The BURJ DUBAI TOWER

Wind Tunnel Testing of Cladding and Pedestrian Level

By Peter A. Irwin, William F. Baker, Stan Korista, Peter A. Weismantle, and Lawrence C. Novak

The Burj Dubai Tower, currently under construction in Dubai, UAE, will be the tallest structure in the world when it opens in 2009. The Tower will be over 600 meters tall, making it the tallest by a significant margin. It is the centerpiece of the Burj Dubai Downtown, a nearly 43,000,000 square-feet (4,000,000 m^2) development currently being built by Emaar Properties PJSC of Dubai. The Burj Dubai Tower part of the development consists of the Tower itself, as well as a 2-story basement and 3-story podium, and separate 6-story Office Annex and 3-story Pool Annex. At 3,000,000 square-feet (280,000 m^2), the Tower is a mixed use reinforced concrete structure containing mainly residential units, but also includes a Giorgio Armani hotel, serviced apartments, boutique offices, an observatory, and communication floors. The 2,000,000 square-feet (180,000 m^2) reinforced concrete basement and podium contains mainly underground parking, but also houses building services and hotel amenities.

Super-tall buildings have historically been termed 'wind generators' reflecting the results of placing a very tall project in the environment that induce downdrafts which become horizontal winds at the tower base. Due to the design team's concern with ascertaining realistic design forces on the building cladding, as well as the resulting wind comfort level of pedestrians at the exterior areas (ground level and terraces), extensive wind tunnel testing was recommended to better understand both the basis of design and to develop mitigation measures.

With the Burj Dubai, Emaar Properties PJSC has stated that their goal is not simply to be the world's tallest building, but also to embody humanity's highest aspirations.

