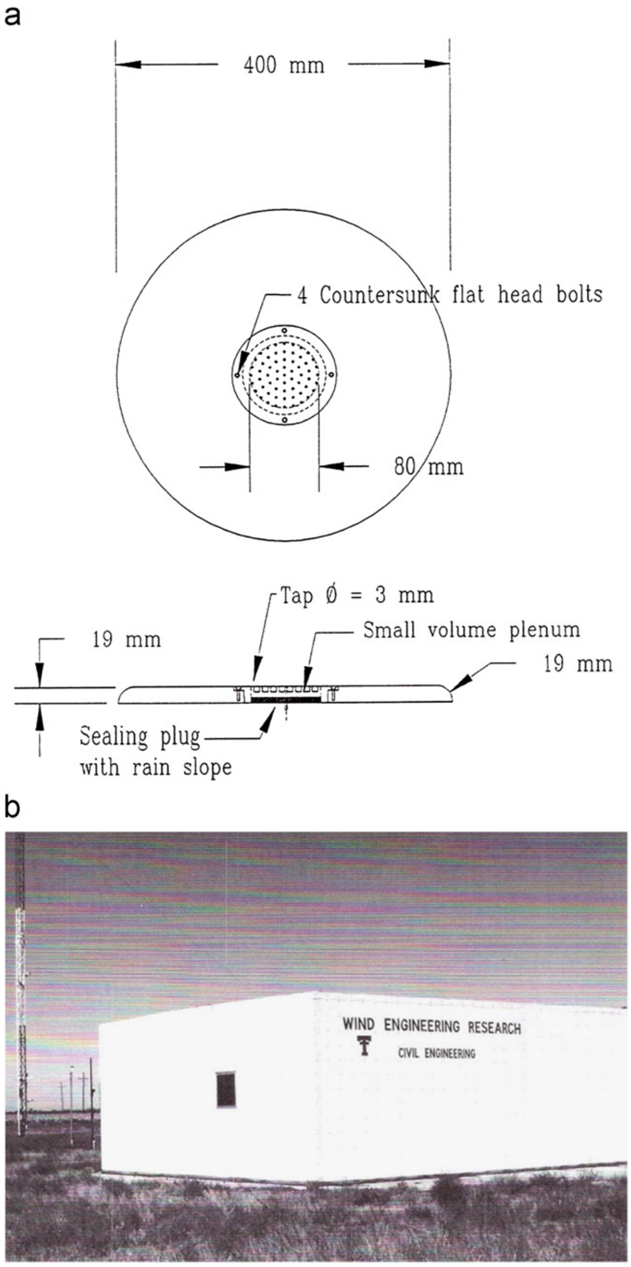

Fig. 7. "Super pressure tap" (SPT) used on the TTU Building (bottom) to illustrate the impact of tap size on the peak data collected. The 80-mm porous-opening diameter corresponds to 0.8-mm value on the 1:100 model.

to reduce peak roof pressures by interfering with the roof vortices of Fig. 5 themselves. One by Cochran and English (1997) used porous screens diagonally placed across the roof corner while another by Banks et al. (2001) used roof edge fairings. Fig. 9 shows a full-scale validation study of the wind-tunnel work by the latter team.

3. Computational Wind Engineering successes

3.1. CWE: a basic introduction

CWE is an evolving field (discussed by Murakami, 1997) that often works best in complement with the wind tunnel, depending on the phenomena being studied, as we shall discuss. Merging the

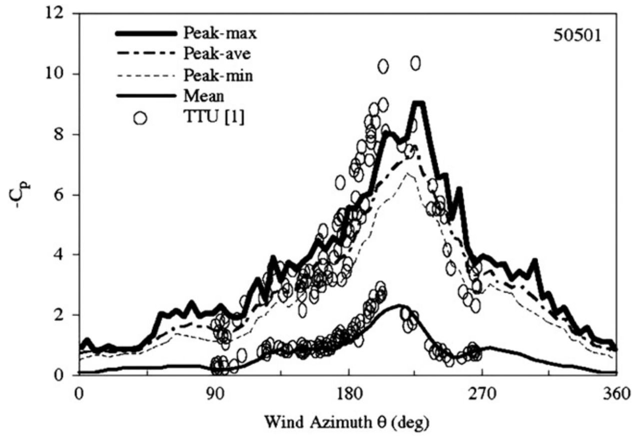

Fig. 8. Range of peak pressure coefficients from a model of the TTU Building collected by multiple ergodic experiments in the wind tunnel (after Endo et al., 2006).

advantages of each can produce a powerful hybrid design and analysis tool. However, it is becoming increasingly apparent that CWE can operate as a stand-alone tool in many circumstances, and sometimes it is the only valid tool. CWE employs a computational fluid dynamics (CFD) software tool that is commercially sold or licensed, or is available as a free download from various web sites. There is a growing wide range of commercial and open source CFD tools applicable to support wind engineering applications. Additionally, there are also several related meso-scale atmospheric modeling tools available. Most of these address the three main classes of CFD.

