Wind Engineering Large Structures in Indonesia.

A State of the Art Review

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ABSTRACT: The use of the wind tunnel as a tool for designing large structures in Indonesia has become commonplace. Over the last decade physical modeling in the wind tunnel has become increasingly sophisticated due to advancements in model fabrication, measurement equipment and analysis techniques and continued full scale validation. A number of technological obstacles remain before computational wind engineering becomes a suitable method for determining design wind loads acceptable for structural design.

1 INTRODUCTION

The use of the wind tunnel as a tool for designing buildings in Indonesia has become commonplace as a design optimization methodology. Its effective use requires close coordination between the architect, the structural engineer and the wind engineer. Many structural engineers find that the assessment of frame loads and local cladding pressures via physical modeling in the wind tunnel generates a better design with both improved confidence and economy in the final product. It is common to see cost savings in the structural and cladding design when compared to the code-based design – in effect the "money" is placed where it is needed in a site-specific, building-specific wind-tunnel study. The structural engineer frequently drives the move into the wind tunnel as custodian of the client's interest in a quality product.

Recent developments in wind-tunnel technology have expanded the usefulness of data generated for the structural engineer and so allow the team to explore unique geometries, unusual load combinations and dynamically sensitive structures, or portions of structures. In addition, the wind engineer is being consulted more frequently at the conceptual design stage when the building shape and orientation are being defined.

2 PHYSICAL MODELING IN THE WIND TUNNEL

2.1 *Introduction to physical modeling*

Modelling of the aerodynamic loading on a structure requires special consideration of flow conditions to obtain similitude between the model and the prototype. A detailed discussion of the similarity requirements and their wind tunnel implementation can be found in Cermak (1971, 1975 and 1976). In general, the requirements are that the model and prototype be geometrically similar, that the approach mean velocity at the model building site has a vertical profile shape similar to the full scale flow, and that the Reynolds number for the model be above some critical value. These criteria are satisfied by constructing a scale model of the structure and its surroundings, and performing the tests in a wind tunnel specifically designed to model atmospheric boundary-layer flows (Figure 1).

Figure 1: Wind tunnel model of Jakarta City Centre in one of CPP's boundary-layer wind tunnels.

Surrounding buildings and terrain features located nearby can have an important influence on wind loads. Consequently, the surrounding area is typically modeled in detail to a radius of about 500 m using Styrofoam and wood. The subject model and surrounding buildings are mounted on the turntable located near the downstream end of the wind-tunnel test section. The turntable permits rotation of the modeled area for examination of velocities from any approach wind direction.

The wind-tunnel floor upstream from the modeled area is covered with roughness elements constructed from cubes, specifically sized to produce the proper wind profile characteristics. Different sets of roughness are used to obtain different characteristics for various approach wind directions. Spires and a low barrier are installed in the test section entrance to provide a thicker boundary layer than would otherwise be available, permitting a somewhat larger scale model. The spires, barrier, and roughness are designed to provide a modeled atmospheric boundary layer approximately 1.2 m thick, a mean velocity power law exponent similar to that expected to occur in the region approaching the modeled area, and a turbulence structure in the modeled atmospheric boundary layer similar to that expected in the full-scale wind.

2.2 *The modern wind tunnel*

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). 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

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.

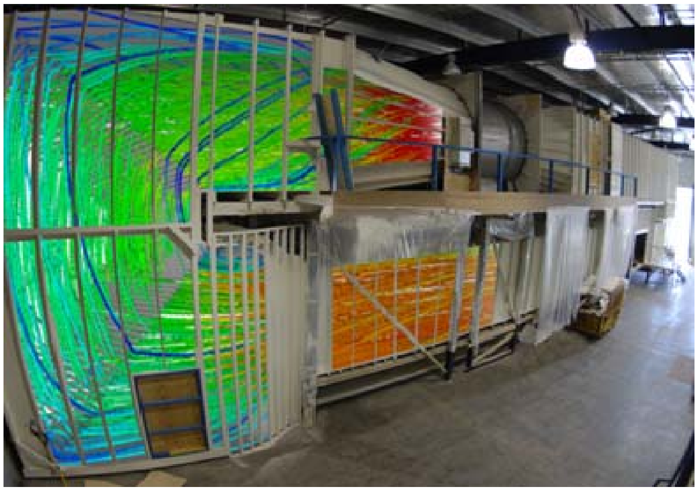

Figure 2: Computational modeling used to design a boundary layer wind tunnel.