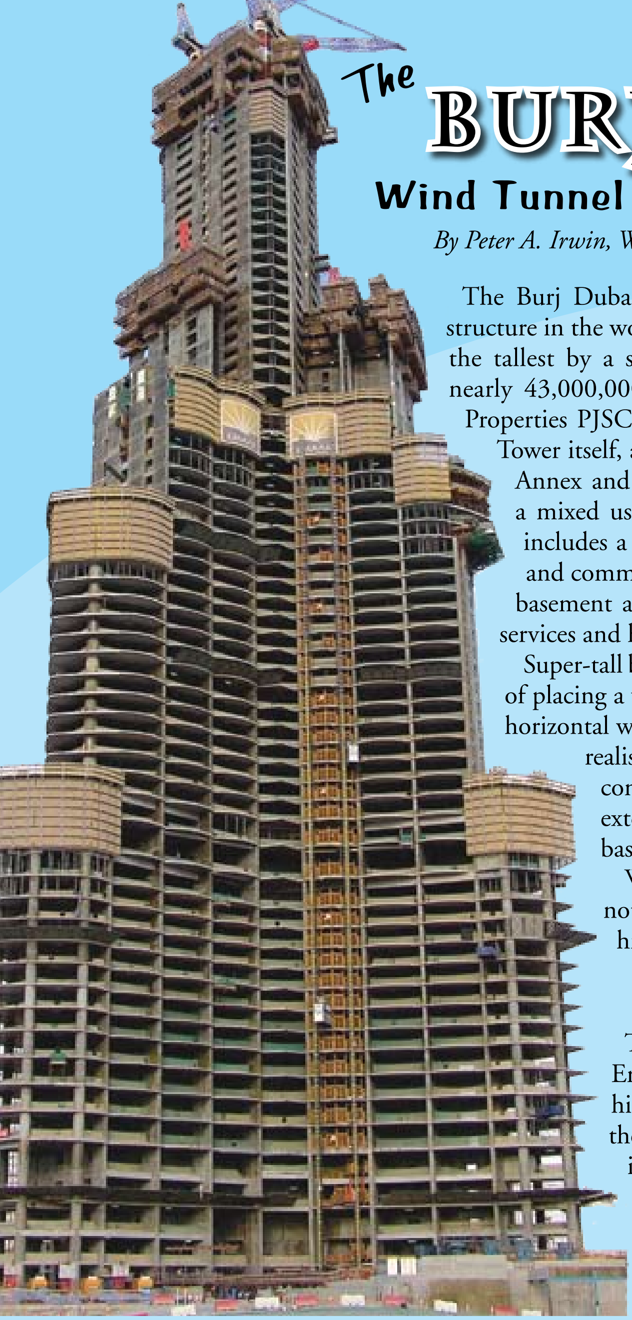

Figure 1: Construction Photo

Architectural Design

The context of the Burj Dubai being in the city of Dubai, in the United Arab Emirates, drove the inspiration for the building form to incorporate cultural, historical, and organic influences particular to the region. The influences of the onion domes and pointed arches in traditional buildings, spiral imagery in Middle Eastern architecture, together with the structure of an indigenous desert flower with its central structure and surrounding petals, resulted in the tri-axial geometry of the Burj with spiral reduction with height. In plan, the Tower is Y-shaped. As the Tower rises, the wings set back in a spiral pattern, emphasizing its height, until it reaches its central shaft, at which point the shaft peels away to reveal the single spire (*Figure 2*). The Y-shape plan is ideal for residential and hotel usage, with the wings allowing maximum outward views and inward natural light, while maintaining privacy.

The central core contains all of the elevatoring and mechanical risers. The Tower is serviced by five separate mechanical zones, located approximately 30 floors apart over the height of the building. Above the occupied concrete portion of the building is the structural steel spire, housing communications and further mechanical floors. The architects and engineers worked hand in hand to develop the building form and the structural system, resulting in a tower which efficiently manages its response to the wind, while maintaining the integrity of the design concept.

Structural System Description

With wind being the critical factor in the design of super-tall buildings, the Tower was shaped so as to minimize the wind forces on the building. Structural simplicity and constructability were also key drivers of the design. The resulting structural system can be referred to as a "buttressed core," with each of the three wings buttressing the other two via a six-sided central core. Constructed utilizing high performance concrete, corridor walls extend from the central core, down the axis of each wing, with hammerhead walls at the end of each corridor. Columns are located at the building perimeter and the tip of each wing, with the floor system consisting of flat plate construction.

