The Burj Dubai Tower

Wind Engineering

Figure 1a: Wind Tunnel Model – Aeroelastic Model at 1:500 scale.

By Peter A. Irwin and William F. Baker

The Burj Dubai tower, currently under construction in Dubai, UAE, will be over 600 meters 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. An extensive program of wind tunnel tests and other studies were undertaken in the Rowan, Williams, Davies and Irwin (RWDI) 2.4- x 1.9-meter, and 4.9- x 2.4-meter 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; however 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 (Figure 1b), of the upper part of the tower in the 9- x 9-meter at the National Research Council facilities in Ottawa. Wind speeds up to 55 meters per second could be obtained in the 9- x 9-meter 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.
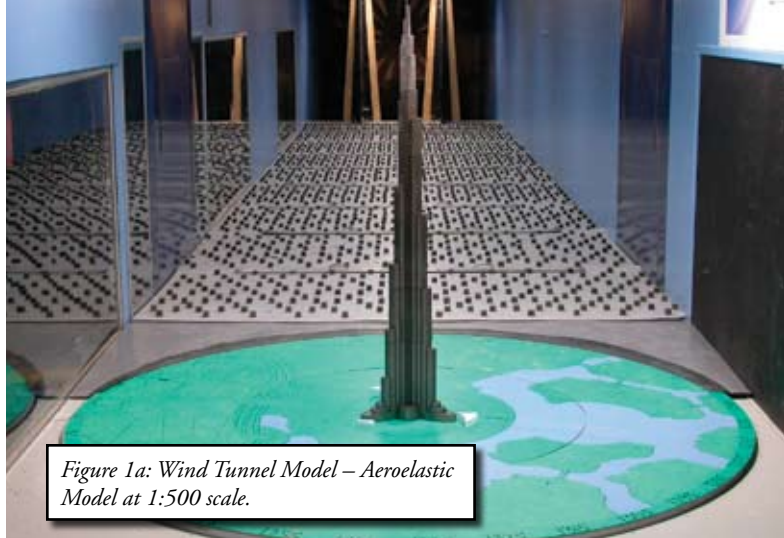

Figure 2: Rendering of Tower

Figure 1b: Wind Tunnel Model – Rigid Pressure Tapped Model of Top Portion at 1:50 Scale.

Structural System Description

The Burj Dubai tower, when completed, will be the world's tallest structure. The final height of the building is a "well-guarded secret". The final height of the classic-style multi-use skyscraper will "comfortably" exceed the current record holder of 509 meter (1671 feet) tall Taipei 101.

Designers purposely shaped the structural concrete Burj Dubai ("Y" shape in plan) to reduce the wind forces on the tower, keeping the structure simple and to foster constructability. The structural system could be described a "buttressed" core (*Figures 2* and *3*). Each wing, with its own high performance concrete core and perimeter columns, buttresses the other via a six-sided central core, or hub. The result is a tower that is extremely stiff torsionally. Skidmore, Owings, Merrill, LLP (SOM) purposely aligned all the common central core elements to form a building with no structural transfers.

Each tier of the building steps back in a spiral stepping pattern up the building. This causes the tower's width to change at each setback. The advantage of the stepping and shaping is to "confuse the wind". The wind vortexes never get organized because at each new tier the wind encounters a different building shape.

The 3,000,000 square foot Tower and 2,000,000 square foot Podium structures are currently under construction (*Figure 3*) and the project is scheduled for completion in 2009.