Modern boundary-layer wind tunnels still adopt the same fundamental approach to simulating the turbulence and velocity profiles, an example is the new Sydney CPP facility servicing the Australasian Region (Figure 2). The tunnel is a closed loop three storeys high and is divided into three test sections with viewing panels, access walkways and video cameras for observation. Closed-loop servo systems control the rotation of the main testing turntable and adjust the topographical floor, roughness elements, and trip boards used to simulate the boundary layer.

Flow treatment devices including expansions and contractions, fan nacelle, turning vanes, and the blockage tolerant section were designed using Computational Fluid Dynamics (CFD). CFD is well suited to bounded-flow simulations and was used to improve the expected initial performance of the 110 kW axial fan beyond specifications.

2.3 *Latest model fabrication techniques*

In recent years the use of stereolithography (SLA) to build wind-tunnel pressure models has largely superseded the traditional, machined Plexiglas pressure model. As architectural designs become more complex, with dual-curvature shapes and fine details like sunshades or solar collectors, the ability to generate these elaborate shapes using software programs like AutoCAD, SolidEdge and SolidWorks allows the pressure tap paths to be incorporated into the design before the laser-induced creation of the physical model commences in the stereolithography vat (Figure 3a). There is some skill on the part of the wind engineer and drafter in knowing the best way to design the pressure model components for useable pressure path lengths, appropriate strength in construction and optimal material volume. However, the competitive cost of SLA models relative to the traditional Plexiglas models means that the vast majority of pressure models are now built using this method at most leading wind-engineering consultancies. Figure 3b shows an example of a 1:400 scale SLA pressure model of the Marina Bay Sands complex in Singapore.

A B

Figure 3: (a) The laser booth and operational console of a stereolithography machine used to build the pressure models. (b) A stereolithographic model of Marina Bay Sands, Singapore.

3 INDONESIAN WIND CLIMATE

It is known that tropical cyclones/typhoons cannot generally form within about ten degrees of the equator, so that most of Indonesia is fortunate in not receiving any influence from these extreme wind events. Throughout Indonesia, the peak design wind speeds result from thunderstorms, the effects of which appear only fully in gust data and the subject of only relatively recent research. A single superstation has been developed by Holmes and Melbourne (1997) with peak gust data from Ipoh (Malaysia), Jakarta (Indonesia), and two stations from Singapore. In addition, the Australian Standards document (HB212-2002) provides a design wind speed classification for the Asia-Pacific region. Indonesia is included in Level 1 which lists a nominal 50-year design wind speed of 32 m/s.

Serviceability design consideration under daily breezes and winds of more regular occurrence in Indonesia need also be considered. Analysis of anemometer data from Soekarno Hatta International Airport in Jakarta by CPP displays prevailing coastal breezes. Tall slender towers in Jakarta prone to vortex shedding excitation at low critical velocities need to be designed to maintain serviceability acceleration levels within acceptable limits as explained further below.

4 LATEST TESTING TECHNIQUES

4.1 *Structural Loads on Tall Buildings*

The vast majority of buildings today are tested for structural loads using the high frequency base balance technique. In essence, this technique seeks to obtain the external loading (base-moment time series) on a given building shape via a light, stiff model in the wind tunnel, after which the dynamic response may be calculated in the time and/or frequency domain for any desired combination of mass, stiffness, damping ratio and wind speed. The structural engineer finds this methodology valuable since revised dynamic properties may be applied to the base-moment spectra or time-series data without returning to the wind tunnel, provided that the external building shape remains unchanged. This encourages a more economic and iterative design scenario for the structural engineer. Some readers will be fully familiar with this approach, but those who wish to read more are directed to work by Boggs (1992) and many others in the wind engineering literature.

