



CTBUH Technical Paper

<http://technicalpapers.ctbuh.org>

Subject: Architecture/Design
Building Case Study

Paper Title: **Burj Dubai: An Architectural Technical Design Case Study**

Author(s): Weismantle, Peter A.
Smith, Gregory L.
Sheriff, Mohamed

Affiliation(s): Skidmore, Owings & Merrill, Chicago, USA

Publication Date: 2007

Original Publication: CTBUH / Wiley Tal Journal, 2007

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 Unpublished conference paper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 Unpublished

BURJ DUBAI: AN ARCHITECTURAL TECHNICAL DESIGN CASE STUDY

PETER A. WEISMANTLE,* GREGORY L. SMITH AND MOHAMED SHERIFF

Skidmore, Owings & Merrill, Chicago, Illinois, USA

SUMMARY

Beyond the aesthetics of the architectural design, the realization of Burj Dubai is very much a technical design effort. Every system in the Tower must be optimized because of the physical and economic constraints of a super high rise building. It is the intent of this paper to discuss the SOM design teams' approach in conceptualizing, investigating and resolving several of these technical topics outlined as follows.

As an introduction; the aesthetic, functional and structural advantages of Burj Dubai's tri-axial 'Y' shaped plan, suggested by the 'desert flower', are discussed. Following that, the vertical stacking of the Tower's mixed use program is described and likened to a small, vertically arranged, city containing residences, places of work, hotels, restaurants, retail shops, amusement areas, revenue generating lease areas. The arrangement of the various functions has been rationalized along with the means and methods of transportation of people, energy, goods and materials. From the standpoint of fire and life safety; Burj Dubai has been designed with additional features in order to compensate for challenges it presents to occupant evacuation and fire fighting. Specialist wind tunnel tests were conducted not only for structural reasons, but also to assess the effectiveness of wind mitigation measures on the accessible terraces. The high outdoor temperature in Dubai and cool indoor condition create a difference in air density that makes the indoor air want to travel downward out the bottom of the building. This 'stack effect' was the subject of a separate study, the results of which were applied to the design. Finally, the author discusses SOM's approach to the design of the exterior wall cladding and cleaning systems. Copyright © 2007 John Wiley & Sons, Ltd.

1. INTRODUCTION

The Burj Dubai (Tower of Dubai) will be the world's tallest structure when completed in late 2008. The superstructure is currently under construction on a site in Dubai, UAE, formerly occupied by the military. It will be the centerpiece of a 3 700 000 m² (40 000 000 ft²) residential, office, and retail development. The final height of the building is currently confidential, but when completed this ultra-modern multi-use skyscraper will comfortably exceed the height of the current record holder, the 509 m (1670 ft) tall Taipei 101.

The 280 000 m² (3 014 000 ft²) reinforced concrete tower is primarily residential, but it also contains a 5+ star Giorgio Armani Hotel and service apartments, corporate office suites and several floors reserved for communications and broadcast equipment at the top. The 180 000 m² (1 940 000 ft²) podium is primarily utilized for parking and building services; however, it also contains hotel-related amenities such as the ballroom, restaurants, and retail. The client, Emaar Properties PJSC, has stated that their goal for Burj Dubai is not simply to be the world's tallest building, but also to stand as an example of humanity's highest aspirations.

Beyond the aesthetics of the architectural design, briefly touched on below, the realization of Burj Dubai is very much a technical design effort. Every system in the tower must not only be optimized

*Correspondence to: Peter A. Weismantle, Skidmore, Owings & Merrill LLP, Chicago, IL 60604, USA. E-mail: Peter.Weismantle@som.com

because of the usual physical and economic constraints of a super-high-rise building, but also the team realized that there would also be technical issues that could not be envisioned at the outset of this unprecedented project. It is the intent of this paper to discuss the Skidmore, Owings & Merrill (SOM) design team's approach in conceptualizing, investigating, and resolving several of these technical topics. We would hasten to add that this process is still ongoing and will continue through construction into the operational life of this unique structure.

2. ARCHITECTURAL DESIGN CONCEPTS

Having had many years' experience in working all over the world and specifically in the Middle East, the SOM design team synthesized many ideas and influences into the final building. First among the aesthetic concepts was that of the 'desert flower'. It is an organic form with tri-axial geometry and spiraling growth that can be easily seen in the form and expression of the tower. Additionally, the application of traditional Islamic forms and intricate geometries further enrich the design.

The tri-axial 'Y'-shaped plan suggested by the 'desert flower' was advantageous in several ways. First, it makes for an ideal arrangement of residential units, having an optimal plan depth-to-perimeter ratio and allowing maximum views outward, without overlooking a neighboring apartment (Figure 1). Second, the shape lent itself beautifully to the 'buttressed' core structural concept. Furthermore, by stepping back one wing at each tier of the tower and varying the distance in height between steps, the tower appears to grow at a constantly accelerating rate as it reaches for the sky, emphasizing its extreme height (Figure 2) while also helping to reduce the wind forces on the tower. Varying the plan cross-section as the tower rises tends to 'confuse the wind'. That is to say, the wind vortices never

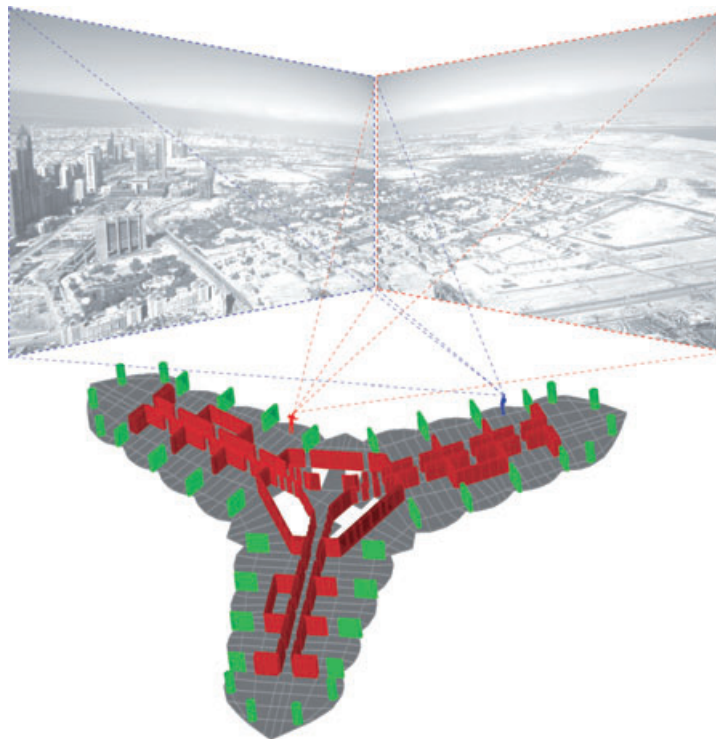


Figure 1. Typical tower floor

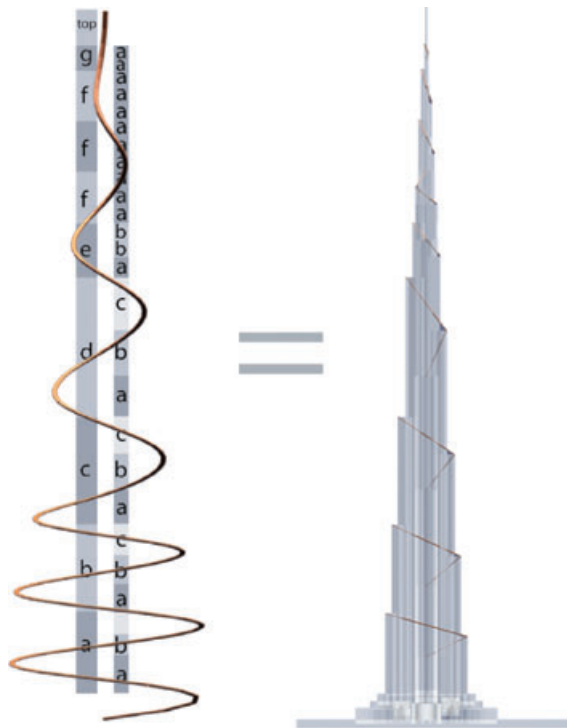


Figure 2. Tower elevation illustrating setback spacing

become organized because at each new tier the wind encounters a different building shape, allowing for a very economical structure.

The Burj Dubai is currently under construction (Figure 3) and is scheduled to be completed in late 2008.