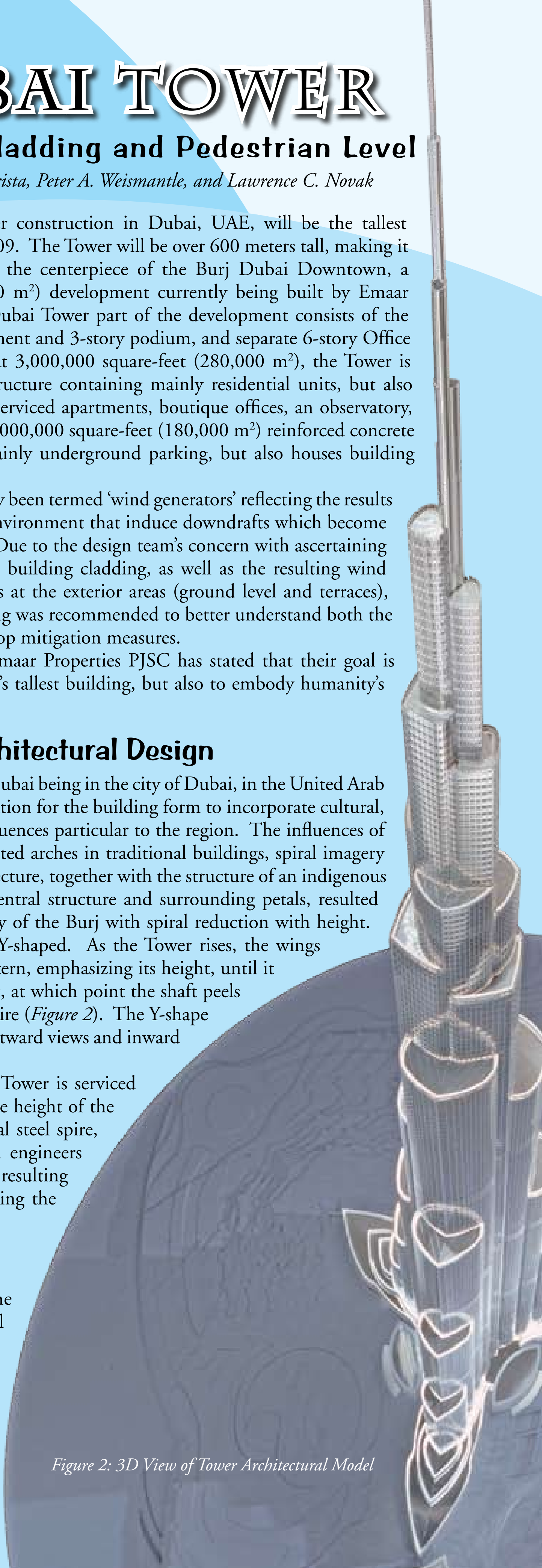

Figure 2: 3D View of Tower Architectural Model

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Figure 3: Cladding Pressure Test Model at 1:500 Scale, Shown in Wind Tunnel

The closed hexagonal core provides an extremely stiff torsional restraint. At the mechanical zones, outrigger walls fully engage all perimeter columns, thus allowing the columns to participate in the resistance of lateral loads, as well as redistributing the gravity loads. The gravity load redistribution balances the stress levels in the vertical elements and minimizes the effects of differential shortening, an especially significant factor in this super-tall building. The building setbacks are located at structural bays and all vertical elements are aligned, negating the need for any transfer structures. The result is a very elegant and efficient structure which utilizes the gravity load resisting system to effectively assist in the resistance of lateral loads.

Wind Climate Studies

To make full use of wind tunnel data so as to predict the relationship 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 of 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 meters. 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 of 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.

Cladding Pressure Testing and Results

For a building of this height and shape, wind forces acting on the cladding cannot be accurately predicted using standard Code Tables or formulas. The Codes recognize this and permit the determination of loads by means of specialized Wind Tunnel testing. The testing takes into account specifics of building geometry, local climate and surrounding details. A more accurate depiction of the actual loads will always lead to a more cost effective solution. A 1:500 scale cladding pressure test model was constructed using upwards of 1140 individual pressure taps (*Figures 3 and 4*). The location of each tap was determined and agreed in consultation between SOM and the RWDI engineers. The model was placed on a turntable in the wind tunnel (*Figure 3*). The structures surrounding the Tower were modified to allow for two separate series of tests. First, the tunnel was configured with the existing (undeveloped) surroundings. Following that, the tunnel was configured with the surrounding buildings of the future development in place. Measurements were taken for 36 wind directions spaced 10 degrees apart. The measured data is converted into pressure coefficients based on the measured mean dynamic pressure of the wind above the boundary layer. The statistical data of the local wind climate accounts for the variable extreme wind speeds with wind direction.