However, what is relatively new in wind-tunnel studies is the availability of cheap pressure transducers (Irwin and Kochanski 1995), which convert the pressures caused by the wind at a point on the model into an electrical signal that may be stored in a data-collection computer for subsequent analysis. As a consequence, many laboratories can apply 500 to 1000 transducers to a pressure model and collect pressure time-series data, essentially simultaneously, over the entire building. To obtain the same base moment data as the force balance one needs to assign tributary façade areas, and moment arms to the global axes for each of the taps – effectively a substantial accounting problem. From that point on, the data-reduction is almost identical to the high-frequency force balance technique.

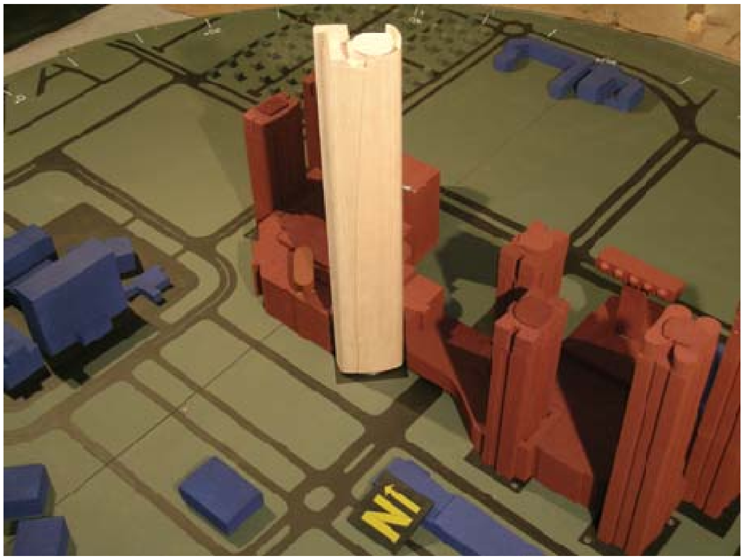

Figure 4: Base balance testing of the St Moritz Tower in Jakarta.

Base balance testing was recently conducted on the 272m St Moritz hotel tower in Jakarta, currently under construction by PT Lippo Karawaci Tbk (Figure 4). Results for the tower were reported as graphs of base moment versus wind direction and tabular design load cases with floor-by-floor loads to be applied to the structural design model. Serviceability accelerations on the highest habitable floor were also calculated for use in the assessment of occupant comfort. Graphs of acceleration were provided along with recommendations on the acceptability of the building accelerations with reference to international guidelines.

Where accelerations levels on any given tower are found to be above acceptability criterion, the tower designer has a number of mitigation options available. With reference to the equation of motion:

$$m\ddot{y} + c\dot{y} + ky = f(t)$$

External loading term of the governing equation of motion *f(t)* is measured directly and for any given wind speed and motion *y* calculated for any combination of mass (*m*), damping (*c*) and stiffness (*k*). If identified early enough in the design process, acceleration levels can be reduced through architectural changes to the outer building envelope, such as changing in tower shape or profile, to reduce the *f*(*t*) term. Most often changes to tower stiffness or mass are the most practical means to alter loads and accelerations, but care is needed to ensure gains from stiffness increases (to reduce dynamic forces) do not adversely impact top-floor accelerations (generally improved by more mass).