3. TALL AND SUPER TALL

From the outset, it has been intended that the Burj Dubai be not only the world's tallest building, but also the world's tallest free-standing manmade structure. The official arbiter of height is the Council on Tall Buildings and Urban Habitat (CTBUH), founded at Lehigh University in Bethlehem, Pennsylvania, and currently based at the Illinois Institute of Technology in Chicago, Illinois. The CTBUH measures the height of buildings using four categories. The categories and current record holders are as follows:

Highest occupied floor:	Taipei 101	439 m (1440 ft)
Top of roof:	Taipei 101	449 m (1473 ft)
Top of architecture (including spires):	Taipei 101	509 m (1670 ft)
Top of pinnacle, spire, antenna or flagpole:	Sears Tower	527 m (1730 ft)

When completed in 1997, the Petronas Towers created a significant amount of controversy in that it was crowned the 'world's tallest', although its 'architectural' spire is 75 m (246 ft) below the top of the Sears Tower's 'non-architectural' antenna and its highest occupied floor is 62 m (202 ft) below the highest occupied floor in Sears. The specific definitions of terms such as 'architectural', 'pinnacle', and 'spire' were subject to much debate and nuance. Burj Dubai means to settle the issue once and for all (at least for now). Although the final height of the building, as previously noted, remains confidential, Burj Dubai will be the tallest, by a significant amount, in all four categories (see Figure 4).



Figure 3. Construction photo of tower, May 2007

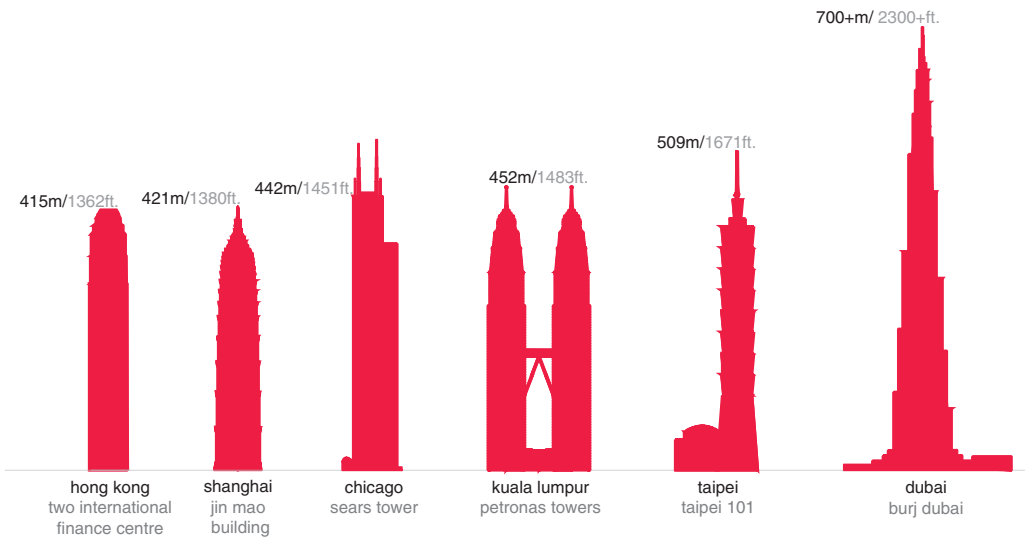


Figure 4. Comparative heights of several of the world’s tallest buildings

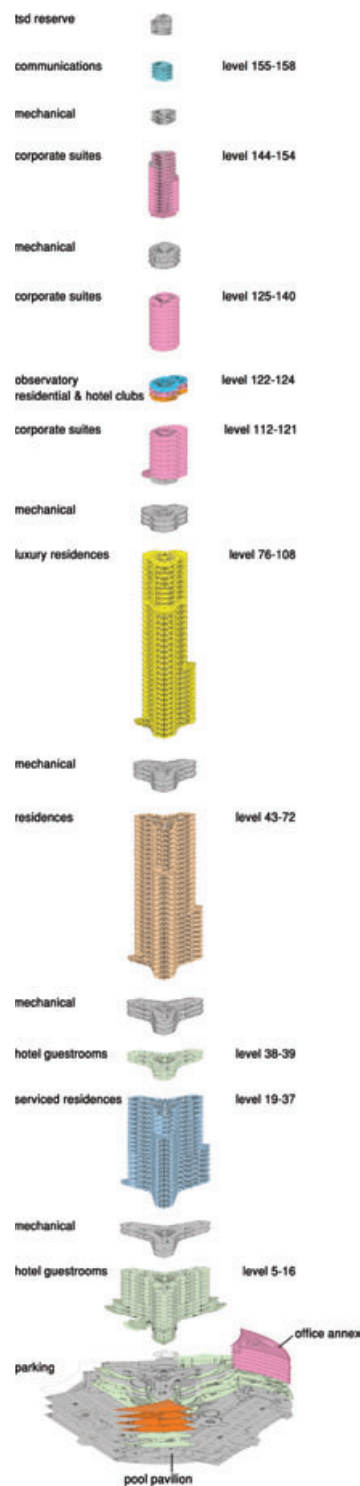


Figure 5. Building diagram showing major uses

4. THE BUILDING PROGRAM AND VERTICAL TRANSPORTATION SYSTEM

4.1 *Burj Dubai: elevating a mixed-use building*

The tower can be likened to a small vertical city. It contains residences, places of work, hotels, restaurants, retail shops, amusement areas, revenue-generating lease areas and all the spaces and equipment necessary for the aforementioned to function properly. The specific programmatic uses and areas are illustrated in Figure 5. Furthermore, similar to but beyond the needs of a small city, the arrangement of the various functions must be rationalized along with the means and methods of transportation of people, energy, goods, and materials.

4.2 *Elevator systems design*

Burj Dubai is termed a 'super-tall' building, but, because of its significant increase in height over any existing structure, it could also be termed the world's first 'mega-high-rise'. In fact, it is so tall that current elevator technology would not permit a single elevator to travel the entire height of the building. Therefore, the only means of serving all floors of this structure is to design a transfer system, connecting elevators serving separate sections of the building. The building utilizes high-speed, non-stop 'shuttle' elevators bringing passengers to 'sky lobby' floors where they transfer to 'local' elevators serving the floors in between. This concept has been applied to many super-tall buildings and is similar in concept to express and local commuter trains used in cities around the world. The design of the system must correspond to both the type of use of the floors served and the physical configuration of the building. The location of the sky lobbies and the type, use, and number of local floors being served from those sky lobbies must be taken into account when the size, speed, and number of elevators are calculated. It is critical that a balance is struck between all these factors, in order to optimize the vertical transportation system and minimize the amount of space the elevator shafts and lobbies occupy. The key to the efficiency of space usage is to stack the local elevators serving the different zones of the building on top of each other. In order to accomplish that, a gap of several floors must be designed into the structure in order to accommodate the required elevator pits, overruns and machine rooms for each group. In order to maintain the efficiency of the building, those 'gap' floors, although not accessible by the public, must be gainfully utilized. In Burj Dubai, we organized the overall building program or 'stack' in a manner to utilize the 'gap' floors as space for mechanical and electrical services. Immediately below both the Level 43 and Level 76 sky lobbies are multistoried plant spaces (Figure 6).

4.3 *Passenger elevators*

Up to Level 39, both the hotel and the lowest zone of residential service apartments are served by separate groups of local elevators with their lobbies at Level 1 and ground level, respectively (Figure 7).

Residential sky lobbies at Levels 43 and 76 are served by two separate groups of high-speed shuttles with lobbies at ground level. The residential floors are served by groups of three local elevators, each in standard 'bottom-up' configuration (Figure 8).

An unusual vertical transportation configuration utilized in Burj Dubai was the result of a re-evaluation by the client of the tower program. In late 2004, after the foundation was completed, with the core started and the elevators out for tender, the client requested that the upper third of the tower be changed from primarily residential use into corporate suite offices. Although the number of floors and floor area remained approximately equivalent, the number of occupants increased significantly. A series of options were studied and the one selected utilized a combination of 'top-down' and 'bottom-

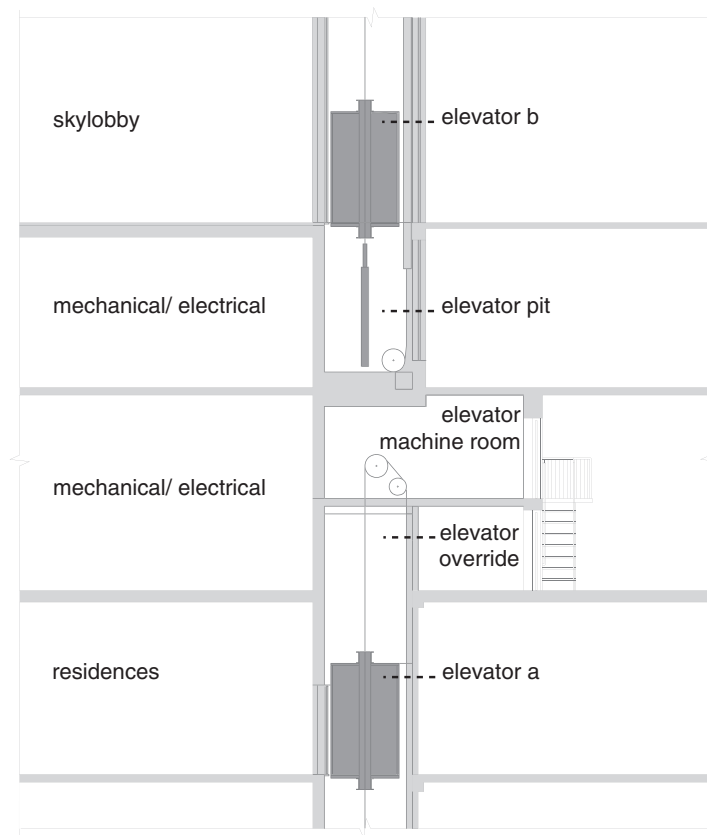


Figure 6. Detail section showing the stacking of elevator groups at mechanical zones

up' groups for the local service to the corporate suites (Figure 9). In this scheme, the Level 123 sky lobby is served by the bottom cars of a pair of double-deck high-speed shuttle elevators. Passengers transfer to two groups of local elevators. One group goes up, serving Levels 123–154, while the other group goes down, serving Levels 123–112. The position of the sky lobby was dictated by the ability of the local groups to handle the increased passenger load and constrained by the massing of the building, which was required to remain unchanged.

