Title: **The Wind Engineering of the Burj Dubai Tower**

Author: Peter Irwin, RWDI

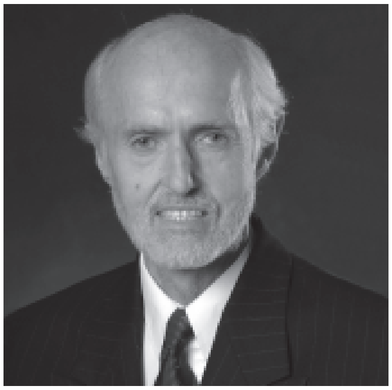
Subjects: Building Case Study
Wind Engineering

Keyword: Wind

Publication Date: 2005

Original Publication: CTBUH 2005 7th World Congress, New York

Paper Type:
1. **Book chapter/Part chapter**
2. Journal paper
3. Conference proceeding
4. Unpublished conference paper
5. Magazine article
6. Unpublished



Peter A. Irwin, Ph.D., P.E.
Rowan Williams Davies & Irwin

Peter Irwin became president of Rowan Williams Davies & Irwin in 1999. His experience in wind engineering includes extensive research and consulting in wind loading, aeroelastic response, wind tunnel methods, instrumentation, and the supervision of hundreds of wind engineering studies of major structures. Examples of tall buildings he has worked on include the Petronas Towers in Kuala Lumpur, Malaysia, the 1,666-foot (508-meter) Taipei 101 in Taiwan, and the 1,312-foot (400-meter) Two International Finance Centre, one of the tallest in Hong Kong. He is currently working on the Burj Dubai in the United Arab Emirates which will be over 2,297 feet (700 meters) tall.

Dr. Irwin earned his Ph.D. in Mechanical Engineering from McGill University. He is a registered professional engineer in the provinces of Ontario, Alberta, and British Columbia, and is a fellow of the CSCE. He has published over 120 papers and won several awards for his work, including the Canadian Society for Civil Engineering's Gzowski Medal in 1995. He serves on several committees for codes and standards, such as the Standing Committee on Structural Design for the Canadian Building Code and the wind committee of the U.S. ASCE 7 standard.

The Wind Engineering of the Burj Dubai Tower

This session highlights a paper by the presenter and William F. Baker of Skidmore, Owings & Merrill.

The Burj Dubai tower, currently under construction in the United Arab Emirates, will be well over 2,297 feet (700 meters) when completed and thus will be the world's tallest building by a wide margin. For a building of this height and slenderness, wind forces and the resulting motions in the upper levels become dominant factors in the structural design.

This presentation will describe how the wind forces on Burj Dubai, the building response, and the wind speeds around the project were predicted through an extensive program of wind tunnel tests. It will also describe how the evolution of the design was influenced by findings from the wind tunnel tests. These initially involved rigid-model force balance tests and later full aero-elastic model tests, all at 1:500 scale. High Reynolds number tests were also undertaken on a much larger model, at 1:50 scale, of the upper part of the tower in a wind tunnel at high speeds to help resolve scale effect issues.

Wind statistics played an important role in relating the predicted levels of response to return, and extensive use was made of wind data, balloon data, and computer simulations employing Regional Atmospheric Modeling techniques. In addition to addressing structural loads, the studies also examined wind loads on cladding, wind speeds at ground level and numerous terrace levels, and stack effect. The tower's form, optimized to reduce the impacts of wind actions, will become a dominant feature of the Dubai urban landscape.

THE WIND ENGINEERING OF THE BURJ DUBAI TOWER

By

Peter A. Irwin[1] and William F. Baker[2]

[1]Rowan Williams Davies and Irwin Inc., Guelph, ON, Canada, Peter.Irwin@rwdi.com