The three main classes of CFD include:

1. Direct numerical simulation (DNS), the most rigorous of CFD tools, employs a fine numerical grid that resolves all scales in a turbulent flow from large energy producing eddies down to molecular dissipation scales. DNS typically is computationally exorbitant and is appropriate only for research and to supplement lesser CFD tools in practical engineering applications. Frequently, DNS also finds use in validating turbulent closure schemes in large eddy simulation (LES) and Reynolds-averaged Navier–Stokes (RANS) tools.
2. Large eddy simulation (LES), often the most practical CFD approach in terms of accuracy for computational cost, resolves all energy producing eddy spatial scales and "models" the turbulence at the sub-grid scales not resolved by a computational grid. Resolved and unresolved scales are separated by spatial filtering. In finite difference (FD), finite volume (FV) and finite element (FE) versions of LES, filtering is conceptual and implicitly assumed by the existence of a discrete computational grid. For pseudo-spectral methods (fully spectral methods are prohibitively costly), which utilize orthogonal basis functions for spectral components and perform computations of the nonlinear advective terms on a spatial grid, filtering is performed at each time step through application of an explicit spectral filter. With LES the sub-grid scale (SGS) turbulence is time-dependent and is required to be in the inertial sub-range where turbulence production and dissipation balance each other and is modeled by various closure methods, from simple to more complex. For accurate simulation results, the skilled CFD user needs to assure that SGS turbulence indeed resides in the inertial sub-range through appropriate grid resolution (there are currently scarce "a priori" means for assuring proper grid resolution, but several "a posteriori" assessment methods exist). Examples of SGS models include Smagorinsky algebraic

Fig. 9. Roof-edge fairing on the TTU Building (after Banks et al., 2001).

closure, dynamic Germano (1992) model, wall adapting local eddy viscosity (WALE), RNG-LES and various of dynamic turbulent kinetic energy (TKE) schemes (e.g. 1.5-order closure with a transport equation for SGS TKE). Murakami et al. (1999) provides a useful comparison amongst the standard, dynamic and LaGrangian dynamic Smagorinsky SGS closure models. All of these models produce an eddy viscosity that represents the SGS turbulence in the transport equations for the resolved scales. Smagorinsky closure is the simplest and least rigorous, and assumes isotropic sub-grid scale turbulence. SGS turbulence modeling was pioneered by Smagorinsky (1963), Lilly (1967) and Deardorff (1973). Deardorff (1980) introduced a transport equation for SGS TKE, leading to the so-called 1.5-order turbulence closure of the transport equations for the resolved scales. There are those who refer to Deardorff as the "father" of LES.

3. Reynolds-averaged Navier–Stokes (RANS), the least rigorous CFD approach, provides only limited levels of transient phenomena that can be critical in many engineering applications. The limitation above refers to a slowly varying time average of the flow. Thus, RANS cannot handle transient dominated or non-stationary phenomena such as downbursts or intermittent "washout" of pollutants in trapped geometries. RANS, by definition, entails time averaging that produces mean quantities and deviations from the mean, leading to time-invariant Reynolds stresses that are modeled by various schemes. A RANS simulation requires less grid resolution than LES, hence is cheaper but less accurate. The Reynolds stresses, based on time averaging, are not sub-grid phenomena, per se. A common approach to modeling Reynolds stresses includes various types of k–ε (turbulent kinetic energy and dissipation, respectively) dynamic transport schemes. The k–ε two-equation approach, which has its basis in an eddy viscosity, is deemed more economical than utilizing direct transport equations for the Reynolds stresses (Deardorff, 1973; Launder, 1991). A rigorous mathematical derivation of the k–ε equations can be found in Scott-Pomerance (2004). The standard k–ε scheme assumes isotropic sub-grid scale turbulence. RNG k–ε (re-normalization group) closure and realizable k–ε closure both assume non-isotropic turbulence, but realizable k–ε closure is more mathematically faithful to the physics of vorticity.

For both LES and RANS, knowledge of the potential implications of the flow geometry in a given engineering problem is useful in selecting the appropriate sub-grid scale turbulence scheme. Likewise, practical computational limits on grid resolution can also drive choices in turbulence closure schemes. It is important to note that available CFD tools vary in the turbulence closure schemes they provide.

There are also other CFD approaches to modeling turbulent flow, and new methods constantly are emerging on the horizon. For example, the detached eddy simulation (DES) model is a hybrid method that reverts to an LES in computational regions for which the grid resolution can economically simulate the inertial sub-range, and switches to a RANS model in locations, such as near a wall, where the length scale of turbulence exceeds the grid spacing. DES ostensibly is advantageous for capturing wall flow separation and reattachment.

A new, promising CFD methodology developed by Perot and Gadebusch (2007, 2009) has emerged recently that entails a self-adaptive (LES/RANS/DNS) turbulence methodology. The authors argue that LES is ready for a two-equation approach as with RANS for turbulence modeling and predicate their developments on seminal work by Germano (1992). Key aspects of the methodology: (a) represents a "universal" turbulence model; (b) comprises a two-equation (k–ε) turbulence model that automatically adapts to RANS, LES, or DNS as a flow evolves, depending on user input for mesh resolution; (c) adds more complexity, hence physical rigor to LES models; (d) allows backscatter from unresolved to resolved scales, which enhances physical realism; (e) improves on length scale deficiencies of DES; (f) no more need for a posteriori assessment of LES simulations; and (g) RANS output does not necessarily result in RANS-like steady solutions.

In closing, as with physical modeling, it is critical in CFD to have the numerical inflow boundary conditions match the mean and turbulent inflow conditions of the prototype. Inflow turbulent conditions are the most difficult to match, but there are various available techniques to achieve this (see, for example, Xie and Castro, 2008). However, in cases where significant obstacles reside between the inflow boundary and the target object, those upstream obstacles often produce the turbulence necessary to match model and prototype. In some cases, the high frequencies generated by upstream obstacles may be highly coherent due to the geometry of those obstacles and their proximity to the target object. Thus, in some cases one may be able to get away with modeling the inflow mean velocity profile and ignoring inflow turbulence. The parallel here with the physical cityscape model on the wind-tunnel turntable model is obvious.