Furthermore, an additional constraint imposed by the client as part of the 2004 reconfiguration was that the observatory floor must open onto an outdoor terrace. Utilizing high-speed, double-deck shuttle elevators allows the top car to stop at the Level 124 observatory while the corporate suite office tenants are simultaneously stopping at their level 123 sky lobby. The entry lobbies for these shuttles are also stacked one above the other at the base of the building. Tourists accessing the observatory enter at ground level, one floor above the concourse-level corporate suite office lobby.

4.4 Service elevators

Again, due to the extreme height of the building, the service elevator system is configured to permit transfers connecting individual elevators so that all the floors of the building are ultimately served. Two 'hotel service' elevators serve every floor throughout the hotel and service apartment zones of the tower from concourse level up through Level 39 (Figure 7).

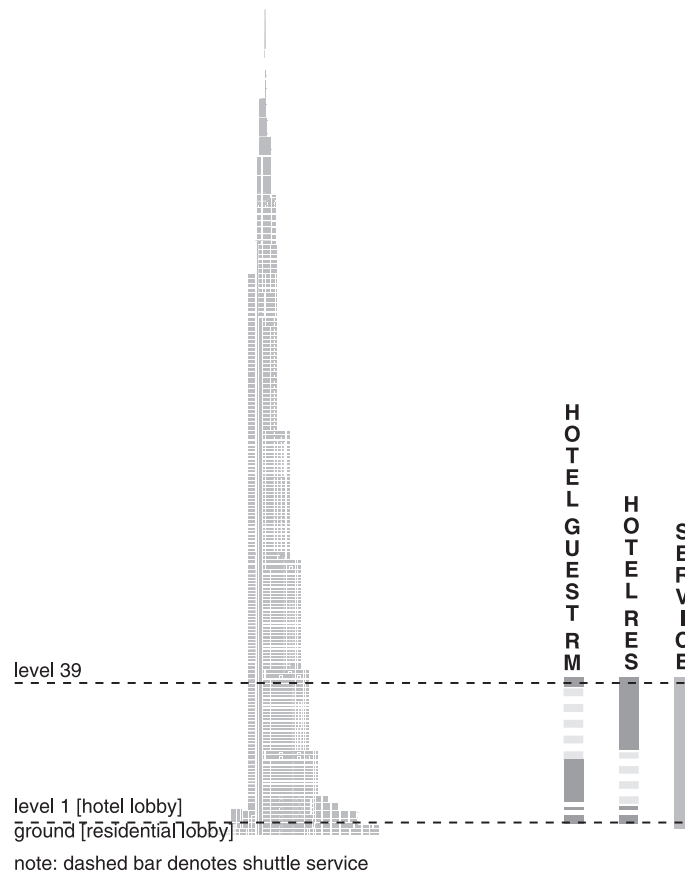


Figure 7. Hotel and serviced apartment passenger elevators

Another two elevators, 'building service', serve every floor throughout the residential zones of the tower from concourse level up through Level 111. Goods receiving, sorting, and storage facilities are provided at this level, where it is possible to transfer to a third service elevator that is dedicated to serve the corporate office suites up through Level 153.

One of those two 'building service' elevators continues past Level 111 and terminates at Level 138. This elevator, will be the tallest elevator in the world, with a shaft height of over 500 m (1640+ ft). At Level 111 it is possible to transfer to a fourth 'building service' elevator that serves every floor up to the top occupied floor at Level 160 (Figure 9).

A number of additional service elevators are provided in the base of the tower and basements primarily to serve the hotel back-of-house functions.

4.5 Fire service elevators

In general, it is desired that firefighters have as quick an access to any floor as possible. Some codes, such as EN 81 adopted in the European Union, require firefighter emergency access using a single elevator within a given period of travel time. Again, due to the extreme height of the building, the fire service elevator system is configured to permit transfers connecting individual elevators so that all the

floors of the building are ultimately served. It is very important the firefighting transfer be safe, simple, and direct. The construction of the enclosure to the transfer should be no less than the fire resistance rating of the elevator shaft and maintain a smoke-free environment. In planning the transfer, the distance between elevators must be as short as possible and the path as clearly defined as possible.

Two 'building service/firefighting' elevators serve every floor throughout the hotel, service apartment and residential zones of the tower from concourse level up through Level 111. One of those elevators continues past Level 111 and terminates at Level 138, where it is possible to transfer to another 'building service/firefighting' elevator that serves every floor up to the top occupied floor at Level 160 (Figure 10).

Because of the constraints imposed by the 3.7 m thick structural foundation, it is not possible to install elevator pits below basement Level B2, within the footprint of the core. It is therefore necessary to serve the basements separately. Two 'parking shuttle' elevators are employed for firefighting service from concourse level down to Level B2 (Figure 10).

4.6 'Lifeboat' emergency evacuation elevator service

Since the World Trade Center tragedy of September 11, 2001, there has been much discussion on the subject of speeding up the process of full building emergency evacuation. Specifically, the use of

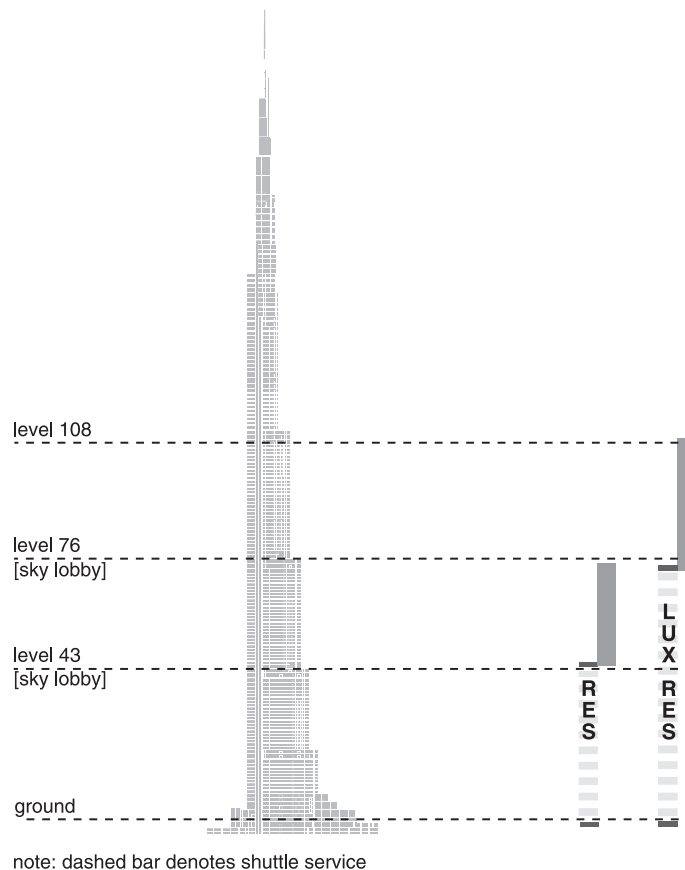


Figure 8. Residential passenger elevators

elevators to supplement the exit stairs, under certain circumstances, has been perceived as a no-cost or low-cost enhancement. At this point, it should be stated that the use of elevators to augment evacuation is proposed primarily for ‘extraordinary’ events. That is to say, that partial or phased evacuation due to a ‘normal’ emergency event, such as a fire in the building, would be handled in a normal manner, without the use of elevators. ‘Extraordinary’ events could include, but are not necessarily limited to, district power outages, seismic events and general or specific security threats to the development, a tenant, or to the building itself.