[2]Skidmore Owings Merrill LLP, Chicago, IL, USA, William.Baker@som.com

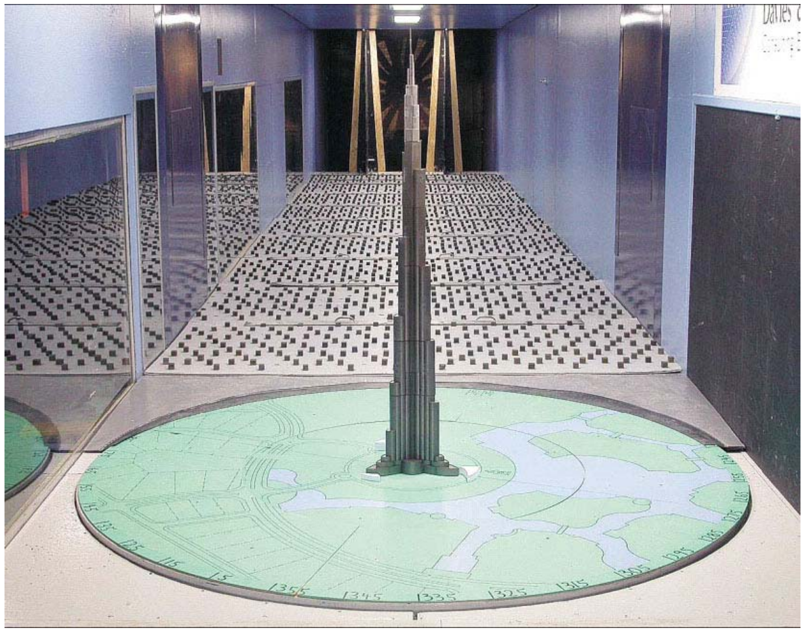
ABSTRACT

The Burj Dubai tower will be the world's tallest building by a wide margin when completed. Wind is the dominant lateral load and thus governed many aspects of the architectural and structural design. In order to optimize the design for wind an iterative sequence of wind tunnel tests and design progressions took place in which results from the wind tunnel tests were fed into each step of the design and vice versa. The wind tunnel tests were done in RWDI's 2.4 m x 1.9 m and 4.9 m x 2.4 m boundary layer wind tunnels. The primary tool in the wind tunnel tests in this iterative process was the high-frequency-force-balance model at 1:500 scale. Final tests for structural response were undertaken with a 1:500 scale aeroelastic model and for local peak pressures using a pressure tapped model. In the aeroelastic model tests some signs of Reynolds number dependency were detected. As a result high Reynolds number tests on a 1:50 scale model were initiated in the 9 m x 9 m wind tunnel at the National Research Council of Canada. The results indicated that the 1:500 results were free from significant Reynolds number effects at the higher end of the test speed range. Detailed meteorological studies were also undertaken using ground based data, balloon data and mesoscale modeling techniques in order to establish a good statistical model of the wind climate. The pedestrian wind environment at ground level and on the numerous terraces was also examined on 1:500 and 1:250 scale models and solutions to high wind conditions developed in critical areas.

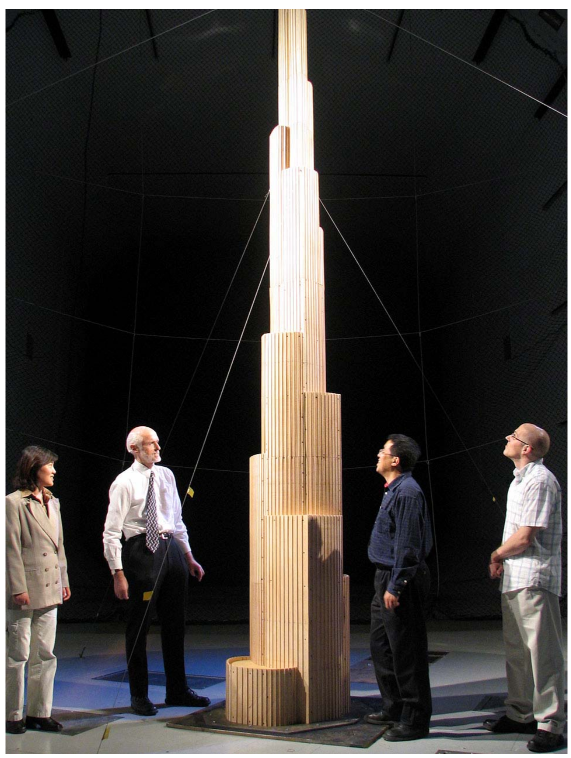
Keywords: wind loading, building motions, meteorology

INTRODUCTION

The Burj Dubai tower, currently under construction in Dubai, UAE, will be over 600 m tall when completed and thus will be the world's tallest building by a wide margin. For a building of this height and slenderness, wind forces and the resulting motions in the upper levels become dominant factors in the structural design. Also the local wind pressures on the building envelope and the wind speeds around the base of the building and on terraces at various levels were of concern. Therefore, an extensive program of wind tunnel tests and other studies were undertaken in RWDI's 2.4 m x 1.9 m, and 4.9 m x 2.4 m boundary layer wind tunnels in Guelph, Ontario, Figure 1a. The wind tunnel program included rigid-model force balance tests, a full aeroelastic model study, measurements of local pressures, and pedestrian wind environment studies. These studies used models mostly at 1:500 scale but for the pedestrian wind studies a larger scale of 1:250 was utilized in the development of aerodynamic solutions aimed at reducing wind speeds. Since some Reynolds number dependency (scale effect) was seen in the aeroelastic model and force balance results, high Reynolds number tests were also undertaken on a much larger rigid model, at 1:50 scale (Fig.1b), of the upper part of the tower in the 9m x 9 m at the National Research Council facilities in Ottawa. Wind speeds up to 55 m/s could be obtained in the 9 m x 9 m wind tunnel. Wind statistics played an important role in relating the predicted levels of response to return period. Extensive use was made of ground based wind data, balloon data and computer simulations employing Regional Atmospheric Modeling techniques in order to establish the wind regime at the upper levels.



a) Aeroelastic Model at 1:500 scale.



b) Rigid Pressure Tapped Model of Top Portion at 1:50 Scale.