Figure 4: Detail of Pressure Taps in Cladding Pressure Test Model

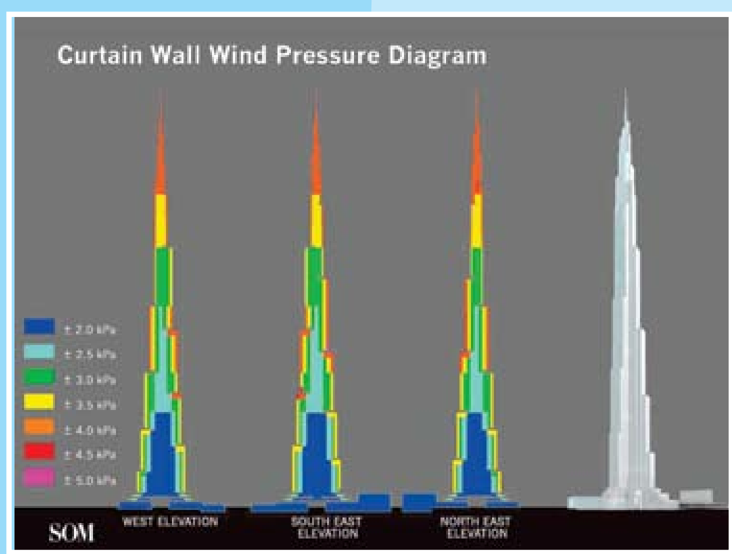

Figure 5: Cladding Pressure Wind Load Diagrams

The results of the test based calculations include both maximum positive and negative pressures based on a return period of 50 years. Negative pressure, or suction, is defined to act outward, normal to the building surface and positive pressure acts inward. Additionally the results include either an allowance for internal pressure due to the mechanical system or stack effect, or consider the instantaneous net pressure differential measured directly across elements exposed to wind on both surfaces. That said, the largest calculated negative cladding wind pressure was -5.5 kPa (-110 psf) and the largest positive pressure was +3.5 kPa (+70 psf). The highest cladding wind pressures are concentrated near the top of the tower and near major setbacks (*Figure 5*).

Figure 6a: Tower Test Mock-up Assembly.

Once the criteria are established and the contractor has completed his initial detail design, the performance of the curtain wall system must be proven. The testing of glass and metal curtain walls to verify their effectiveness in meeting the criteria to which they have been designed has been common practice for decades. This laboratory testing is aimed at evaluating the walls' performance under conditions simulating the environment that the wall will be exposed to before full scale production of the wall system begins.

Not every panel type is required to be tested; however, the aim is to test the typical systems covering the majority of the building enclosure. It was determined that five multi-panel test mock-up specimens would be sufficient to cover the major systems on Burj Dubai. In the case of Burj Dubai, each mock-up will be tested for air infiltration, water penetration under varying conditions, structural performance, incidental loads, seismic movement and exposure to cyclical temperature. *Figure 6* shows the test mock-up assembly and chamber in position and the specimen setup for the test for dynamic water penetration. Additionally, special tests have been devised for the wall type at the mechanical floors which acts as a louver. The intent is to measure the performance of the wall as a louver, and separately to test it to verify that it will not generate excessive sound under operating conditions.

The knowledge gained from the mock-ups and testing invariably leads to improved design and performance of the wall system. At the very least, it verifies the suitability of the design and provides an opportunity for the contractor to check out the fabrication and installation procedures.

Figure 6b: Tower Test Mock-up Dynamic Test for Water Penetration

Pedestrian Level Wind Studies

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 on-line version of this article, **www.STRUCTUREmag.org**, contains references regarding the methodology for assessing pedestrian comfort.*)

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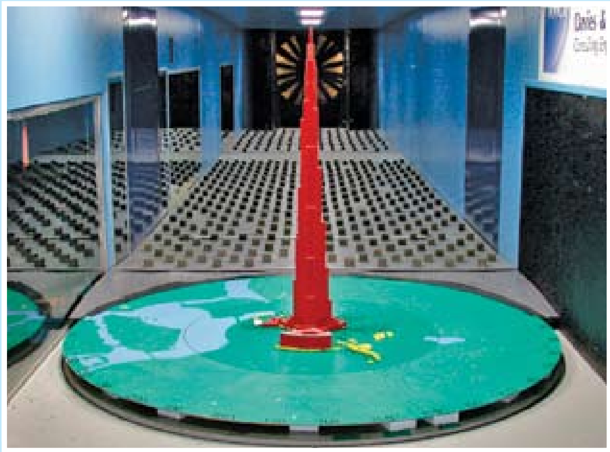

Figure 7a: Pedestrian Level Wind Tunnel Study (without surrounding future structures)