In early 2004, when SOM and the project’s elevator consulting firm, Lerch Bates & Associates, Inc., approached the client about incorporating this concept, there was no generally accepted standard. However, it was agreed that certain prerequisites should apply. There should be a significant improvement in time to fully evacuate the building. The elevators selected should all be on full emergency power. They should be located in as secure positions as possible, generally within the structural core, and enclosed in robust, fire-rated construction. Their passenger pick-up location should be on a floor that can accommodate crowds and be related to the areas of refuge associated with the exit stairs. The system should be ‘managed’ in the sense that its operation can only be activated from the building automation or fire command center and that each elevator should have attendant operation, to assure the orderly flow of passengers. When first activated, each elevator in each group should be manually

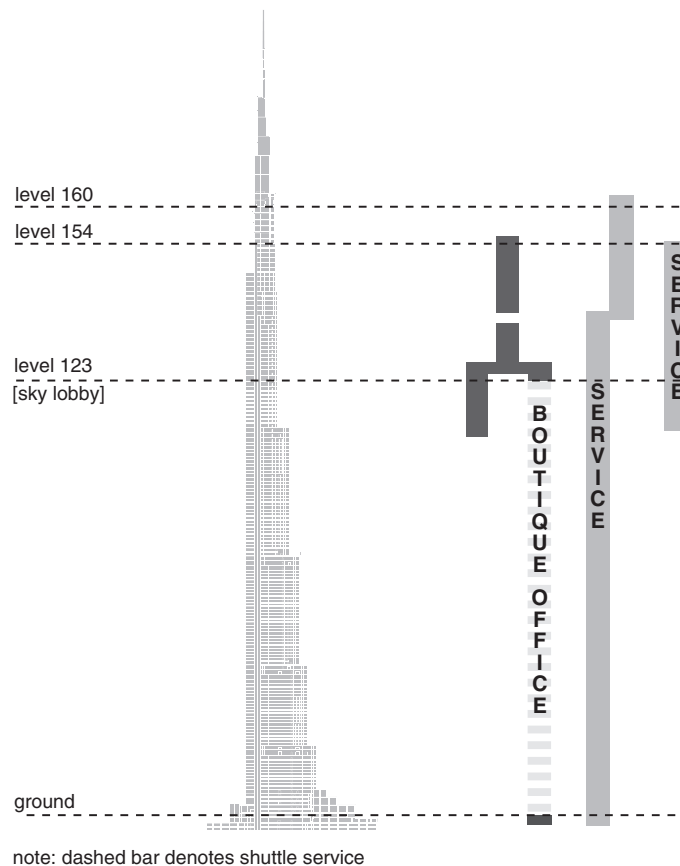


Figure 9. Corporate Suites passenger elevators

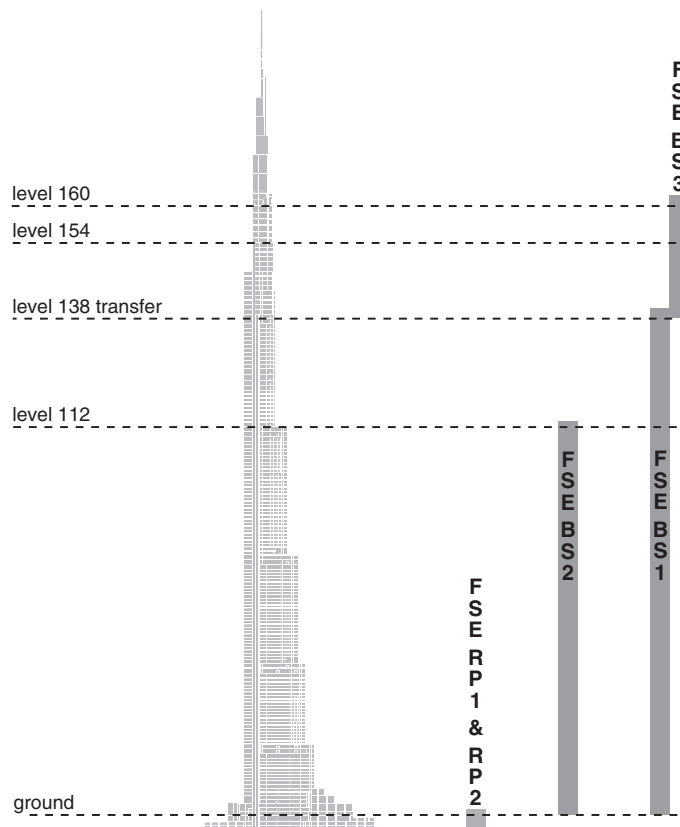


Figure 10. Fire service elevators

dispatched on a low-speed 'clearing' trip extending the complete height of the shaft. During that 'clearing' trip, a car canopy-mounted CCTV camera with lights will be turned on to illuminate, inspect, and display the status of the elevator equipment and hoistway equipment. Computer terminals are equipped with joystick control to direct the viewing of the camera. Procedures for managing 'lifeboat' operation should also include the means and methods of communicating instructions and directions to the occupants exiting the building.

The elevators identified for 'lifeboat' emergency operation are the three high-speed shuttles serving the Level 43 residential sky lobby, the three high-speed passenger shuttles serving the Level 76 residential sky lobby, the two very-high-speed double-deck passenger shuttles serving the Level 124 observatory and Level 123 corporate suite sky lobby and the two building services/firefighting elevators, both serving up to Level 111 and one serving up to Level 138 (Figure 11). The estimated time to fully evacuate the building using stairs and 'lifeboat' emergency service was reduced by 46% from that of using stairs alone.

5. FIRE AND LIFE SAFETY

5.1 *The code and beyond*

It is generally understood that building codes establish the minimum requirements for the design and construction of a building. Any building designed and constructed 'to code', meeting all statutory

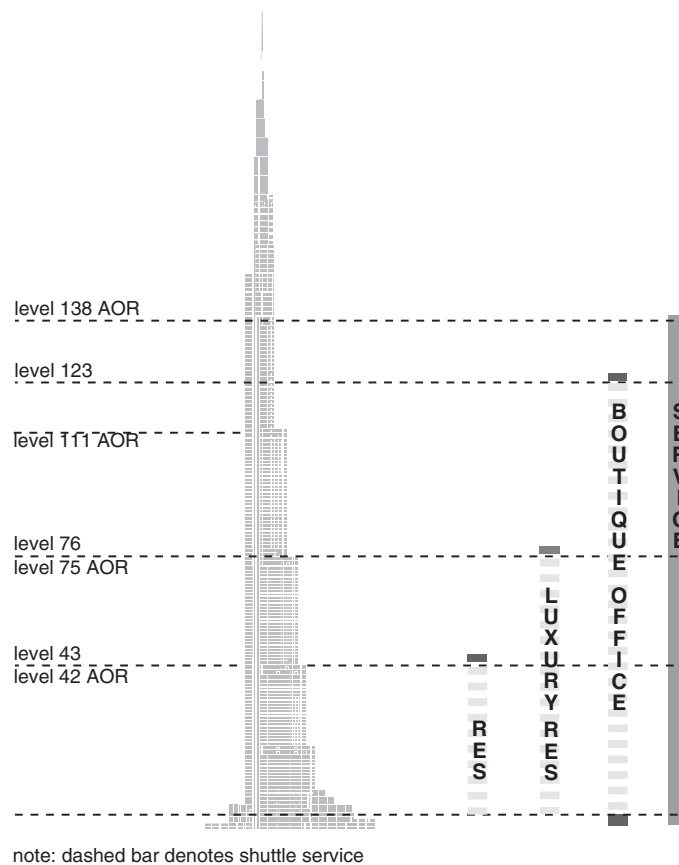


Figure 11. Building section showing 'Lifeboat' emergency service elevator operation

requirements, would be perfectly acceptable. In the case of a super-tall building, however, it is not unusual for it to be provided with additional fire and life safety features in order to compensate for challenges it presents to occupant evacuation and firefighting. These features or 'enhancements' are intended to improve the life safety and firefighting capabilities in the building, thereby mitigating some of the inherent risk in building tall. Using the minimum code requirements as a basis, 'enhancements' can be approached, in two steps. Firstly, the concept of 'best practice' can be applied to design in additional reliability or capacity in code-required systems or features. An example would be the provision of an additional exit stair for additional capacity or an added level of redundancy beyond code requirements. Secondly, 'additional features' are life safety systems or elements that are not code required, but have been used elsewhere on similar structures. An example would be the incorporation of areas of refuge to provide safe protected areas within the building where people exiting down the stairs can rest and receive additional instructions.

In the case of Burj Dubai, the SOM design team and RJA, the fire and life safety consultants, tried to take advantage of some of the otherwise necessary features of a super-tall building. For example, the necessity of very thick reinforced concrete structural walls was turned into an advantage by using them to enclose the exit stairs and firefighting emergency elevators, thereby enhancing the robustness of those enclosures. Due to issues of confidentiality, discussion of further specific examples of enhancements to the fire and life safety provisions is not possible at this time.