Fig. 1 Wind Tunnel Models

WIND LOADING ON THE MAIN STRUCTURE

To determine the wind loading on the main structure wind tunnel tests were undertaken early in the design using the high-frequency-force-balance technique. In this well established technique, (Tschanz, 1980), the model itself is rigid and is mounted on a fast response force balance. It is then tested in a boundary layer wind tunnel where it is subjected to a simulated wind in which the full scale wind profile and wind turbulence are properly reproduced at model scale. The advantage of the technique is that it is relatively quick to undertake and provides the complete spectra of the wind-generated modal forces acting on the tower. The wind tunnel data were then combined with the dynamic properties of the tower in order to compute the tower's dynamic response and the overall effective wind force distributions at full scale. For the Burj Dubai the results of the force balance tests were used as early input for the structural design and allowed parametric studies to be undertaken on the effects of varying the tower's stiffness and mass distribution. The building has essentially six important wind directions. Three of the directions are when the wind blows directly into a wing. The wind is blowing into the "nose" or cut water effect of each wing (Nose A, Nose B and Nose C). The other three directions are when the wind blows in between two wings. These were termed as the "tail" directions (Tail A, Tail B and Tail C). It was noticed that the force spectra for different wind directions showed less excitation in the important frequency range for winds impacting the pointed or nose end of a wing, see Figure 2, than from the opposite direction (tail). This was born in mind when selecting the orientation of the tower relative to the most frequent strong wind directions for Dubai: northwest, south and east.

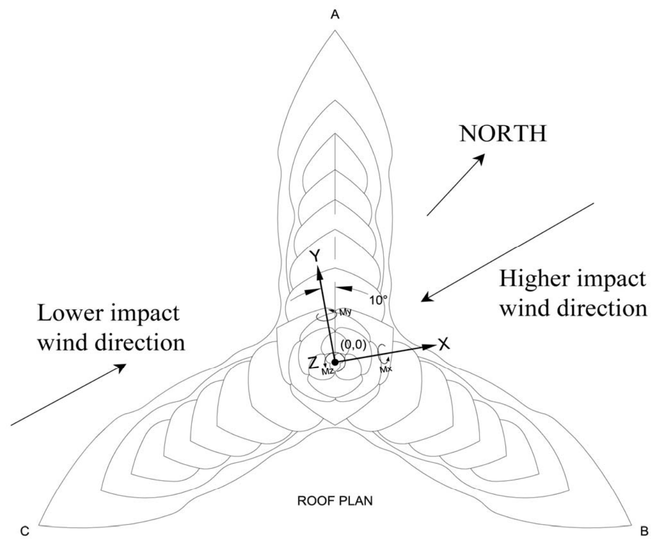
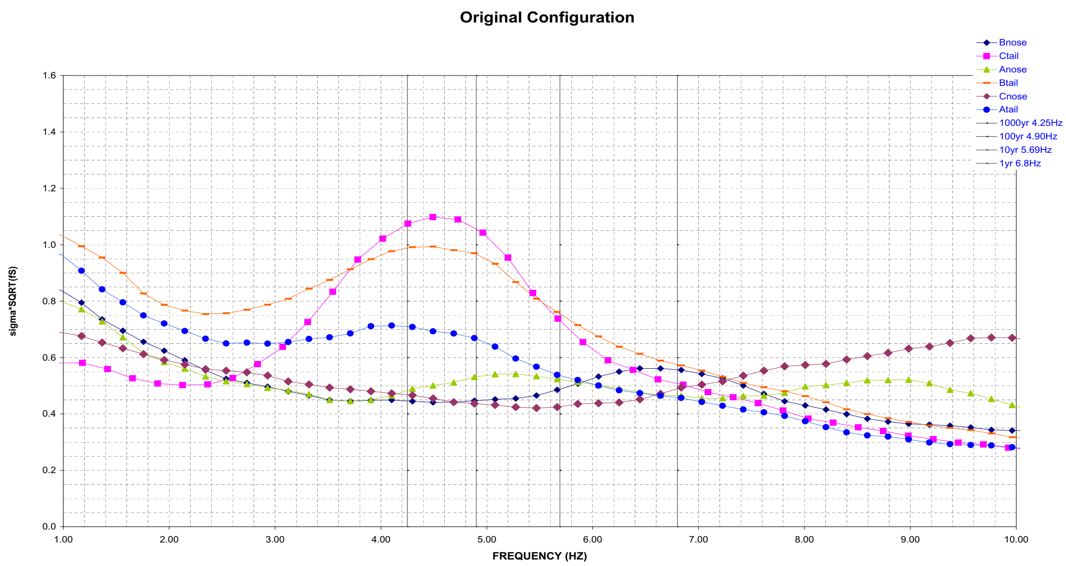


