

# Case Study: Nakheel Tower – The Vertical City



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## Mark Mitcheson-Low

Mark has an expansive portfolio of major projects in all sectors of design across the world in his 30 years of experience in Architecture. Projects include mixed use developments of commercial, retail, hospitality and residential sectors and major projects in transportation, education, and infrastructure developments. Mark has been a director since 1998 and joined Woods Bagot in 1986. His role has included the development of new markets and the procurement and design management of a diverse range of projects across the globe.

## Ahmad Rahimian

With over 28 years of experience, Ahmad, an internationally recognized expert in tall buildings, is president of WSP Cantor Seinuk, a leading structural engineering firm based in New York and part of WSP Group PLC. He is the recipient of 2007 AISC Special Achievement Award, 2005 ASCE-CERF Charles Pankow Award and ENR -Top 25 Newsmakers Award of 2003. Among many notable projects, he directed the structural engineering of the Trump World Tower and Hearst Tower, New York; and Torre Mayor, Mexico City.

## Dennis O'Brien

Dennis O'Brien is the Deputy CEO for the International Group and Regional Director for Middle East. Dennis established the office in Dubai following NDY, appointment as Building Services Consultants for the Nakheel Tall Tower. In addition to roles on the Board of the Company, he is responsible for areas of Quality Assurance and Risk Management for the International Group. He is also active in assisting international offices in concept design and design reviews for major projects.

"The Nakheel Tower is a feat of design intelligence on all levels and across all disciplines – it truly is a mark of the epoch. It is an example of the resilience of the human spirit to overcome the forces of nature to create a monument dedicated to past, present and future generations of the Gulf."

Nakheel Harbour & Tower, Dubai's new capital, will be a beacon of inspiration for the region and the world, incorporating elements from Islamic culture. Encompassing more than 270 hectares, this mixed-use development will be located in the heart of New Dubai, and will include the world's tallest building, a harbour, cultural podium and residential districts. Nakheel Tower in itself will be a vertical city, accommodating residents in an efficient LEED rated, sustainable building. This is the world's first true, very tall mixed use development combining offices, a 5 star hotel, luxury residential and serviced apartments, an

experience centre and observation facilities along with a special sky function space – creating a vertical community of over 15,000 people (see Figure 1).

The lessons learned from the Nakheel Harbour Tower hold implications for future buildings of this magnitude. Although the technical difficulties associated with such a large project are many, none are insurmountable. This provides optimism for the future of tall building design and demonstrates the possibilities in building towers that reach higher than any that have come before.

Figure 1. Nakheel Harbour & Tower



## Architecture

Global design practice Woods Bagot were appointed as the Architects for the Nakheel Tower and Masterplanner for the harbour precinct in 2006.

Building on the theories of past visionaries such as Le Corbusier, Frank Lloyd Wright and Paolo Soleri, the Nakheel Tower is the first, true realisation of a vertical city. Over 15,000 inhabitants will live, work and socialise all within a footprint smaller than a New York City block. With the ever-changing global environmental climate affecting not only Dubai, but the world as a whole - The Nakheel Tower seeks to reduce the human impact on the environment by being a beacon of passive



Figure 2. Nakheel Harbour & Tower Plan



Figure 3a. Tower Components

ESD initiatives, striving to counteract and minimise its carbon footprint by intelligent design solutions and reducing urban sprawl (see Figure 2).

Reaching heights of over one kilometer was made possible by implementing a design concept that divided the Tower into four separate towers. Typical tall buildings are usually planned around a single, central core and taper towards the top to mitigate the

wind forces. In contrast, the Nakheel Tower deals with the issues of wind by allowing the wind to pass through the tower, rather than around it. This is achieved by incorporating two slots through the height of the tower which effectively creates four separate towers, each with their own core and structurally linked at every 25 levels by "skybridges". Each of these skybridges acts as a "podium" for each of the tower sections above it. The end result is large floor plates at high levels as the tower does not taper as it gets taller (see Figures 3a+b). ↗