Auxiliary damping systems installed near the top of the tower allow the designer to increase the damping term *c* and have proven effective at keeping resonant vibrations on towers below perceptible limits. Typically a solid mass is suspended on springs and dashpots of tuned frequency and damping, often referred to as a ‘tuned mass damper’; liquid sloshing dampers and liquid column dampers are alternative forms. Example installations include Sydney Tower and Taipei 101. CPP are currently designing a damper for a 400m+ tall tower in Dubai (Figure 5).

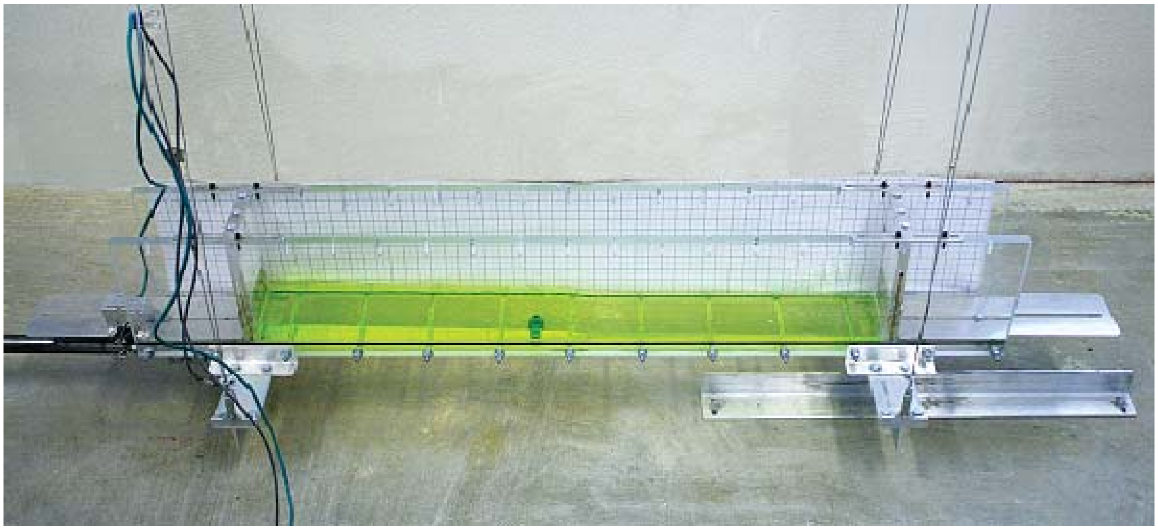

Figure 5: Liquid sloshing damper testing as a scaled model.

4.2 *Validation: ultra-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.

The era of the ultra tall tower is seeing tower heights exceed atmospheric boundary layer depths previously tested in conventional wind tunnels and further full scale validation has become necessary. At 828 m in height, Burj Khalifa is the world’s tallest building and CPP has been engaged to monitor its full scale performance under seismic and wind loading conditions. These measurements will form an integral part of the Building Management System as well as provide a direct comparison between predicted and actual performance during extreme wind or seismic events. As part of this project, monitoring equipment is being installed throughout the building (every ten floors) to give an overall picture of any building motion and the causes of that motion. Outputs from accelerometers, anemometers and GPS systems are being locally and centrally logged, with both raw data and key statistics delivered in real time to key members of the operations and design teams through customized user-friendly internet interfaces.

Figure 6: Full scale measurements are currently being conducted on the Burj Khalifa.

4.3 *Structural Loads on Large Span Structures*

For most large span structures the dynamic wind loading and response is often dominated by the sub-resonant fluctuating or ‘background’ components of low frequencies. Low correlation of the background wind forces acting on large structures with significant tributary areas result in large spatial variation in the wind forces loading the structure.

Until fairly recently a method of defining an equivalent static loading for background response was not practical. The ability now to measure 1000 or more pressure time-series simultaneously in the wind tunnel has allowed the wind engineer to obtain a complete matrix of correlation coefficients for every pair of fluctuating pressures on a large SLA model structure, e.g. stadium roof. Integrating the correlation coefficients with structural influence lines over the structure using the 'Load Response Correlation' formula derived by Kasperski and Niemann (1992) gives the instantaneous pressure distribution associated with the expected load effect, an example is shown in Figure 7.