Figure 2 Plan view of the tower

Several rounds of force balance tests were undertaken as the geometry of the tower evolved and was refined architecturally. The three wings set back in a clockwise sequence with the A wing setting back first. After each round of wind tunnel testing, the data was analyzed and the building was reshaped to minimize wind effects and accommodate unrelated changes in the Client's program. In general, the number and spacing of the set backs changed as did the shape of wings. This process resulted in a substantial reduction in wind forces on the tower by "confusing" the wind. Figure 3 is a plot of the response of original building configuration and the response after several refinements of the architectural massing. In these plots, the horizontal axis is the wind tunnel model frequency that can be related to the recurrence interval for wind events and the vertical axis is proportional to the resonant dynamic forces divided by the square of the wind velocity. Towards the end of design aeroelastic model tests were initiated. An aeroelasatic model is flexible in the same manner as the real building, with properly scaled stiffness, mass and damping. It is more accurate than a force balance study since the aeroelastic interaction between the structure and wind is fully simulated, including such effects as aerodynamic damping, and also the statistics of the dynamic response can be measured directly providing a more accurate determination of the relationship between peak response and RMS response. For the Burj Dubai the modal deflection shapes were similar to those of a tapered cantilevered column. Therefore it was possible to obtain excellent agreement between frequencies and mode shapes on the model with those predicted at full scale by using a single



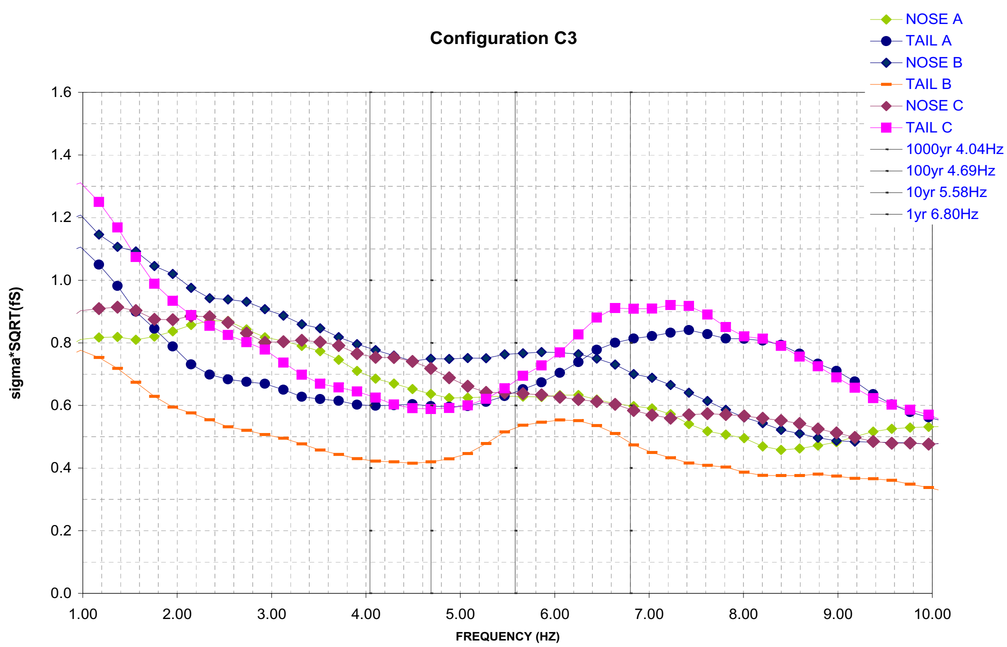


Figure 3 Spectra of across-wind modal force in original configuration and refined configuration (C3)

machined metal spine in the model with outer shell segments attached to it. The aeroelastic model was able to model the first six sway modes. Bending moments were measured at the base as well as at several higher levels. Accelerations were also measured in the upper levels. In comparing the aeroelastic model test results with the more approximate force balance results it was found that the base moment and the accelerations in the upper levels were significantly lower in the aeroelastic model results. A part of this was identified as a Reynolds number effect because the force balance tests had been run at lower Reynolds number. On a very tall slender tower like Burj Dubai, the challenge in the force balance method is to keep model resonance frequencies high enough to avoid them interfering with the frequency range of interest and one solution is to run at lower tunnel wind speeds, which entails reducing the Reynolds number. However, most of the differences between the force balance method and the aeroelastic method on Burj Dubai were due to approximations in the force balance procedure as applied to a highly tapered towered. Figure 4 illustrates the relative change in mean base moment coefficient on the aeroelastic model as a function of wind tunnel test speed for two wind directions. The fact that the moment coefficient dropped with test speed was a sign that Reynolds number effects were present. It can be seen, that the results tended to flatten out at higher test speeds indicating an asymptotic trend.