3.2. Structural loading

An example of a hybrid CWE/wind-tunnel study for structural loading is the slim, 50-storey, beachside condominium shown in Fig. 10. The long axis of the lenticular shape points into a common and strong wind direction coming off the ocean with little oncoming turbulence from upwind buildings. For this wind azimuth the initial force-balance study in the wind tunnel

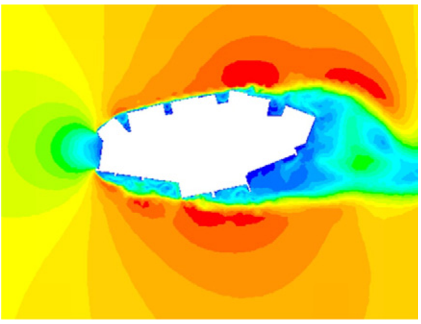

Fig. 10. The flow is from left to right in this LES, unsteady, snapshot of the velocity magnitude contours (blue = 0 m/s and red = 15 m/s). This initial design formed a baseline for modifying the building shape to reduce the crosswind response (after CPP Inc.). The full flow video may be seen at www.aawe.org. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

indicated a crosswind response that was unacceptably strong on the upper floors. The architect was receptive to some minor shape changes to the design. Rather than building several balsa wood force-balance models, it was decided to use CWE with an LES CFD model over a three-dimensional slice of the prismatic building at about three quarters of the building height where the approaching longitudinal turbulence intensity was about 12%.

The CFD model was then calibrated to the local pressure data (particularly in the separated region) collected in the wind tunnel on the 1:300 pressure model. Small geometry changes could then be explored cheaply using CWE for this critical single wind azimuth. The final result was a bullnose at the leading edge and some added curvature in the balcony walls. The CWE effort suggested these features as a solution, and they were confirmed with a second physical-model study of the new shape in the wind tunnel. This hybrid approach yielded a more cost effective, timely design than if pursued by either the wind tunnel or CFD alone.

A point to be made here is that, although we want to stress validation over calibration as a fundamental tenet in both physical and CFD models, it is totally appropriate to employ calibration in this example in which measured pressures in the wind tunnel provided critical input for the CFD model. In time, as CWE evolves, calibration will play a decreasing role. However, CWE/wind-tunnel hybridization speaks to the necessity of calibration, and calibration can go both ways: (a) the wind-tunnel calibrating the CFD model, as elucidated in the preceding example and (b) the CFD model calibrating or superseding the wind tunnel, as in thermally driven flows (e.g. Froude number controlled flows in complex terrain where flow really moves around peaks, rather than over them) that cannot be simulated in a standard wind tunnel.

3.3. Natural ventilation

Another hybrid use has been to aid in the design of naturally ventilated buildings. A physical pressure-tapped model is first installed in the wind tunnel to collect simultaneous times-series pressure data at all the potentially open parts of the façade for 36 wind directions. These data then form the time-varying external boundary conditions for a CFD study of flows internal to the building itself, driven by the external ambient building pressures that occur for common return periods (seasonal, annual, monthly, etc.). When compared to the older approach with CFD of assuming a simple mean-pressure differential from the ambient wind across the building, the gusty, time-dependent perimeter conditions provided by the physical model result in a more realistic understanding of the "flushing" of stale air inside the structure.

Recent comparisons by Meroney (2009a) between the wind tunnel and CFD in exploring natural ventilation suggest that CFD can provide both the external and internal flow analysis, precluding the need for the wind tunnel, at least in some cases. In this study, CFD was compared to wind tunnel efforts by Karava (2008) and Karava et al. (2007) in which particle image velocimetry (PIV) was employed to gather velocity vectors and simultaneous pressure distributions for ten ventilation cases, including cross-ventilation, for a single, isolated building. However, Meroney's results make clear that the correct choice of turbulence closure in a CFD model is critical to capturing correct flow separation and reattachment behavior, hence correct exterior pressure distributions. Errors in pressure distribution around a building would, of course, lead to errors in simulated ventilation flows with CFD. Thus, the skill and knowledge of the CFD practitioner, in turbulence model choice and simulation operation, are critical. Also, the study does not assess how well CFD would do as a stand-alone tool with multiple buildings upwind, laterally and downwind of the target building.

It is important to note that the current inability of CFD to generate the correct peak pressures (more so with negative values than positive values) around a bluff body is not critical to ventilation studies, unlike structural applications. The latter is better covered by the physical model.

The structural study in Section 3.2 and the natural ventilation study mentioned above that combine physical modeling and CFD use the best features of each approach at the current state of the art, but that appears to be rapidly changing as CFD forges the way to a solely computational future. Currently, the physical model is better at producing the external transient pressures on a bluff body, particularly if multiple buildings and complex geometries are involved, but Reynolds number issues pertaining to the small (say, 1:300) openings (operable windows) result in an unsatisfactory modeling of air flow within the structure in the wind tunnel. However, the use of CFD within the building can negate this shortcoming. Thus, CWE and physical modeling form a powerful hybrid tool for ventilation studies. We shall see how the scenario with stand-alone CWE progresses in time.