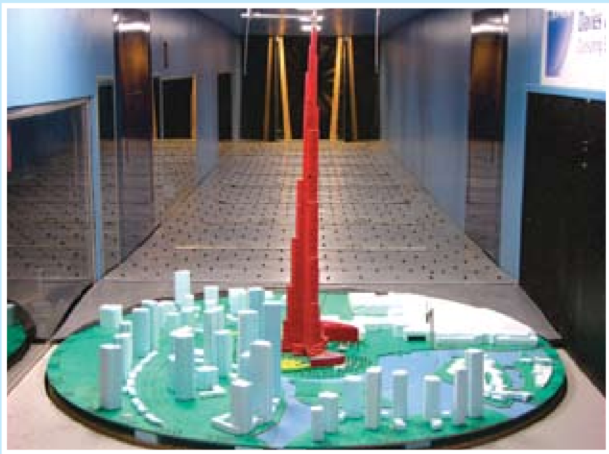

Figure 7b: Pedestrian Level Wind Tunnel Study (with surrounding future structures)

Figure 7c: Pedestrian Level Wind Tunnel Study

Figure 8a: Terrace Testing: Initial Parapet Design

Figure 8b: Terrace Testing: Full Height Parapet Design

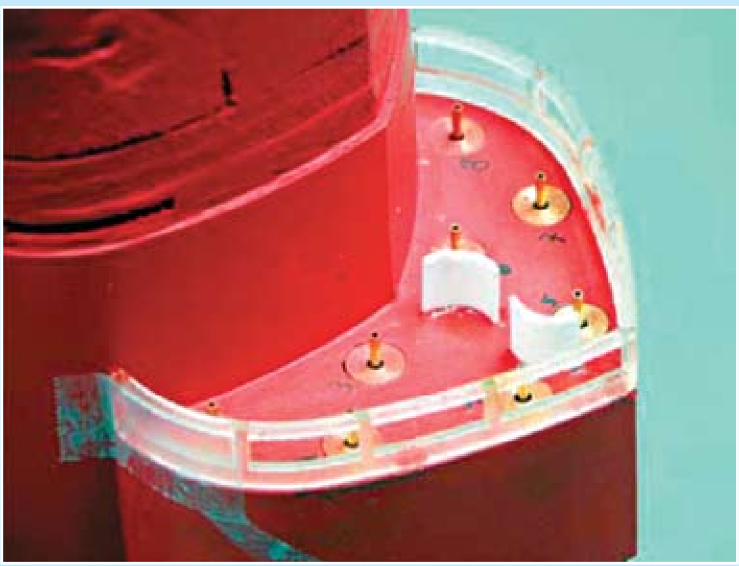

Figure 8c: Divider Screens with Modified Parapet

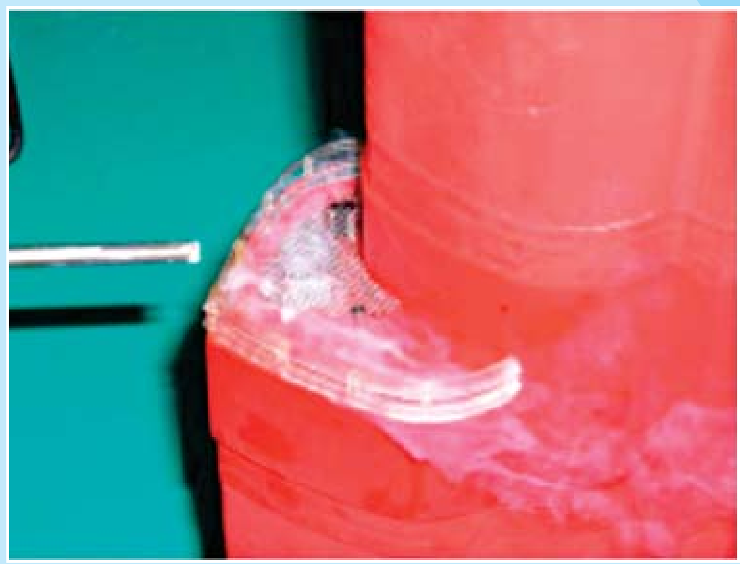

Figure 8d: Smoke Visualization Testing: Divider Screens and Trellis with Modified Parapet

References

The general methodology for assessing pedestrian comfort is described in the following two references:

1. Soligo, M.J., Irwin, P.A., Williams, C.J. and Schuyler, G.D., 1997, *A Comprehensive Assessment of Pedestrian Comfort including Thermal Comfort*, Eighth U.S. National Conference on Wind Engineering, Baltimore, Maryland, USA, June
2. ASCE 2003 State-of-the-Art Report, *Outdoor Human Comfort and its Assessment*, written by a Task Committee of the Aerospace Division chaired by Irwin, P.A.