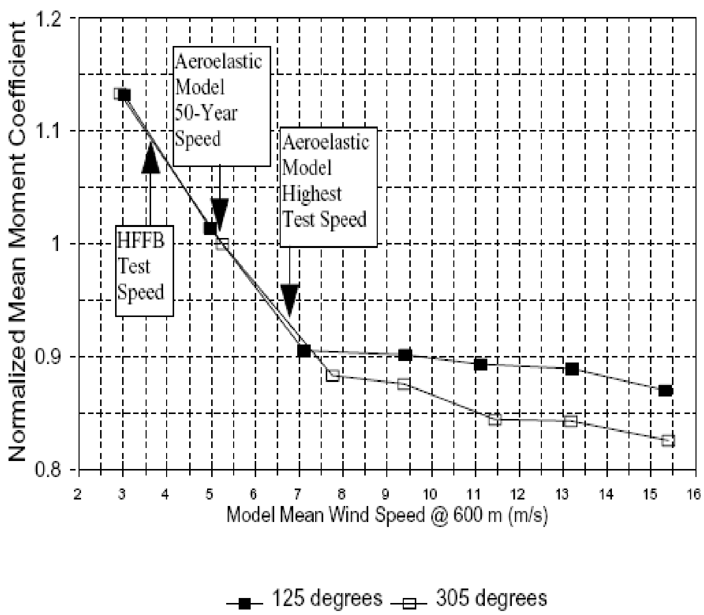
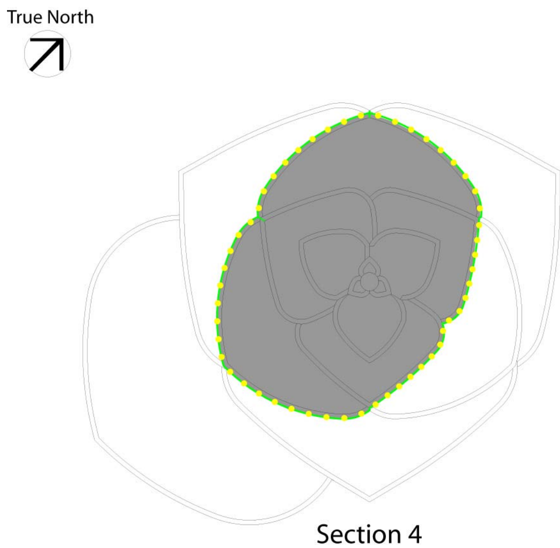


Figure 4 Effect of test speed on mean base moment coefficient for two wind directions relative to north

On a circular cylinder the mean drag coefficient also drops at a certain critical Reynolds number but then climbs again as the Reynolds number is further increased. To be sure a similar phenomenon did not occur on Burj Dubai, special high Reynolds number tests at 1:50 scale were initiated using the model shown in Figure 1b. Due to size limitations of the NRC 9 m x 9 m wind tunnel the 1:50 scale model was limited to the top part of the tower only. The tests were run at wind speeds up to 55 m/s. Measurements were made of the mean and instantaneous pressure distributions around six cross-sections of the tower and were compared with similar measurements made at 1:500 scale in RWDI's 2.4 m x 1.9 m wind tunnel. Fig. 5 compares the sectional force coefficient on one of the cross-sections at the two model scales and shows very little difference. On the 1:500 scale model, tests were made both with and without vertical ribs that are a feature of the tower's wall system in order to understand how much their effect was. At 1:500 scale the ribs were very small and thus had been left off for the main test program. The conclusions from the comparison of the high Reynolds number results with those at normal test Reynolds number were that the aerodynamic coefficients did indeed reach asymptotic values and that the 1:500 scale aeroelastic model and pressure model tests had reached high enough Reynolds numbers for the asymptotic state to be achieved closely enough for engineering purposes. Thus no special Reynolds number corrections were needed. Furthermore, the 1:500 results with and without ribs showed that the effects of the ribs were very minor.



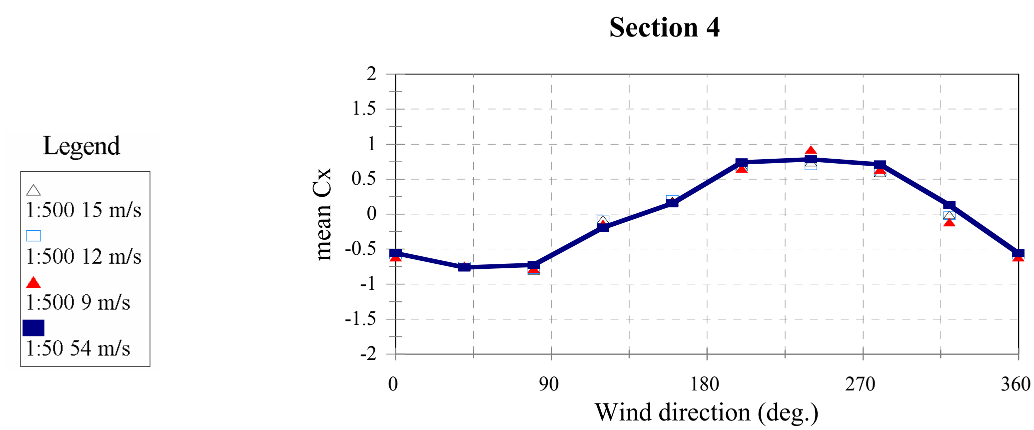


Figure 5 Example of Reynolds Number Test Results. Effect of Model Scale and Test Speed on Sectional Force Coefficient