3.4. Thermally dominant flows

Since the CWE technology includes the exchange of energy in most forms within a flow field, the technique is quite suited to flows that are principally thermally driven, rather than mechanically driven. Examples might include: HVAC designs for large, enclosed arenas; fire simulations in hotel or office building atria; and flow within large, double-glazed solar walls.

Presumably the full-scale validation, in a gross sense, of HVAC studies within a large public space (Kent, 1994) is ultimately determined by the success or failure of that public space. Indeed, CFD in the hands of a capable analyst has proven to be quite effective in a range of HVAC designs, leading to observable mechanical efficiency and human comfort. One could thus argue that the CFD approach to HVAC design, not physical modeling, is the most cost-effective way to analyze such complex internal spaces, and if the end product is not a success the consequences are not life threatening (unlike, say, a structural or cladding failure). In contrast, the smoke from an atrium fire could be life threatening. Thus, significant studies with physical test facilities and other validation methodologies (McGrattan et al., 2009) have been done by the National Institute of Standards and Technology (NIST) in order to develop a powerful CFD tool for smoke analysis,

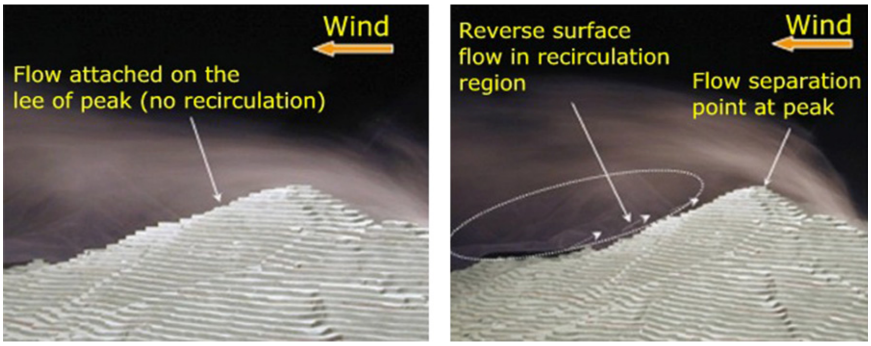

Fig. 11. Wind tunnel simulation showing intermittent flow separation and reattachment over a terrain peak on scale model of Lantau Island near Hong Kong. Modeling separation behavior with CFD can be erroneous and lead to misrepresentation of flow downwind of peak as shown by Derickson and Peterka (2004).

the Fire Dynamics Simulator (FDS). One could argue that for both types of thermally driven problems, the appropriate CFD tool provides the current best analysis for design.

The third type of study that has become popular and valuable is the analysis of air movement in the large double-glazed solar walls. This is also an example of a hybrid approach and could be considered part of Section 3.3, but the focus here is the low flow-rate, thermal nature of the domain being investigated. These wide (500–800 mm) double glazed walls often have operable louvers at the top and bottom regions of the facade. A wind-tunnel study is used to create the external, time-varying, pressure boundary conditions at these louvered openings, and the CFD simulation establishes the heat-transfer and flow inside the wall—often around shading elements and structural components. As green building design blossoms, this type of hybrid study is becoming more common. In time, as discussed in Section 3.3, CFD seems certain to replace the wind tunnel in determining external flow-induced pressures.

3.5. *Long-span bridges*

For quite some time now the initial dynamic response of long-span cable-stayed and suspension bridges has been done by body-fixed-coordinate CWE studies. There are several features of this sort of fluid-structure interaction that lend themselves to CWE: (i) the approach flow typically has low ambient turbulence since the bridge is usually over a large body of open water, (ii) the section shape is usually somewhat streamlined (fairings) and is constant along the bridge length (useful two-dimensionality) and (iii) earlier work on wing sections means that the aeroelastic response is reasonably well understood. Once the section shape is defined using CWE, the design must be checked via a full aeroelastic physical model in a boundary-layer wind tunnel for influences like tower or terrain induced turbulence and, possibly, the impact of trains and traffic on the bridge response in strong winds. This particular use of CWE during the early stages of long-bridge design seems to be a success story.

3.6. *Terrain flows*

CWE has made useful inroads into siting wind farms in complex terrain, particularly when thermal stratification plays a crucial role, as it often does. To date, this has usually been most successful in gently undulating terrain where flow separation does not occur. Early studies showed the validity of CFD for unseparated, thermally stratified flow (stable, neutral and unstable) over smooth hills with slopes of 1:4 and 1: 3 through comparison to wind-tunnel (neutral thermal conditions) and field measurements (Derickson and Meroney, 1977). The wind stays attached only to gentle, smooth terrain. Intermittent or complete flow separation will occur if the change in slope is large enough (Derickson and Peterka, 2004a) as shown in Fig. 11. An LES CFD simulation (using the multi-scale atmospheric model ARPS, Advance Regional Prediction System) for thermally neutral flow over the terrain shown in Figs. 11 and 12 did not do well in simulating the flow at locations downwind of the peak, even with vertical grid stretching for better spatial resolution near the surface and refined 1.5-order turbulence closure.