6. WIND ENGINEERING

6.1 Wind tunnel testing

An extensive program of wind tunnel tests and other studies were undertaken in RWDI's 2.4 m × 1.9 m (8 ft 0 in. × 6 ft 4 in.), and 4.9 m × 2.4 m (16 ft 4 in. × 8 ft 0 in.) boundary layer wind tunnels in Guelph, Ontario. The wind tunnel program included rigid-model force balance tests, a full aeroelastic model study, measurements of localized pressures, and pedestrian wind environment studies. These studies used models mostly at 1:500 scale; however, the pedestrian wind studies utilized a larger scale of 1:250 for the development of aerodynamic solutions aimed at reducing wind speeds.

6.2 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 allow for 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. The cladding pressure test model was constructed using upwards of 1140 individual pressure taps (Figure 12). 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 13). 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° apart. The measured data are 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 account for the variable extreme wind speeds with wind direction.

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 either include an allowance for internal pressure due to the mechanical system or stack effect or they consider the instantaneous



Figure 12. Detail of pressure taps in cladding pressure test model. (Image courtesy of RWDI)



Figure 13. Cladding pressure test model at 1:500 scale, shown in wind tunnel. (Image courtesy of RWDI)

net pressure differential measured directly across elements exposed to wind on both surfaces. That said, the largest calculated negative cladding wind load was -5.5 kPa (-110 psf) and the largest positive load was $+3.5 \text{ kPa}$ ($+70 \text{ psf}$). With RWDI's input, SOM rationalized the data, resulting in the cladding pressure wind load diagrams issued with the exterior wall tender documentation (Figure 14).

6.3 Upper terrace levels wind studies and resulting measures

An unusual feature of this super-tall building 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 assess the effectiveness of wind mitigation measures on the setback terraces for improving pedestrian comfort and safety. The means by which this objective was to be achieved was through 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. Initial tests were conducted in the spring of 2004 (Figure 15a). At that time, each terrace was given a slightly different combination of parapet wall heights, opacity and/or interior divider screens (Figure 16).

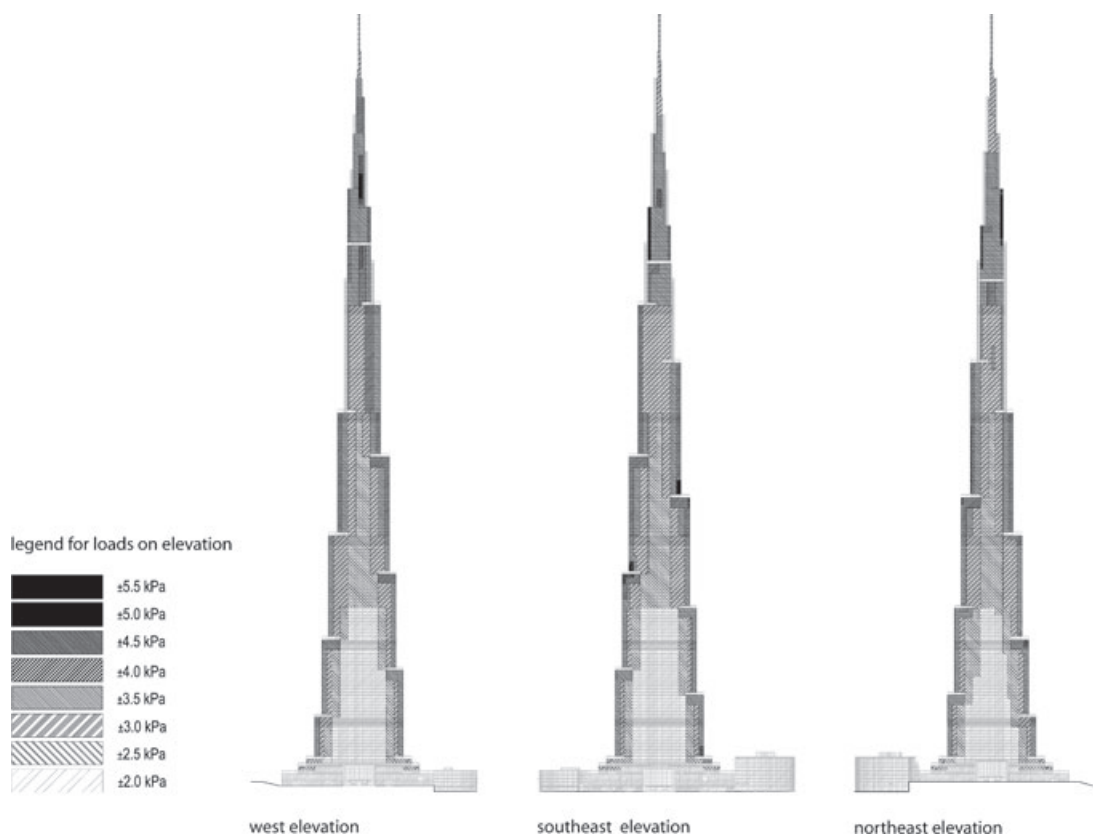


Figure 14. Cladding pressure wind load diagrams

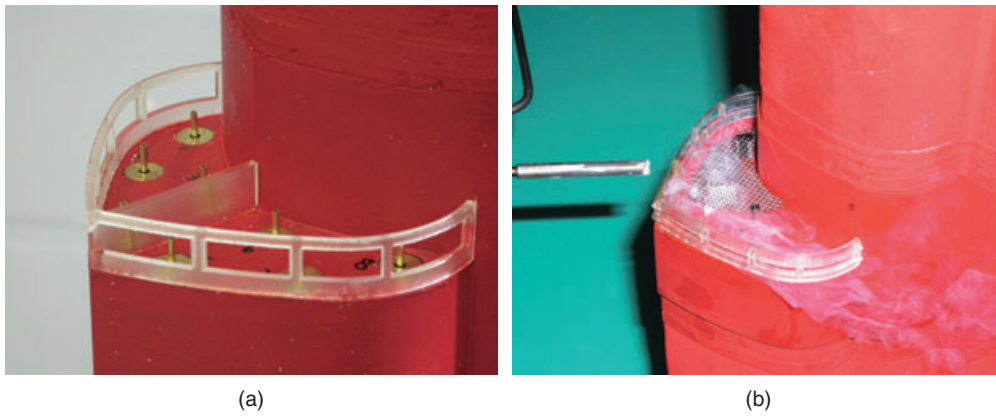


Figure 15. (a) Terrace testing: initial parapet design. (Image courtesy of RWDI). (b) Smoke wand showing wind pattern at Level 87 terrace. (Image courtesy of RWDI)

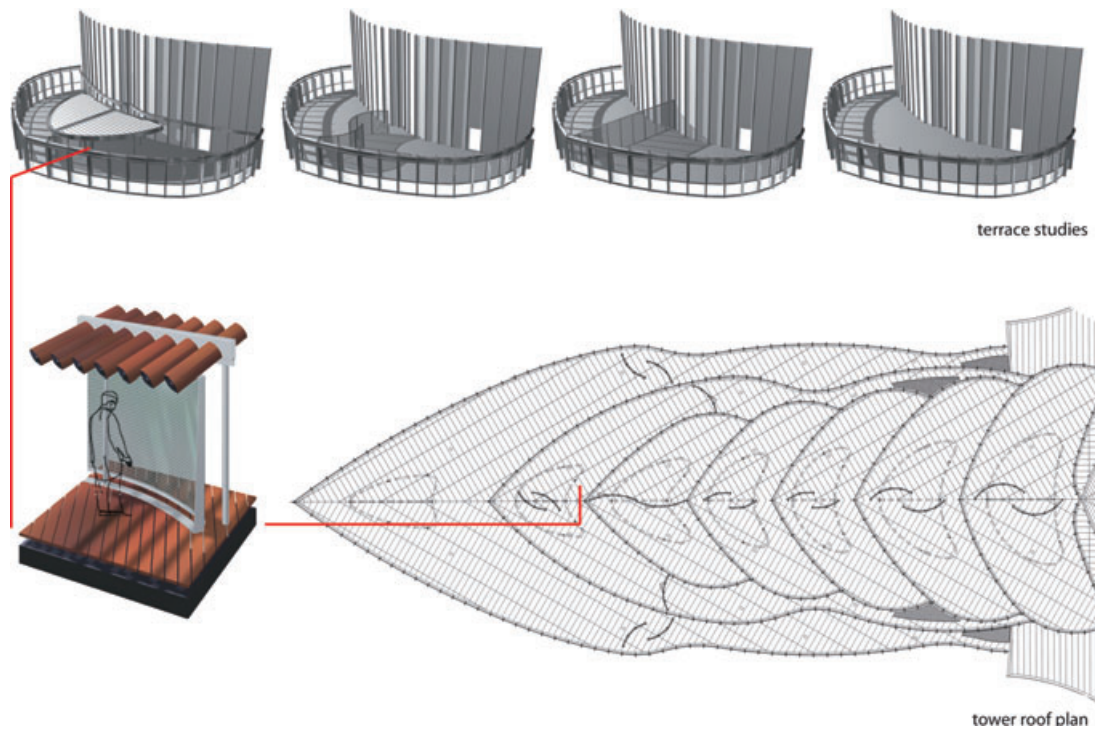


Figure 16. Divider screen design and terrace layouts

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., wind speeds exceeding 19 kph (12 mph) more than 20% of the time). It was also recognized at this time that an overhead element, such as a trellis, could potentially improve conditions beyond the results obtained. SOM designed divider screens and had them included in the exterior wall cladding tender package in the spring of 2004.