BUILDING MOTIONS

Based on the High-Frequency-Force-Balance test results combined with local wind statistics the building motions in terms of peak accelerations were predicted for various return periods in the 1 to 10 year range. Initial predictions obtained in May 2003, at over 37 milli-g for the 5 year return period were well above the ISO standard recommended values. However, through a combination of re-orienting the tower, adjusting its shape, modifying the structural properties, and more in-depth studies of the wind statistics for the region the predictions came down By the end of 2004 November 2003 they had come down to about 19 milli-g for the same return period and at a slightly higher level. About half of this improvement came about as a result of improved knowledge of the wind statistics and the rest through re-orientation, structural improvements and shape adjustments.

Subsequently, when the aeroelastic model results became available the predictions were further improved. Several variations of tower height were tested using aeroelastic models. The accelerations were found to be significantly less than indicated by the force balance tests, down in the range of 12 milli-g. Part of this was due to the lower Reynolds number of the force balance tests, which put them in a range where Reynolds number effects were beginning to become significant, but aerodynamic damping and a lower kurtosis in the dynamic response were also contributors. This indicates the importance of considering aeroelastic effects in cases where building motions are having important consequences.

A range of damping values was considered in the test program. The acceleration results quoted above were all evaluated assuming a damping ratio for the building of 1.5% in its fundamental modes of vibration for each direction. This is a likely value for a slender concrete structure such as the Burj Dubai. For higher modes, which involved significant flexing of the upper part of the tower, lower damping values were examined also since the upper part of the tower is primarily steel. Higher modes contributed little to motions in the residential levels. Studies were also undertaken to examine adding supplementary damping systems such as tuned mass dampers but for the residential units the wind tunnel predictions indicated the motions would be well within acceptable limits without supplementary damping. The upper reaches of the spire are quite slender and supplementary damping systems are still under study for controlling those motions.

CLADDING LOADS

Cladding loads were evaluated through testing a 1:500 scale model instrumented with 1142 pressure taps and using the methodology described by Irwin, 1988. The procedures were essentially the same as for a tower of lesser height and the predicted 50 year peak suctions, including an allowance for internal pressures and stack effect, ranged from 2.0 kPa to 5.5 kPa. Most 50 year suctions were in the range 2.0 kPa to 3.5 kPa. The highest suctions were seen, as might be expected, near discontinuities in the surface geometry. Peak positive pressures ranged from 1.5 kPa to 3.5 kPa with the great majority being in the range 1.5 kPa to 2.5 kPa.

WIND CLIMATE STUDIES

To make full use of wind tunnel data so as to predict the dependence of wind loads and wind response on return period a good statistical model of the joint probability of wind speeds and direction is needed. In the course of the Burj Dubai studies local ground based data from several weather stations in the region were used, including most importantly the data from Dubai International Airport. Other stations examined were Abu Dhabi, Sharjah, Ra’s al Khaimah, and Doha. Gust data from all stations were merged into the equivalent a super-station to obtain an enlarged database and were analyzed using extreme value fitting methods to produce a relationship between gust speeds in the region and return period. The 50 year 3 second gust from this analysis was estimated to be 37.7 m/s in standard open terrain at the 10 m level. In addition the mean hourly data from Dubai were used to obtain a model of the parent distribution of hourly winds, from which mean hourly wind speed versus return period could be predicted. The analysis took account of the terrain around the airport, adjustments being made to correct the anemometer data for non-ideal exposure conditions using ESDU (1982) methods. This yielded a 50 year mean hourly speed of 23.5 m/s, again in standard open terrain conditions at 10 m. Depending on exactly which method one used to estimate the relationship between mean and gust speeds the corresponding gust was estimated to be in the range 35.7 m/s to 37.6 m/s. This agreed well with the value obtained from the super-station analysis. Therefore the parent distribution from Dubai International Airport was adopted as the appropriate statistical model to use with the wind tunnel results.

An important question when designing a tower of over 600 m height is the nature of the wind velocity profile and wind turbulence in the upper levels. It is a large extrapolation to go from ground-based data at the 10 m height to heights of over 600 m using standard assumptions about planetary boundary layer profiles. Therefore for Burj Dubai more direct measurements of upper level winds were sought. The closest station with balloon records was Abu Dhabi, where about 16 years of data were available taken on average about twice per day. The balloon readings gave wind speeds at various milli-bar levels. An interpolation procedure was used to extract out wind speeds at heights of 600 m, 1000 m and 1500 m, from which wind speeds versus return period could be estimated. However, this approach gave a considerably lower 600 m level 50 year wind speed than deduced from the ground based data and standard boundary layer models and it was conclude that the sparseness of the balloon data was probably the main reason. With only two readings a day it was unlikely that the balloons had captured the highest wind speeds in the period of record.