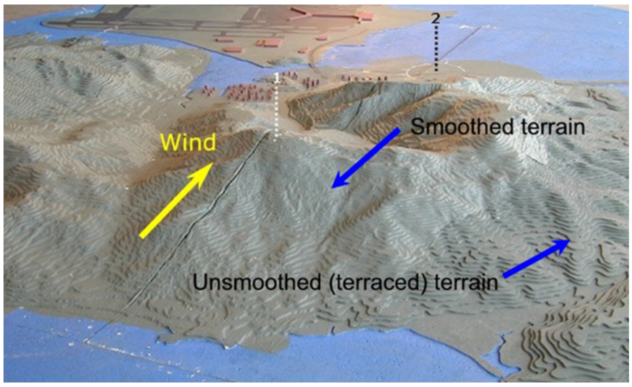

Fig. 12. Full view of scale model of Lantau Island near Hong Kong. Point 1 denotes the peak shown in Fig. 11. Because of poor representation of intermittent cycles of flow separation and reattachment, the CFD model was poor in simulating the flow at all locations between Points 1 and 2. Also note the smoothed and terraced portions of the terrain model in the study (from Derickson and Peterka, 2004).

Deeper discussion on flow separation over terrain is vital. The terrain peak shown in Figs. 11 and 12 (denoted as Point 1) is not sharp as the corner of a building is, for example. Consequently, the separation point is not clearly defined and can be observed to oscillate between points upwind and downwind of the crest. Therefore, the separation bubble in the wake of the peak can assume a myriad of shapes, with extreme consequences on the magnitude and character of the flow at all downwind locations.

Thus, even slight errors in simulating the point of flow separation and capturing the intermittent cycles of separation and reattachment led to unsatisfactory results of mean winds and standard deviation values at downstream locations. In this thermally neutral flow case, the wind tunnel provided superior assessment of the wind field compared to CFD throughout the entire terrain, except for windward slopes where flow separation did not occur.

Other investigators have experienced identical difficulties with atmospheric numerical models in accurately simulating the flow separation and its intermittency at topographic peaks in complex terrain, despite great efforts at refining their LES simulations. These investigators include Raithby et al. (1987), Castro et al., 2003, Chow and Street (2004), Bechmann et al. (2006) and Andersen and Laursen (2008). Chow and Street (2004) used the same ARPS model with 1.5-order TKE closure as Derickson and Peterka (2004). More recent efforts by Chow and Street (2009), building on the dynamic reconstruction model (DRM) developed for LES by Chow et al. (2005), resulted in improvements in simulating flow separation over complex terrain. DRM employs an explicit filter to separate resolvable and SGS turbulence and reconstructs resolvable subfilter-scale stresses (RSFS) with series expansions. This results in a scale-similarity model for turbulence. As mentioned in Section 3.1, LES typically has no explicit filtering, so this new method introduces a significant innovation. Chow and Street (2009) claim that utilizing the standard 1.5-order TKE closure found in most LES models with a low order reconstruction scheme is a practical way to treat flow separation better and its intermittency. The jury may still be out as to how well the DRM improves LES solutions for flow over complex terrain when flow separation is a major factor.

Wind tunnels model flow over complex terrain well, but are generally limited to thermally neutral conditions. Atmospheric models are superb at thermally stratified flows as long as flow separation due to terrain complexity is not the determining factor in downwind flow accuracy. So, until LES evolves to a definitively higher state of turbulence closure, the hybrid use of physical modeling and CFD may be the best choice for the wind engineer.

Another major influence on flow (both flat and complex terrain) is aerodynamic roughness, z_o, which typically varies spatially and seasonally as a function of surface obstacles such as buildings and vegetation. Derickson and Peterka (2004) explored the effect of variations in z_o on the surface boundary layer over complex terrain. Meroney (1980) looked at the influences of the typically used "terraced" terrain scale models used in wind tunnel studies versus smoothed contour terrain and found crucial differences due to the fact that the terraced "steps" produce artificial flow disturbances near the surface, as would be expected. Derickson and Peterka (2004a) independently confirmed this effect. Fig. 12 shows the "smoothed" terrain and the original terraced terrain adjacent to the smoothed region targeted for flow analysis.

Let us turn our attention to more extreme terrain as shown in Fig. 13. The importance of separated shear layers impacting wind turbines cannot be overemphasized. At best, the efficiency will decrease dramatically if mis-sited, and at worst, the varying mean velocity and turbulence structure with height will severely damage the turbine itself. As the wind-energy designers move into more complex environments (escarpments, cliffs and even the tops of buildings) we are likely to see shortened turbine lives and some dramatic failures if more validation is not performed on the CWE models with the wind-tunnel terrain models and full-scale data (Derickson et al., 2004). Fig. 13 (left) shows a terrain model study in the wind tunnel designed to explore the size and extent of the separated shear layer off a steep escarpment.

Because an escarpment has a sharper edge, the separation point is more defined, but perhaps not as well as a sharp corner of a building. Thus, one could perhaps expect a good CFD LES model that employs high grid resolution and refined turbulence closure to do an adequate job in simulating the flow field for wind power micro-siting and assessment in such extreme terrain. Ironically, current meso-scale models employed for research and practical application in the field of atmospheric science, such as ARPS (Advanced Regional Prediction System), WRF (Weather Research and Forcasting) and RAMS (Regional Atmospheric Modeling System), can only handle moderately complex terrain, such as shown in Figs. 11 and 12, and are unable to model escarpments or other extreme terrain. However, the other CFD models mentioned in Section 3.1 can handle extreme geometries with proper grid resolution and turbulence closure, but have not generally been used in geophysical flow simulations. In closing, it remains that the hybrid use of wind-tunnels and CWE may best serve the analysis of flow over complex terrain for wind power applications.