Initial wind tunnel tests utilized 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. In the development of pedestrian wind studies, it is important to adequately model natural wind breaks such as trees. The pedestrian ground level studies were conducted with and without possible future surrounding buildings (*Figure 7*).

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.

Upper Terrace Level Wind Studies and Resulting Mitigation Measures

An unusual feature of this super tall building, and a significant design challenge, is the provision of accessible terraces at several of the setback floors over the height of the Tower. These terraces, up to and including that at level 152, can be accessed by occupants or visitors to certain residential units, amenity floors, Corporate Suite office floors and the Observatory. Being that occupant access of this extent and at these extreme heights is unprecedented, RWDI was retained to conduct a separate study at the setback terraces. The purpose of the study was to asses

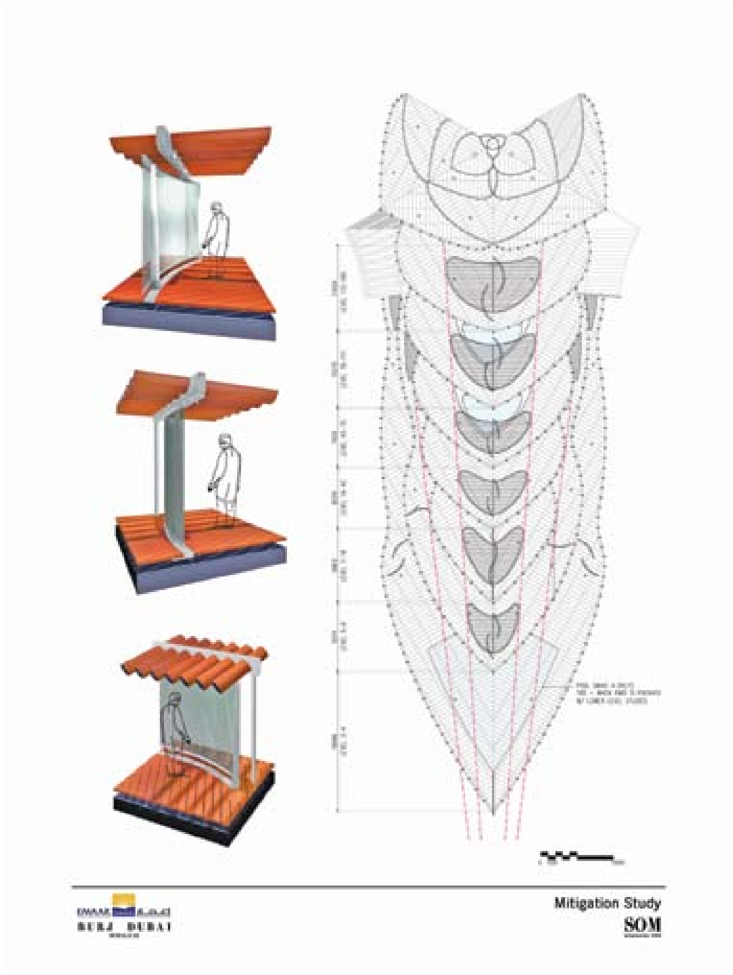

Figure 9a: Divider Screen Design and Terrace Layouts

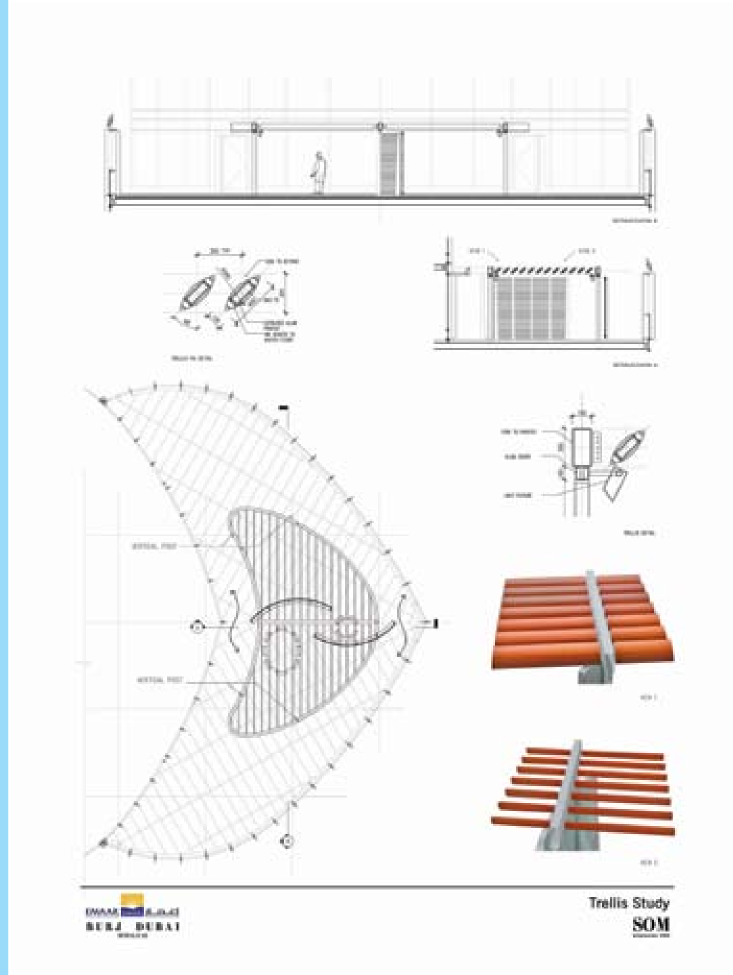

Figure 9b: Plan and Section through Terrace and Trellis Details

the effectiveness of wind mitigation measures on the setback terraces for improving pedestrian comfort and safety. The study consisted of wind tunnel testing a 1:250 scale model of a portion of the Tower covering terraces at the setbacks to levels 87, 126 and 142 (*Figure 8*).