A method of correcting for this was sought and the method adopted involved advanced meso-scale modeling techniques (Qiu et al, 2005). Information on upper-level winds can be obtained from the National Center for Atmospheric Research / National Center's for Environmental Prediction (NCAR/NCEP) global reanalysis data set. These data are based on world-wide meteorological observations interpolated to a 3-dimensional grid by means of meteorological modeling. The NCAR/NCEP Global Reanalysis combines 4-dimensional data assimilations of surface and upper air meteorological observation data, and provides outputs at six hour intervals on the global grid. Horizontal and vertical grid resolutions are too coarse on the global grid for a through study of local wind profiles at the study site (2.5 degree latitude by 2.5 degree longitude for most of the historical record, improving to 1 degree grids since 1997). To improve resolution for the Burj Dubai project the NCAR/NCEP reanalysis data was combined with a high resolution numerical meteorological model to reproduce high-resolution 3-D wind fields for a selection of historical high wind events in the UAE area, including a number of Shamals. The model known as the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5), was used to predict mesoscale atmospheric circulations (Grell et al, 1995). MM5 is a widely used meteorological model that is based on solving the fundamental equations of atmospheric motion on a 3-dimensional grid. The model incorporates parameterizations for the various grid and sub-grid scale physical processes that influence atmospheric conditions such as convection, cloud formation, precipitation, radiation, surface heat transfer and moisture flux etc.

The main results of the MM5 studies can be summarized as follows. When stronger surface winds occur the ratio of 600 m mean winds to 10 m mean winds asymptotes towards a value of about 1.6 to 1.7, see Figure 5. This is slightly lower than the value of about 1.8 implied by the standard boundary layer assumptions. Comparing the peak winds at the upper levels computed by the MM5 method with the balloon records at Abu Dhabi indicated that the balloons generally missed the peak winds of each storm event resulting in an underestimate of extreme upper level wind speeds by about 15% on average. With this correction the balloon data indicated a 600 m level 50 year wind speed of about 36 to 38 m/s, compared with the value 41.7 m/s predicted from the ground data using standard boundary layer assumptions. The MM5 simulations also showed that the relationship between ground and upper level winds at Dubai was essentially the same as at Abu Dhabi. For design purposes it was decided to retain the standard boundary layer model assumptions. Thus the main benefit of the detailed MM5 studies was to lend confidence that the design wind assumptions used for the Burj Dubai were, if anything, slightly conservative, which is not inappropriate for such a monumental structure.

PEDESTRIAN WIND ENVIRONMENT

The comfort of pedestrians at ground level and on the numerous terrace levels was evaluated by combining wind speed measurements on wind tunnel models with the local wind statistics and other climatic information. Two aspects of pedestrian comfort were considered: the effect of the mechanical force of the wind and thermal comfort, bearing in mind air temperature, relative humidity, solar radiation and wind speed. The general methodology has been described by Soligo et al, 1997, and in the ASCE state of the art report on Outdoor Human Comfort and Its Assessment (ASCE, 2003). Initial wind tunnel tests used 1:500 scale models. Subsequently three 1:250 scale partial models were employed to examine ground level areas, lower level terraces and higher level terraces in more detail, and to develop detailed mitigation measures.