These distributions can be applied to static structural analysis computer programs for use in detail structural design. This method has been used on major sports stadiums in Australia (Holmes 1997), Mexico (Figure 8), and is currently being adopted on the Singapore Sports Hub project.

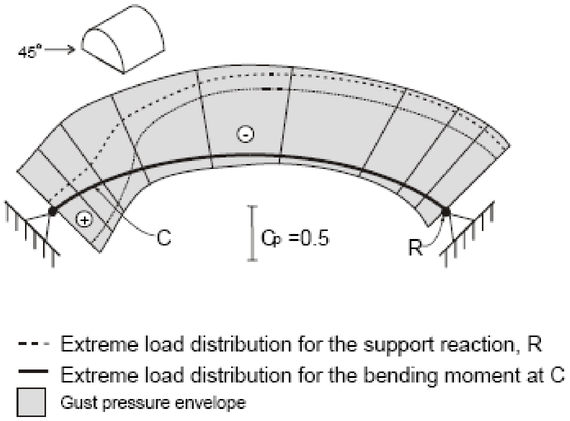

Figure 7: Extreme Load distributions for an arch roof (after Holmes 1997).

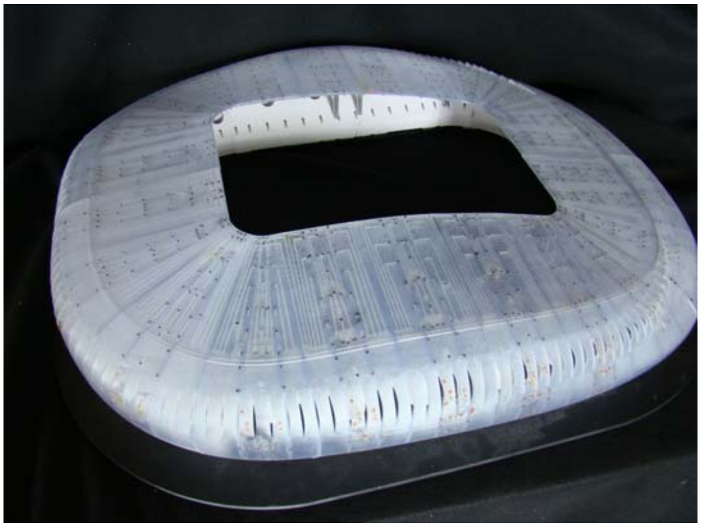

Figure 8: Hundreds of simultaneous pressure tap pairs used on the roof of the Monterrey Stadium in Mexico.

5 COMPUTATIONAL WIND ENGINEERING

CWE is an evolving field that often works best in complement with the wind-tunnel, depending on the phenomena being studied. Merging the advantages of each can produce a powerful hybrid design and analysis 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. Commercial CFD tools include such software products as Fluent, Flow-3D and Phoenix.

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.

6 CONCLUSIONS

Physical modeling in a boundary-layer wind tunnel is the only sanctioned means of superseding a code calculation in determining wind loads on buildings and structures. Its effective use requires close coordination between the architect, the structural engineer and the wind engineer and a number of successful studies have been completed for Indonesian tower projects in recent years. Over the last decade physical modeling in the wind tunnel has become increasingly sophisticated due to advancements in model fabrication, measurement equipment and analysis techniques and continued full scale validation.

Computational Wind Engineering is an evolving field that often works best in complement with the wind-tunnel, depending on the phenomena being studied. A number of technological obstacles remain before CWE becomes a commonplace method for determining design loads and pressures acceptable for building codes and standards.

7 ACKNOWLEDGEMENTS

The Jakarta City Centre project is by PT Greenwood Sejahtera (a subsidiary company of KG Global Development). St Moritz project is being developed by PT Lippo Karawaci Tbk.

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