By the spring of 2005, several fundamental parameters of the tower had changed. The height of the tower had increased by over 80 m, the program had changed, adding corporate suites to the mixed-use make-up, and the client saw the wisdom in adding permanent shading elements to the terraces. That said, it was determined to run another series of tests to assess the effectiveness of modified wind mitigation measures on the terraces. In this case, a 1:250 scale model of a portion of the tower covering the Level 87 terrace. The tests were conducted in the summer of 2005. Similar to the initial testing, the terrace was given a slightly different combination of parapet wall opacity and interior divider screens, and tested with and without the trellis (Figure 15b). The results led the team to adopt the trellis option with divider screens while maintaining the original parapet design (Figure 16).

Beyond the mitigation measures noted above, it was felt that 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 out onto their terrace. Therefore, adjacent to each door opening onto a terrace, the design provides for a wind-tracking panel. The panel is connected to an outdoor sensing device on the terrace trellis and will indicate wind speed and direction. The panel can signal an alarm if the wind speed exceeds a set level. Additionally, each trellis is provided with a couple of pennants so that the residents can see the wind condition safely from the inside. Finally, to prevent the terrace door from swinging wildly in the wind, it is provided with motor-assisted operation.

6.4 Level 3 terrace wind studies and resulting measures

Another unusual feature of this super-tall building is the provision of accessible terraces at several levels at the base of the tower. These terraces can be accessed by hotel visitors and guests. RWDI was retained to conduct a separate study of these setback terraces. The purpose of the study was to assess the effectiveness of wind mitigation measures for improving pedestrian comfort and safety as well as to improve the possibility of using the terrace for hotel dining functions. The means by which this objective was to be achieved was through wind tunnel testing a 1:250 scale model of the base of the tower (Figure 17). The tests were conducted in the summer of 2005. At that time, the terrace was given a slightly different combination of parapet wall heights, opacity and/or interior divider screens.

7. STACK EFFECT

7.1 The phenomena

To a person from a temperate climactic zone, stack effect is sometimes called 'chimney' effect. It is the draft of air up the chimney in winter time due to the difference in temperature and density between the flue gas within the chimney and that of the outside air. The height of the chimney will also influence this phenomenon. In the case of Burj Dubai, however, this effect is reversed. The high outdoor temperature and cool indoor conditions create a difference in density that makes the indoor air want to travel downward, out the bottom of the building. This pressure difference is proportional to the temperature difference and building height and can be calculated mathematically. The design team

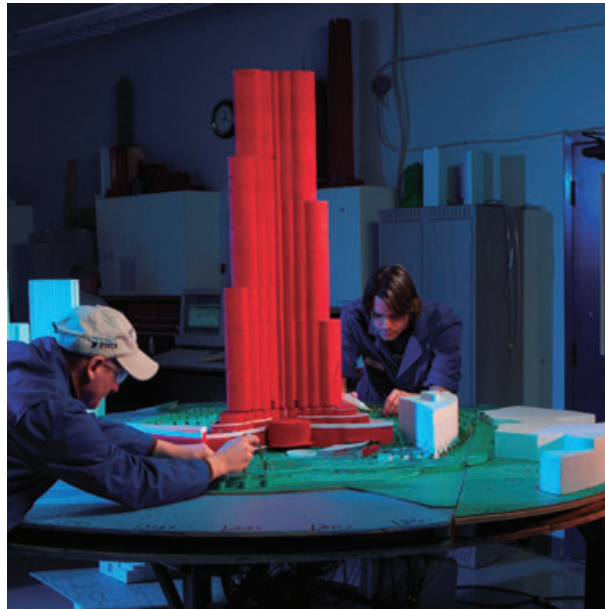


Figure 17. Level 3 terrace wind study: 1:250 model. (Image courtesy of RWDI)

enlisted the advice of RWDI with respect to this issue. Working with SOM and using the design criteria developed for the various elements, their report, issued in late 2005, quantified the pressure differentials across the height of the building. Having had extensive experience on other super-tall buildings, SOM had already taken certain measures to mitigate the stack effect in the building. Based on these results of RWDI's report, SOM went back and verified the basic design as well as adopting a few additional measures.

7.2 Architectural mitigation measures

The following measures were incorporated into the architectural design with the intent to mitigate the negative impact of stack effect:

- The infiltration/exfiltration rate of the exterior wall is designed to a very tight standard. Operable doors/windows are minimized. Terrace doors are 'alarmed' so that they are discouraged from being open at the same time that the unit entry door into the corridor is open.
- The sky lobby elevator system is an advantage in that the shuttle and local elevator shafts are separated. In effect, the building tends to act as a series of shorter buildings, separated, but stacked on top of one another.
- The tallest elevator shaft (the primary service elevator of 140 stories in height) has door openings at every floor. It is, however, provided with a vestibule at each floor with tight-fitting doors. Also, the elevator doors themselves have been provided with additional gasketing to improve the airtightness of the shaft. Furthermore, the elevator is located within the heart of the core, separated from the exterior wall (source of infiltration or location of exfiltration) by at least two additional sets of doors.
- Vestibules, with revolving doors, are provided at the entry level to each of the highly trafficked passenger shuttle elevators.

- The exit stair transfers at area-of-refuge floors act in a similar fashion to the sky lobby elevator system. The stairs are not in a continuous shaft: each shaft is much shorter and each is separated from the other by at least two doors.
- The service shafts between mechanical floors are separated where the risers from the lower zone meet those descending from the upper zone.
- Additional sets of doors were placed in the corridors between the elevator lobby in the core and the residential corridors.
- The perimeter of the floor slab is sealed at every level to the inside surface of the exterior wall.
- The pipes and other services within the service shafts are sealed off at every floor.
- The residential unit entry doors are provided with adjustable door bottom seals so that the air flow due to stack effect can be adjusted seasonally and under operating conditions, if necessary.

7.3 *Building services mitigation measures*

The following measures were incorporated into the mechanical systems design with the intent to mitigate the negative impact of stack effect:

- The building is slightly pressurized or neutral compared to outside.
- Major air systems in the tower have variable-speed drives to allow systems to dynamically react to different pressure conditions.
- All air systems in the tower are divided into vertical sections to avoid excess differential pressure between top and bottom of the risers.
- Outside air intake and exhaust systems have air flow monitoring stations to track the amount of air in and out of the building.
- At each air system section, static pressure inside the tower is measured and compared to the static pressure outside to maintain a slightly positive or neutral pressure in the building.
- The smoke exhaust system is doubled up as air relief to avoid over-pressurization of the building.
- Air balance is studied to bring in the appropriate amount of outside air and exhaust without over-pressurized the building.

8. EXTERIOR WALL SYSTEMS

8.1 *Design criteria and factors influencing the design*

Organizing the logistics of construction is what makes building a super-tall project like Burj Dubai such a challenge. Similar to the 'just in time' system employed by automobile manufacturers, the controlled flow of materials onto the constrained construction site is essential, firstly, to keep feeding materials to the site so that the work keeps progressing and, secondly, to prevent materials from arriving too early, overwhelming the site with stored materials. In the case of the curtain wall, unit production, shipment, and erection must be planned for months if not years in advance. SOM approached the design of the exterior wall systems with the knowledge that simplicity, repetition, ease of transport, and prefabrication are essential for success.

The curtain wall was conceptualized and designed from the outset as a 'unitized' system consisting of interlocking prefabricated panels. As much work as possible is performed in the controlled environment of the factory and the individual units brought to site. Once the units reach site they are hoisted to a temporary storage location on the floor where they are to be installed. Manual or powered manipulators handle the panels from the floor and bring them to their final erected position. The panel supports have been previously installed in the slab edge and the crew aligns the panel fixing bracket

to them. Each panel is designed to interlock with each of the four panels adjacent to it. Each panel joint is weathertight, but designed to permit movement due to temperature change, wind, seismic events, and long-term movements of the structure. Final adjustments are made and fixing bolts installed, then the crew does the same for the next panel.

The aesthetic design of the curtain wall was influenced by several factors. Both the verticality of the structure and the shape of the plan are emphasized by and reflected in the stainless steel vertical mullion/fin. The spacing of the fins is fairly regular on the body of the tower but increases as it approaches the end of the wings, reflecting the acceleration and growth of the tower shaft itself and providing more expansive views from the more prestigious residences. The selection of the high-performance silver reflective glass, along with the bright stainless steel of the spandrel panels, tends again to emphasize the verticality of the tower as well as providing surfaces to reflect the changes in its environment. Because of the importance of the aesthetics of the exterior wall, a visual mock-up was erected on site in the late fall of 2003 (Figure 18).