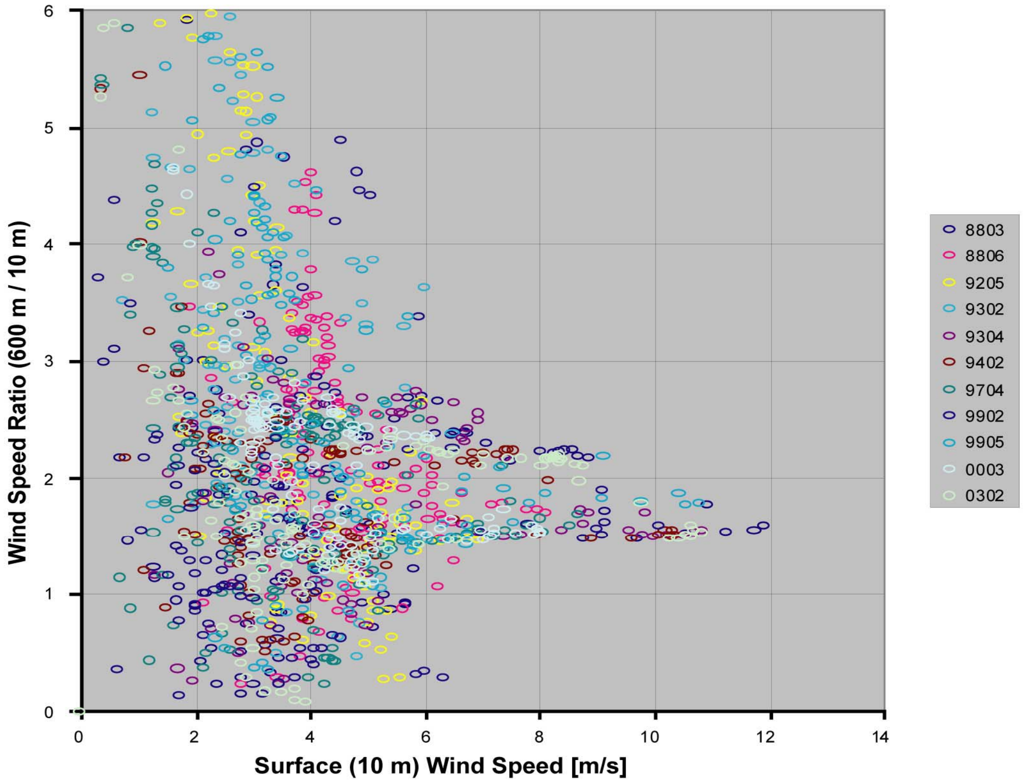


Fig. 6 Relationship between 600 m level wind speeds and 10 m level wind speeds from meso-scale modeling.

Initial results from the thermal comfort study highlighted the need to introduce shade structures to avoid the strong adverse impact of solar radiation on thermal comfort in Dubai. A number of canopies and other types of shade structure were architecturally designed at ground level. Initial tests on the bare terraces indicated the potential for frequent uncomfortably strong winds. Further tests on the terraces showed that significant improvements could be obtained through a combination of parapet walls, overhead trellises, and vertical screens.

CONCLUSIONS

Wind Tunnel testing can be a powerful tool in the architectural and structural design of a building. Utilizing several rounds of force balance wind tunnel tests each followed by a refinement of the architectural shape dramatically reduced the forces and accelerations of the Burj Dubai.

Aeroelastic model tests produced significantly lower overall wind loads and accelerations than force balance tests. This was partly due to Reynolds number effects in the force balance tests but also was because of aerodynamic damping effects and different peak factors in the response from those of a purely Gaussian process.

The high Reynolds number tests on a large model at 1:50 scale in speeds up to 55 m/s indicated that at the Reynolds number of the aeroelastic model and pressures model tests the results were not greatly affected by Reynolds number.

Accelerations in the upper residential floors are predicted to be within normal comfort criteria without the use of supplementary damping.

Balloon data combined with meso-scale modeling enabled the relationship between upper level and ground level winds to be examined. The meso-scale modeling allowed correction factors to be developed to compensate for the sparseness of the balloon data. The indications are that application of the normal boundary layer models up to heights of order 600 m is slightly conservative in the UAE region.

Pedestrian comfort, including thermal comfort, was evaluated at ground level and on the terraces. Special measures such as shade structures, wind screens and landscaping were developed to improve comfort in an architecturally pleasing manner.

REFERENCES

ASCE, 2003
OUTDOOR HUMAN COMFORT AND ITS ASSESSMENT, State of the Art Report, prepared by a Task Committee of the Aerodynamics Committee of the American Society of Civil Engineers, chaired by P. Irwin, published by ASCE, Reston, Virginia.

ESDU, 1982
STRONG WINDS IN THE ATMOSPHERIC BOUNDARY LAYER. PART 1 – MEAN HOURLY SPEEDS. No. 82026 issued September 1982 with amendments to 1993.

Grell, G.A., Dudhia, J., and Stauffer, D.R., 1995
A DESCRIPTION OF THE FIFTH-GENERATION PENN STAE/NCAR MESOSCALE MODEL (MM5). NCAR Tech.Note. NCAR/TN-398+STR.

Irwin, P.A. 1988
PRESSURE MODEL TECHNIQUES FOR CLADDING LOADS, *J. Wind Engineering and Industrial Aerodynamics*, 29, pp 69-78.

Soligo, M.J., Irwin, P.A., Williams, C.J., and Schuyler, G.D., 1997
A COMPREHENSIVE ASSESSMENT OF PEDESTRIAN COMFORT INCLUDING THERMAL COMFORT, Proceedings of the Eighth U.S. National Conference on Wind Engineering, Baltimore MD, June.

Tschanz, T., 1982
MEASUREMENT OF TOTAL DYNAMIC LOADS USING ELASTIC MODELS WITH HIGH NATURAL FREQUENCIES. *Proceedings of the International Workshop on Wind Tunnel Modeling for Civil Engineering Applications*, Gaithersburg, Maryland, USA, April, pp 296-312.

Qiu, X., Lepage, L., Sifton, V., Tang, V., and Irwin, P., 2005
EXTREME WIND PROFILES IN THE ARABIAN GULF REGION, Proceedings of the 6th Asia Pacific Conference on Wind Engineering, Seoul, Korea, September