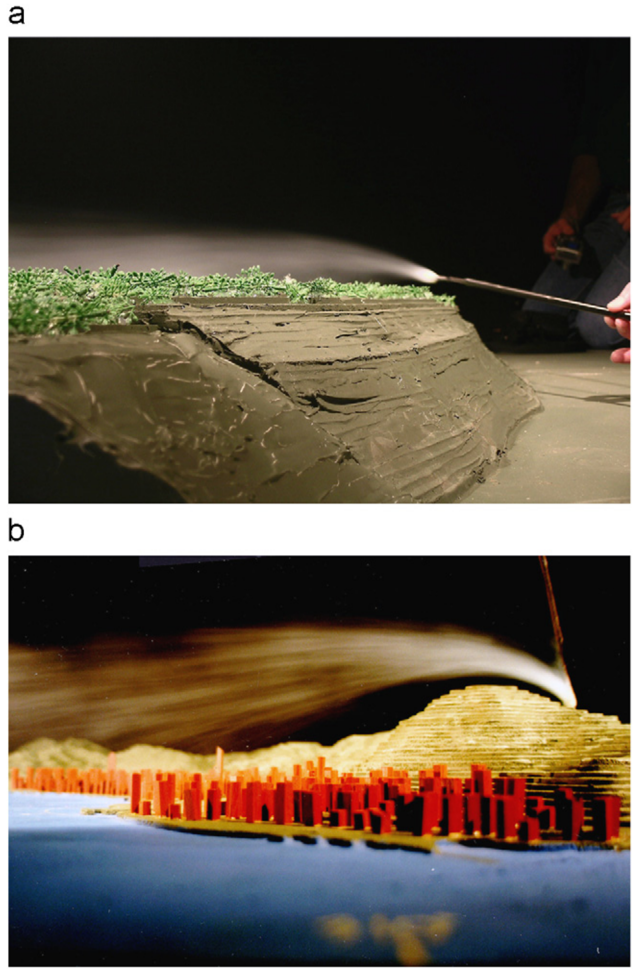

Fig. 13. Exploring flow separation on an escarpment model for a potential wind energy project (top) and over Victoria Peak on Hong Kong Island (bottom) for the wind structure at Central in the boundary-layer wind tunnel.

3.7. Mean pedestrian winds and architectural massing

Useful design guidance for the architectural community is provided by the investigation of pedestrian-level wind conditions at ground level during the massing stage of a new development (Stathopoulos and Baskaran, 1996). The resulting mean-velocity contours can give good guidance on the placing of wind-sensitive elements like entrances, restaurants, pools and other long-term outdoor spaces (Cochran, 2004). Even though the peak velocities from CWE may not be reliable for the assessment of ambient conditions, as might be suggested by the criteria of Lawson (1990), the mean-velocity overview has value to the preliminary design. It is well known that the streamline curvature of some flow phenomena, such as separation, is influenced by the ambient turbulence. Thus, perhaps the final design should be studied in the wind tunnel with instruments, such as a hot-film anemometer (or similar), to obtain a better understanding of the mean and peak gust windspeeds in these highly turbulent flows around buildings. The very gusty conditions (often) and the proximity of the ground means that CWE is not yet a provider of the needed peak velocity data, but that may change in the not-too-distant future. When combined with the relatively large velocity steps in

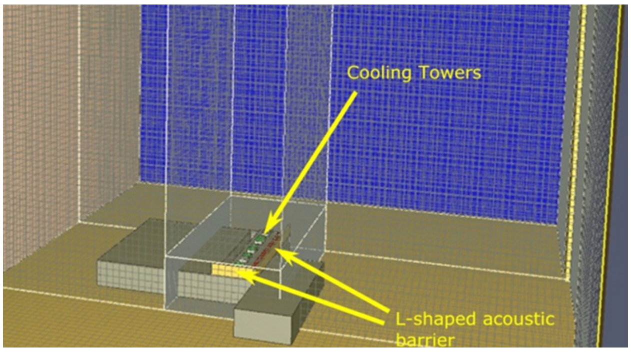

Fig. 14. Computational grid to study re-entrainment of cooling tower plumes into flow inlets due to addition of an acoustic barrier surrounding the towers on the edge of the building roof. Grid resolution is refined in the vicinity of the acoustic barrier and cooling towers (white-line box) to capture the flow physics more accurately.

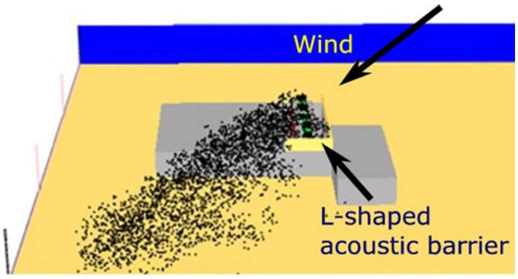

Fig. 15. An instantaneous snapshot, using SmokeView, of particles depicting the transport and dispersion of the cooling tower water-vapor plume. Note direction of wind and location of acoustic fence.

the published criteria (Lawson, 1990), it seems likely that CWE will be making further inroads into this aspect of wind engineering. The recent work by Chang and Meroney (2003), though focused on dispersion in city canyons, suggests that CFD may be capable of capturing gusty flows in complex geometries that could be relevant to pedestrian wind analysis.

Further validation with the full scale or wind tunnel is needed before pedestrian-wind studies are done purely by CWE. Work to date on validation, such as that discussed by Stathopoulos (2002), indicates that mismatches in the range of 50–200% are common in the turbulent regions of a cityscape. In the meantime, the mean-velocity contour plots determined by CWE have a valuable place in the preliminary design process.