Figure 3: Construction Photo of Tower

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. 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 cutwater 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 (*Figure 4*) 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 4: Plan view of the tower
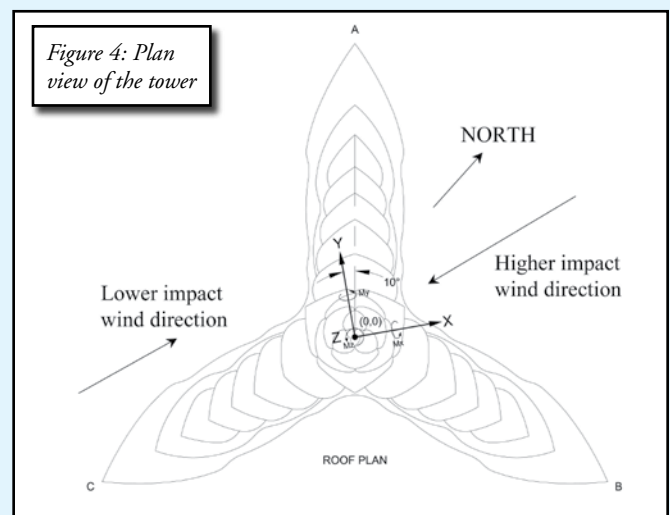
Several rounds of force balance tests were undertaken as the geometry of the tower evolved and was refined architecturally. The three wings set back in a clockwise sequence with the A wing setting back first. After each round of wind tunnel testing, the data was analyzed and the building was reshaped 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 5* 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, more accurate aeroelastic model tests were initiated. An aeroelastic model is flexible in the same manner as the real building, with properly scaled stiffness, mass and damping.

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. *Figure 6* illustrates the relative change in mean base moment coefficient on the aeroelastic model as a function
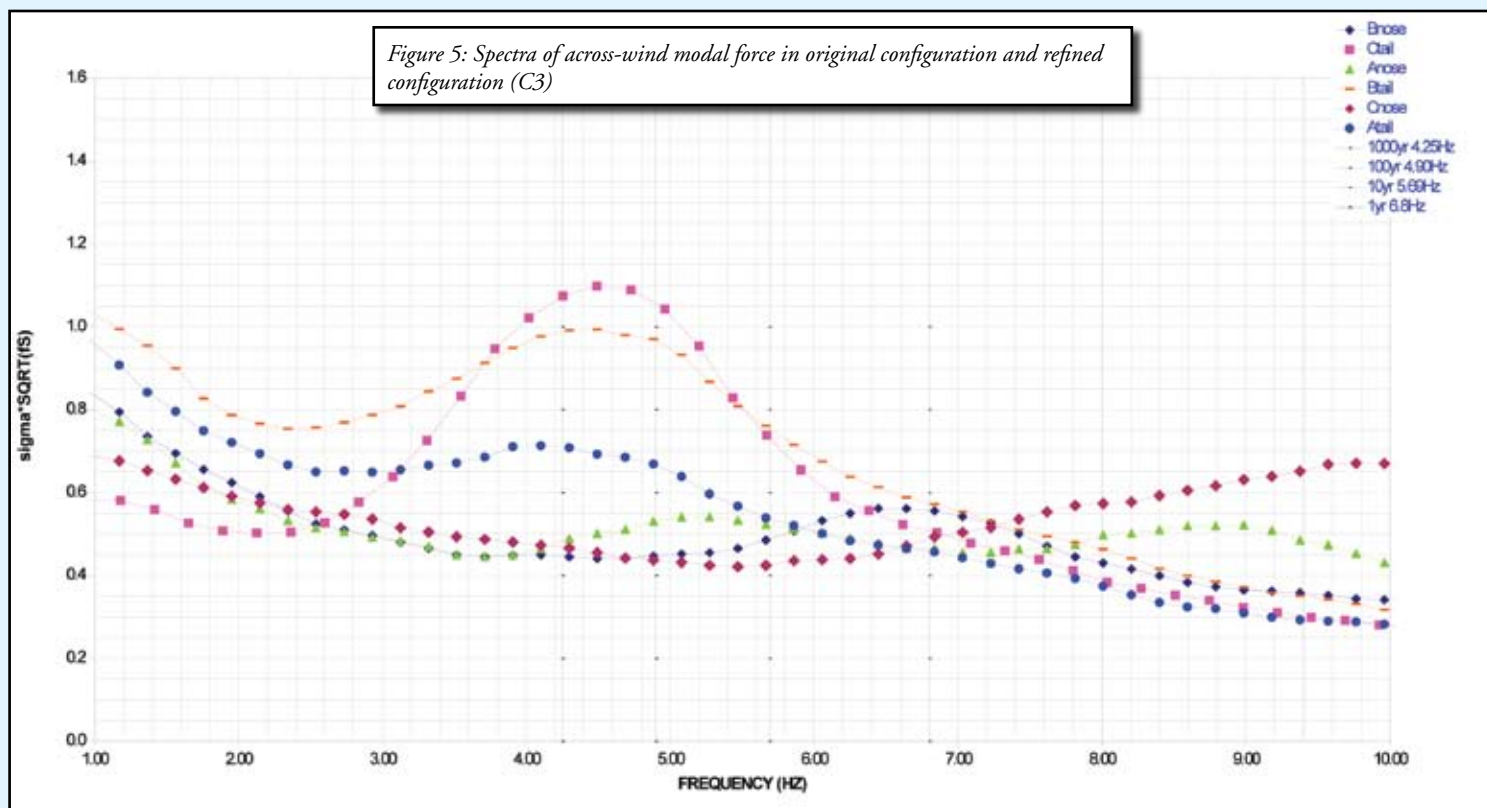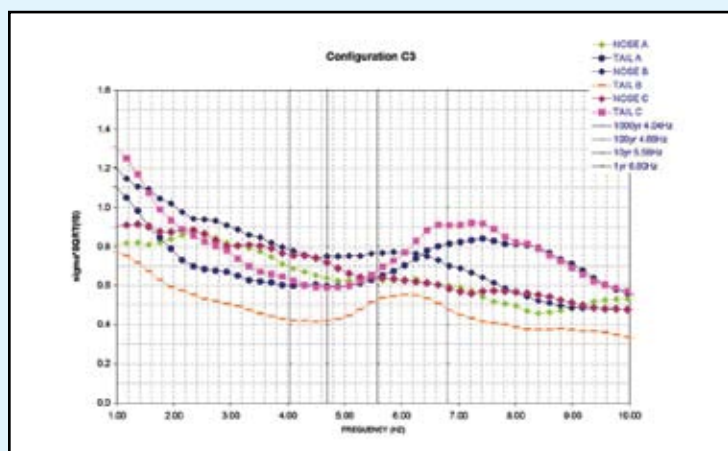
Figure 5: Spectra of across-wind modal force in original configuration and refined configuration (C3)