The detailed technical design of the curtain wall also had to take into account many factors. The extremely hot and humid environment in Dubai, being both desert and coastal marine, influenced the design criteria and material selection. The curtain wall is designed to accommodate thermal movements due to an ambient temperature range of between $+2^{\circ}\text{C}$ ($+36^{\circ}\text{F}$) and $+54^{\circ}\text{C}$ (129°F) as well as a material surface temperature in excess of 82°C (180°F). This is coupled with an extremely humid environment, with a dry-bulb temperature of 46°C (115°F) and wet-bulb of 29°C (84°F). Additionally, the abrasive nature of the airborne desert sand (really a very fine talc-like powder) must be acknowledged. Other building movements due to slab edge deflections, column shortening and inter-story drift due to wind and seismic events must also be accommodated. Additional criteria have been established for the acoustic and thermal performance of the wall. Finally, the curtain wall must be designed to withstand the myriad of structural loads that it might see in its lifetime. The wind loads, as determined by wind tunnel testing discussed in Section 6.2 above, are the most obvious. There are other loads, however, that must be taken into account. These include incidental or accidental loads



Figure 18. Tower exterior wall visual mock-up

applied by the building's occupants, the loads applied by the building maintenance (window-washing) equipment and the loads on elements and support fixings generated by seismic events.

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 wall. 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. Refer to Figure 19 to see the test mock-up assembly and chamber in position and the specimen under test for dynamic water penetration. Additionally, special tests have been devised for the wall type at the mechanical floors which functions as an air intake and exhaust 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 his installation procedures.

8.2 *Tower systems*

There is approximately 1 350 000 square feet of curtain wall and cladding on the Burj Dubai Tower. There are 21 major panel types, ranging in size from 1.3 m × 3.2 m (4 ft 4 in. × 10 ft 8 in.) up to 2.25 m × 8.0 m (7 ft 6 in. × 26 ft 3 in.). In order to permit the curtain wall contractor flexibility in his ability to complete the detail design, SOM produced a series of drawings detailing the assumptions made with respect to both the prefabrication of each panel type, method of fixing, location of loading and support back to the building structure, and accommodation of movements between panels (Figure 20).

The typical curtain wall panel is constructed of extruded aluminum mullions with a natural silver anodized finish, polished stainless steel external mullion cover/fin, patterned stainless steel spandrel panel with insulated back-up, and high-performance insulated glass (Figure 21). The glass itself is an insulating unit consisting of two pieces of clear glass with a 16 mm air space. The outer piece of glass has a high-performance silver metallic coating deposited on its inner surface and the inner piece of glass has a metallic low emissive type coating on its surface, also facing the air space. The combination of coatings results in a glass that permits over 20% of the visible light into the building while allowing less than 16% of the associated heat.

8.3 *Entry pavilion cable supported double wall system*

The entry pavilions located at 'grade' on each of the three sides of the tower are very special 'crystal-line' glass elements, utilized as entries to the three primary functions of the tower. The Armani Hotel is entered from the north, the residences are entered from the southwest, and the corporate suite offices are entered from the southeast (Figure 22).

As each pavilion is a major entry to the tower, transparency is a primary aesthetic goal in their design. Of course, the desire for transparency, in a hot and sunny desert climate, creates a significant challenge to maintaining environmental comfort within each pavilion. At night, specialist designed



Figure 19. (a) Tower test mock-up assembly. (b) Tower test mock-up dynamic test for water penetration

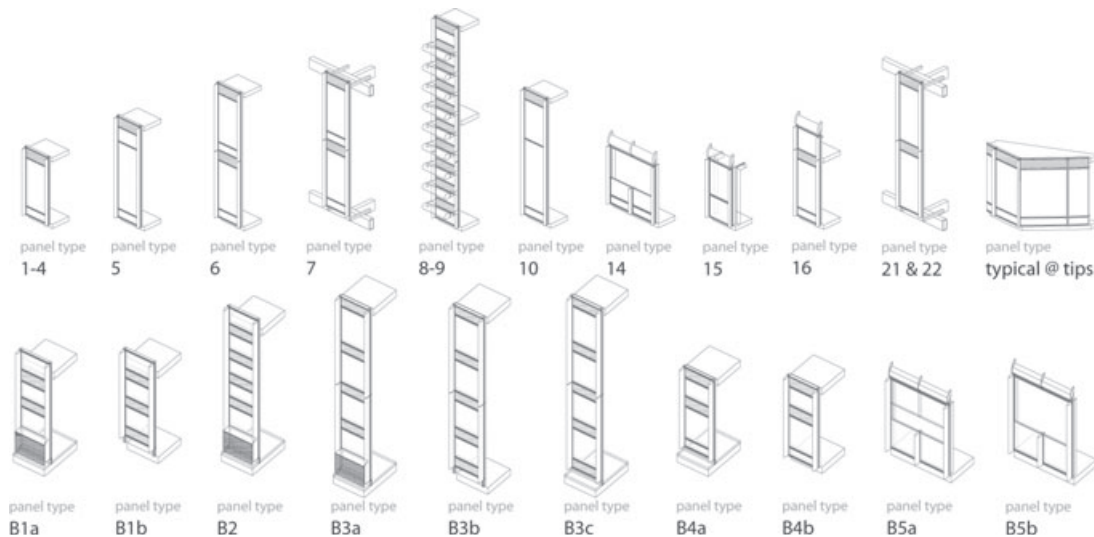


Figure 20. Tower exterior wall prefabricated panel types

lighting combined with the extensive glazed area creates a transparent ‘lantern’ effect; however, during the day the excessive amount of solar gain must be controlled.

Transparency is accomplished by maximizing the extent of glass and minimizing the glass support elements. SOM designed a cable net wall structure, utilizing stainless steel cables, tensioned between rigid structural elements in the floor and roof, and stainless steel ‘arch’ rods spanning horizontally between cables to steel corner parabolic trusses (Figure 23a). There are two layers of cables separated a distance of 1500 mm by stainless steel spacer rods. Super-clear, low-iron glass is supported by each net in a minimal fashion utilizing ‘patch’ fittings in the corner of each piece of glass (Figure 23b).

Environmental control is accomplished firstly by placing computer-controlled, motorized, metallic sunshades between the double walls of glass, (Figure 23b) and secondly by ventilating the heat built

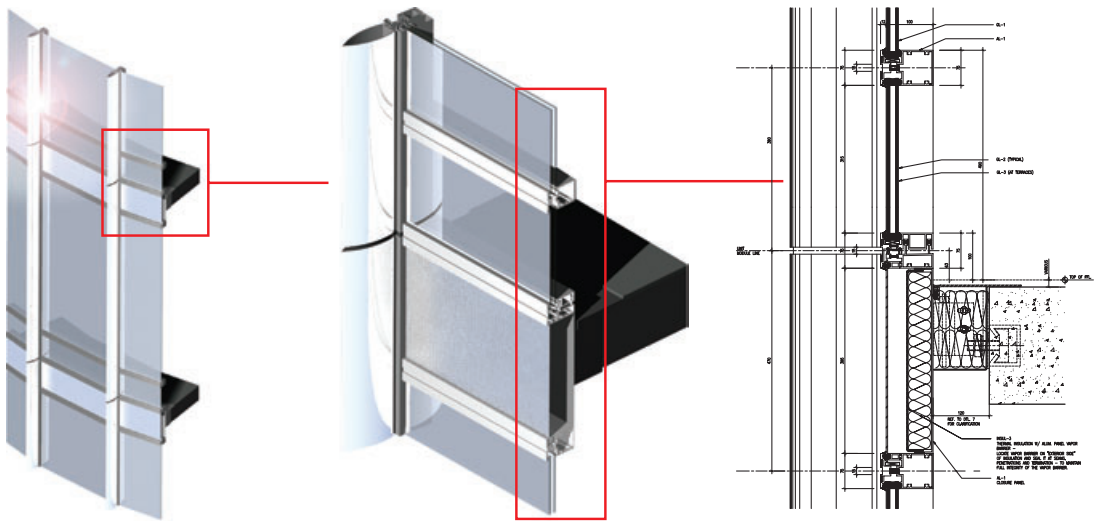


Figure 21. Typical tower exterior wall panel system details

up within the void to the outside. Interior conditioned air is introduced at the bottom of the void and exhausted at the top, creating a tempered zone between the extremely hot exterior and cool interior (Figure 24a). In order to be assured that there would be little or no condensation on the glass, SOM modeled the performance of the wall system over an entire year. The parameters modeled included the temperature of each glass surface, the outside air temperature and humidity, the inside air temperature and humidity, and the air temperature and humidity within the void. The results indicated that, even with the extremes of the Dubai climate, conditions that would produce condensation are present only a few hours each year (Figure 24b).