3.8. Dispersion

A stand-alone LES CFD study was performed by one of the authors of this paper to assess the re-entrainment of water vapor from cooling towers due to the addition of an acoustic barrier on the edge of a roof. Fig. 14 displays the computational grid employed with the NIST-FDS tool and the NIST SmokeView visualization package. Grid refinement (within the white box surrounding the cooling towers) was utilized in the vicinity of the cooling towers to effectively capture the critical, interactive flow physics between the acoustic barrier and the cooling tower plumes.

Figs. 15 and 16 show the instantaneous snapshots of particles depicting the transport and dispersion of the cooling tower plumes. CFD simulations were performed with and without the acoustic barrier for a range of wind directions. Based upon previous validation knowledge of similar low-rise dispersion studied, the CFD results are believed to yield an accurate and

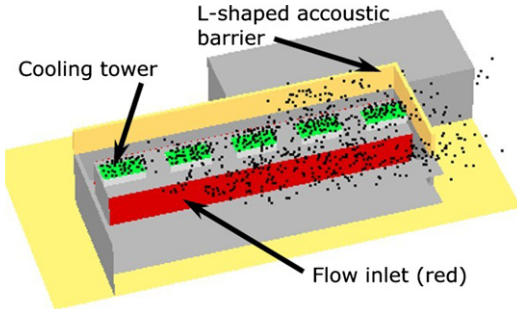

Fig. 16. Close-up snapshot, using SmokeView, of water-vapor particles emanating from the cooling towers and re-entraining into the flow inlet (shown in red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

practical analysis of the effects of the acoustic barrier on the tower plumes. Since the flow geometry entails sharp edges, including the acoustic barrier itself, flow separation points are clearly defined. In addition, great pains were taken to establish sufficient grid resolution relative to the scale and shape of the various solid geometries present. Parametric variations with the grid resolution validated this assumption. FDS uses a Smagorinksy turbulence closure scheme, which works well if the grid resolution is sufficient to ensure that the sub-grid scale eddies are in the inertial sub-range and reasonably isotropic. Simulation results in this study appeared to confirm this assumption.

A multiple participant CWE dispersion study around a low-rise building described by Cowan et al. (1996) indicated that user choices and experience radically impact the agreement between CWE practitioners. Their study also had some wind-tunnel data of dispersion parameters around the building and the range of comparative CWE around the wind-tunnel data reinforced the need for validation before computational techniques are used as a solo methodology. More recent studies by Chang and Meroney (2003) and Meroney (2006) lend confidence to CWE as an emerging tool that may supersede the wind tunnel in dispersion analysis. However, at this point in time the skill of the CWE practitioner, their understanding of the underlying flow physics, and the turbulence closure choices are all critical in achieving a realistic simulation. Dispersion CWE is not yet for the casual user in a design office.

4. Validation, not calibration

4.1. Cladding pressures

Determining peak cladding pressures using CWE seems to be the most elusive task to be achieved. Validation studies to date seem to produce reasonable agreement with the full scale (or wind tunnel) for the peak positive pressures on the windward face. However, the peak negative pressures on the other building surfaces fall disturbingly short of any match with either the wind tunnel or full-scale data. Since the integration of peak cladding pressures over the surface of a building is the first step in obtaining design structural loads this need is also not satisfied. A clear reason for CWE's failure in this regard stems from not being able to address flow separation and reattachment accurately enough. This issue will be solved as computer power increases to enable greater grid resolution and more refined turbulence closure schemes are developed to handle extreme flow deformations associated with flow separation and highly complex geometries. Overcoming these obstacles will be essential for the transition of CWE to the commonplace generation of design loads and pressures acceptable for building codes and standards. In the interim, perhaps a hybrid database approach using wind-tunnel data extrapolated by an expert system or Database Assisted Design (DAD) may be shown to be reliable. To date, that approach does not seem to be a promising design tool either.

Ultimately, the validation of peak pressures for building and cladding design needs to be largely independent of the CWE practitioner and knowledge of the target solution—validation, not calibration.

4.2. Downwash and turbulence profiles

At the most fundamental level the CWE practitioner needs to develop the correct approach profiles of mean windspeed and turbulence structure—as does the physical modeler in the wind tunnel. When reviewing papers on CWE validation (comparing CWE to the wind tunnel, for example) about, say, flows around a single tall building it is not uncommon to see the most basic flow physics missing. One author (who shall remain nameless) did not even have the essential windward-face downwash in the pathline image presented as part of the CWE flow visualization. This was probably due to the lack of a proper boundary-layer approach flow in the numerical domain, but it emphasizes the need for a good understanding of atmospheric science, and what is expected in the solution, by the CWE practitioner.

When one combines observations like this with the substantial added complexity of having three or four blocks of a city in each direction modeled in the flow domain (as is done in the wind tunnel) considerable technical improvement and validation effort is needed before we can use cladding pressures and structural loads from CWE in the design process. When that is genuinely achieved those of us who do physical modeling in the wind tunnel will be able to stop crawling around turntables checking tubing, building surrounding models and dealing with the interminable frustration of electronic instrumentation.