Figure 5

Figure 5

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.

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

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.

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- x 9-meter 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 meters per second. 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- x 1.9-meter wind tunnel. 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

Figure 6: Effect of test speed on mean base moment coefficient for two wind directions relative to north
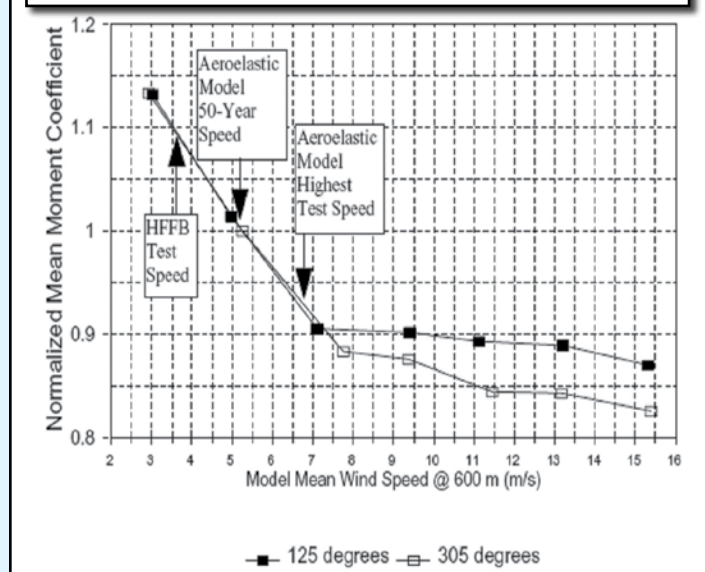
recommended values. However, through a combination of re-orienting the tower, adjusting its shape, modifying the structural properties, and more in-depth studies of the wind statistics for the region the predictions came down By the end of November 2003, they had come down to about 19 milli-g for the 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.

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.▪

*Peter Irwin is the President for the Rowan Williams Davies and Irwin Inc., in Guelph, Ontario, Canada. He also was in charge of the wind studies of the world's two previous "tallest buildings", the Petronas Towers in Kuala Lumpur and Taipei 101. Peter can be reached at **Peter.Irwin@rwdi.com.***

Mr. Baker is the Partner-in-Charge of Structural Engineering for the Chicago and London offices of SOM. He is the lead structural designer for both the 92 story Trump International Hotel and Tower, currently under construction in Chicago and the Burj Dubai which is also currently under construction and will be the world's tallest structure.

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