8.4 Building maintenance (window-washing) equipment system

SOM and CCI, the building maintenance equipment (BME) consultant, confronted several challenges in designing the window-washing system for Burj Dubai. The local climate is very severe, with extremely high temperatures, high humidity and a significant amount of windblown sand and dust in the air. There are well over one million square feet of exterior wall and 21 setbacks and different plan configurations below the spire portion of the tower. Furthermore, the sheer height at which the equipment and operators must work makes the maintenance process even more difficult. Lastly, over a period of about 2 years, from the initial concept to the final design, the overall building height increased by almost 50% and the client increased the frequency that he wanted the building cleaned. The resulting BME system design, therefore, provides multiple systems in order to meet the client's requirements for maintaining the cleanliness of the façade. For the 'shaft' of the tower, there are a total of nine permanently installed machines, parked in 'garages' located on Levels 40, 73, and 109: the mechanical floors. They traverse the building on externally mounted tubular tracks which are expressed as a feature on the façade of the building (Figure 25). The manned cleaning cradle on each machine is capable of cleaning the façade downward to the next mechanical floor and, by extending its jib arm to a reach of 10 m (33 ft), covers all the terrace 'nose' areas and setbacks. Additionally, there are three



Figure 22. (a) Site plan. (b) View of hotel entry pavilion

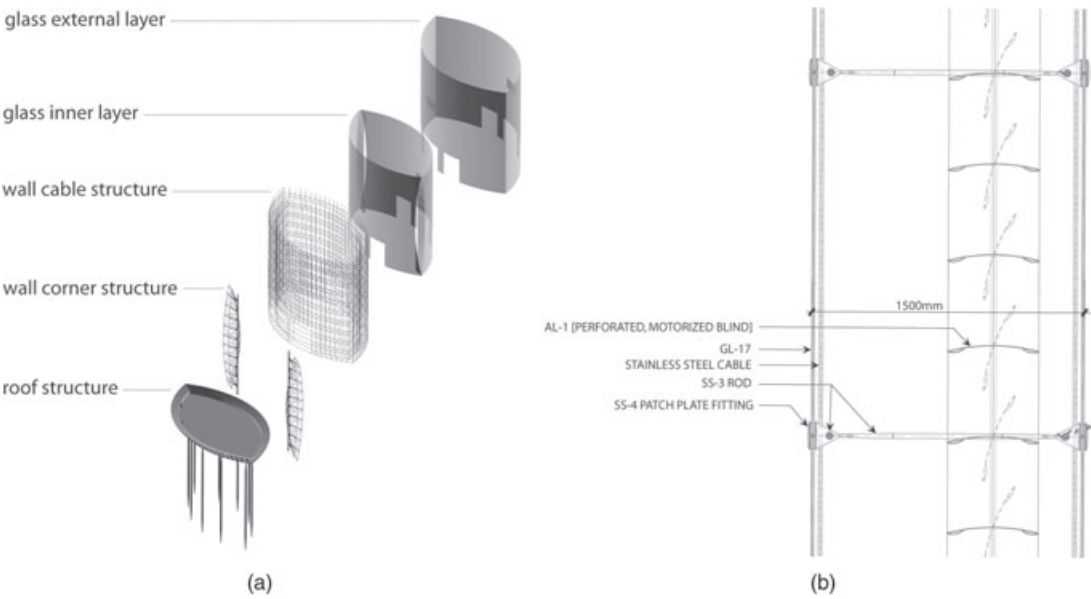


Figure 23. (a) Entry pavilion. (b) Detail of entry pavilion glass fixing and cable support

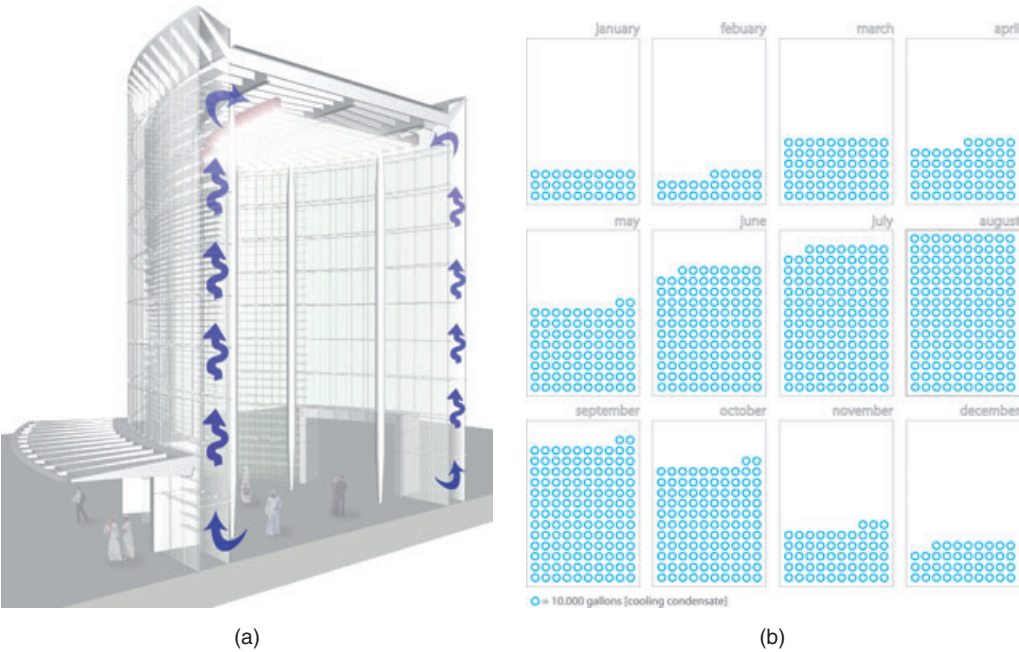


Figure 24. (a) Section through entry pavilion. (b) Predictive yearly condensation chart

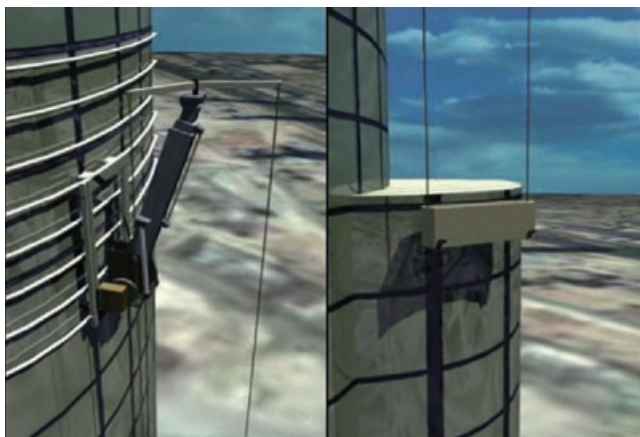


Figure 25. BME unit in operation. (Images courtesy of Citadel Consulting Inc, A division of Lerch Bates Facade Access Consulting Group)

permanently installed, roof-powered, gimbal-mounted telescopic machines at the roof levels below the spire. The manned cradles in each of these machines are capable of cleaning the façade down to the Level 109 mechanical floor. Each machine has an overall reach of 20m (66ft). Under normal conditions, it will take 6–8 weeks to clean the entire building.

There is a separate system for the tower spire consisting of several permanently fixed outrigger arms and internal ladder access systems.

Separate systems, including a mobile area work platform and removable davit arms, will access the podium levels and entry pavilions at the base of the tower.

9. CONCLUSION

9.1 *From the past into the future*

In the period immediately after the tragic events of 9/11, it would have been hard to imagine that the skyscraper would be undergoing a renaissance of the magnitude we are now experiencing. When completed, Burj Dubai will raise the bar by establishing a new height record not by a few meters, but by hundreds of meters. The question we have pondered is: 'Is the Burj Dubai an evolution based on designs that have come before it or is it a revolution in design, more significant for more than just its unprecedented height?' Our current answer, as one might suspect, is that it is both.

As we hope this paper has explained, the materials and systems applied on Burj Dubai are not fundamentally new or untried. What is new is the innovative ways in which they have been employed or combined in order to optimize performance and fulfill the clients needs. Our approach has been multidisciplinary and our philosophy has always been to maintain as much simplicity as possible in order to successfully achieve complicated and ambitious projects. Maintaining that approach will be essential as we progress the design of this new generation of super-tall buildings. Beyond sheer height all tall buildings must be measured in terms of efficiency, sustainability, and level of appropriateness as we move into the future. We trust that Burj Dubai will also have raised the bar in those respects also.

PROJECT TEAM

Owner:	Emaar Properties PJSC
Project manager:	Turner Construction International
Architect/structural engineers/MEP engineers:	Skidmore, Owings & Merrill LLP
Architect and engineer of record/field supervision:	Hyder Consulting Ltd
Wind Engineering Consultants:	Rowan Williams Davies and Irwin Inc
Building Maintenance:	Citadel Consulting Inc, A division of Lerch Bates Facade Access Consulting group
General contractor:	Samsung/BeSix/Arabtec