One fairly rare combination of a wind-tunnel study, CWE study and full-scale observations occurred during a study of the sailing conditions (turbulence and mean velocity profiles) in the lee of hotels at Palm Beach in Aruba (Cochran, 2009). A wind-tunnel study defined the extent of the recirculation zone, which diminished the sailing conditions in the lee of the hotels on the beach. Interviews with the Aruban windsurfing community on site confirmed the data generated. A later LES CFD study by Meroney (2009b) was in good agreement with the wind tunnel and sailors' observations—an encouraging confluence of data sources.

4.3. Cost of CWE and WT

With the current state of the CWE art there is a selection of problems that lend themselves to the numerical approach. As more work moves over to the computer the cost of CWE will need to come down. The cost of performing 36 wind directions of LES for cladding pressures (assuming that the peak pressure techniques evolve into being good enough for design in the future) is substantially more than the collection of the same data on 600 taps of a physical model in the wind tunnel, a factor between three and five. These are the real costs associated with running a wind tunnel (personnel, instrumentation, the building and other indirect costs) compared to the real costs of owning and using commercial CFD software (personnel, commercial user fees, the building and other indirect costs). This practical reality will have to be addressed when the validation gives us sufficient confidence in the technology.

5. Conclusions

Computational fluid dynamics (CFD) is a numerical, computer-based method for solving various types of flow problems in engineering and scientific applications. Surprisingly, current use of CFD for the analysis of structural loading on buildings is generally far less successful than its application to a broad range of atmospheric problems including numerical weather prediction, which entails many more variables (including thermal stratification and Earth's rotation) and a greater range of geophysical scales. Daily weather forecasts, which stem from a form of CFD, are typically of high accuracy and can be used effectively to make economic and general societal decisions. However, atmospheric forecasters are not without their problems. While forecasting results are generally in the ball park, they can be significantly off in predicting the exact locations and timing of severe storms. This can be critical in certain cases such as tornadoes and severe thunderstorms.

While CFD analysis of wind pressures on buildings are impressive when displayed in colored graphics and seem to look physically realistic even to the trained eye, close inspection of the numerically generated peak pressures are typically wrong to a disturbing degree. Thus, some practising structural engineers have referred disparagingly to CFD as ''colorful fluid dynamics'' or ''colorful flow drawings''. The interested reader is also referred to Stathopoulos (2002) and Holmes (2007) for their assessments of CFD in wind engineering applications.

So why is structural analysis with CFD so troublesome, yet the whole atmospheric science community revels in its success in so many of its applications? As we have elucidated in this paper, the answer lies in the complex nature of flow separation and reattachment around the bluff body shapes typified by buildings and complex terrain. No such counterpart exists in atmospheric flows, except in certain micro-scale applications entailing very complex terrain. Certainly the geometries of individual and arrays of buildings are far more angular in their complexity than the most rugged terrain. However, complex terrain is not without its challenges to CFD, as we have discussed herein. Gentle terrain does not produce flow separation, except perhaps in highly localized settings that do not disturb the larger flow field. Moderately complex terrain does not yield clearly defined points of flow separation; while severe terrain (e.g. escarpments) and buildings possess more angular features that establish precise locations of flow separation.

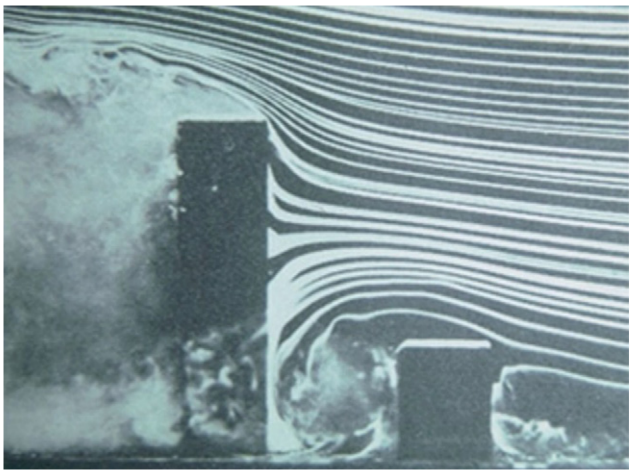

Fig. 17. Massively separated flow in the lee of the tall building (after Van Dyke, 1982).

At every level of geometric complexity, the issue of proper capture of flow separation and reattachment with CFD resides in adequate grid resolution and effective treatment of sub-grid scale turbulence. Looking further into CWE applications, we observe that flow around an isolated building often results in a massively separated flow, as visualized in Fig. 17. Depending on building shape and aspect ratio (along-flow length divided by cross-flow width), the patterns of flow separation and reattachment can behave in startlingly complex ways. In a group or cluster of buildings, the flow patterns become exceedingly more irregular and amorphous as turbulent wakes from one building serve as inflow to downstream buildings. Current CFD programs are improving rapidly, but still have trouble in accurately simulating peak pressures on an isolated building let alone a whole city of buildings, even with supercomputers. This is changing in large computational centers at universities, but remains the case in commercially available CFD codes. Interestingly, however, while computer memory may limit the simulation of huge arrays of buildings in a city, the flow patterns actually become more forgiving to simulate as clearly defined separated shear layers are mixed into more amorphous forms.

In the final analysis, with faster computers, greater memory and better turbulence closure schemes we will eventually be able to address the current vagaries of CFD in wind engineering applications. Thus, CWE as a discipline can look forward with warranted hope. The biggest remaining challenge for CWE is the treatment of peak structural wind loads and peak cladding pressures on buildings. Continued hybrid use of wind tunnels and CFD with cross comparison validation between wind-tunnel (or full-scale) results will be essential to gain confidence in the methodology.

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