The results indicated that the addition of a divider screen benefited the wind climate at the terrace levels, although there were still several cases that indicated "uncomfortable" conditions (i.e. mean wind speeds exceeding 19 km/hr more then 20% of the time). It was also recognized that an overhead element, such as a trellis, could potentially improve conditions beyond the results obtained. The results led the team to adopt the trellis option with divider screens, while maintaining the original parapet design (*Figure 9*).

Beyond the mitigation measures noted above, it was felt that, for reasons of safety, the tenants whose residential units open onto a terrace should be provided with a means by which to judge the exterior wind conditions, prior to going outside onto their terrace. Therefore, adjacent to each door opening onto a terrace, the design provides for a wind tracking panel. This indoor tracking panel is connected to an outdoor sensing device on the terrace trellis and will indicate wind speed and direction, as well as indicate conditions of excessive wind speed. Furthermore, it can signal an alarm if the wind speed exceeds a set level. Additionally, to prevent the terrace door from swinging wildly in the wind, it is provided with motor assisted operation. Finally, in the case that the wind tracking panel is inoperative, "visual wind speed indicators" (i.e. flags) have been placed on the trellis to give a visual clue to the actual terrace wind conditions.

Conclusions

Cladding and pedestrian level wind tunnel testing can be powerful tools utilized by the design team in ascertaining the realistic design forces on the building cladding as well as the resulting wind comfort level of pedestrians at the exterior areas (ground level and terraces). Wind tunnel testing can also assist in the development of proposed wind mitigation measures to improve pedestrian comfort in exterior areas.▪

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