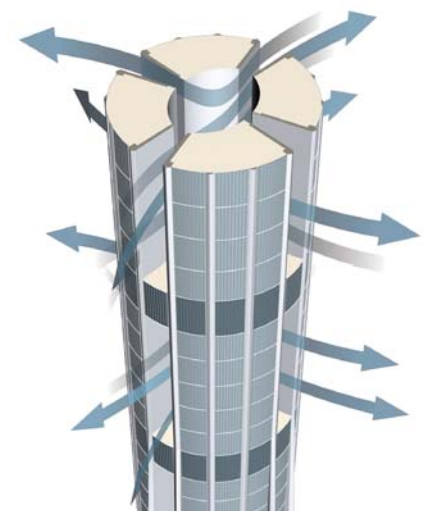
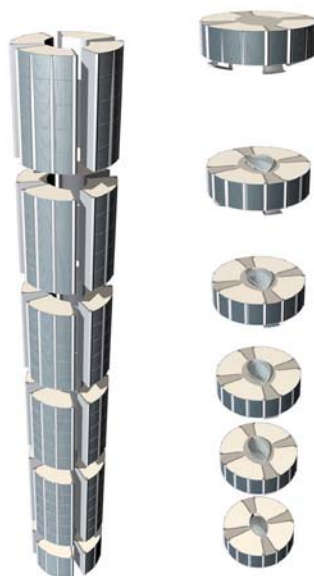


Figure 3b. Slots through Nakheel Tower allow wind to pass through



Figure 4a. Arabic Pattern Base

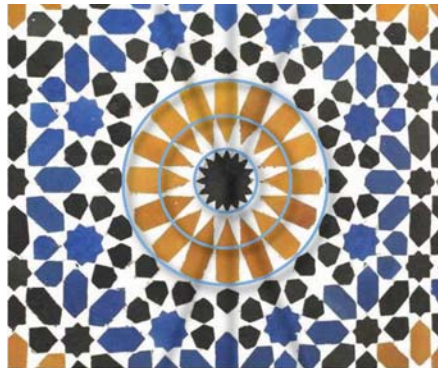


Figure 4b. Concentric Circles



Figure 4c. 16 points

“In the concept stages of the design, the architects searched for cultural and regional inspiration. A key element that came up time and time again from an engineering perspective was that a building that was symmetrical would evenly distribute the massive loads. This was keyed into Arabic pattern-making, which is the same notion about symmetry, harmony and the centre point. From a cultural point of view and from an engineering point of view there is an overlap that basically tells the same story.”

*Alf Seeling, Principal, Woods Bagot*

The design essence of the Tower is thus deeply routed in the regional influences of pattern-making and geometry, stemming from the harmony, unity, order and balance of the radiating circle and 16 pointed star often seen in regional designs. The 16-pointed star, from which the Nakheel Tower draws its inspiration,

is a regular geometric shape that symbolises equal radiation in all directions from a single point. This is a fitting symbol for the spread of the teachings and influence of Islam throughout history. When the star motif is replicated and radiated, it creates junctions at the points where they meet. This, in turn, defines further points of a circle, creating a series of concentric circles all emanating from the centre point, again reinforcing Islamic principles (see Figures 4a-c).

In developing the Nakheel Tower, the circle has been adopted as the essential form of the plan. The locations of the columns supporting the tower represent the points of a 16-point star. Instead of forming the star from straight lines, circles were used. As these circles crossed the

circle of the plan they created crescents, and the intersection of these crescents, in turn, form the shape of the columns. As they fan out from the base of the tower, these larger circles inform the geometry of the surrounding areas, reinforcing the importance of the tower's geometry and the way it sits in its context (see Figure 5).

There are many buildings that claim to offer vertical communities. However, the Nakheel Tower will far exceed the existing paradigm of vertical living with the inclusion of 'sky bridges' in the proper sense of the term. The sky bridges perform multiple roles, offering community and public spaces where visitors and residents alike can interact - the Village Squares for the building inhabitants. They will also serve

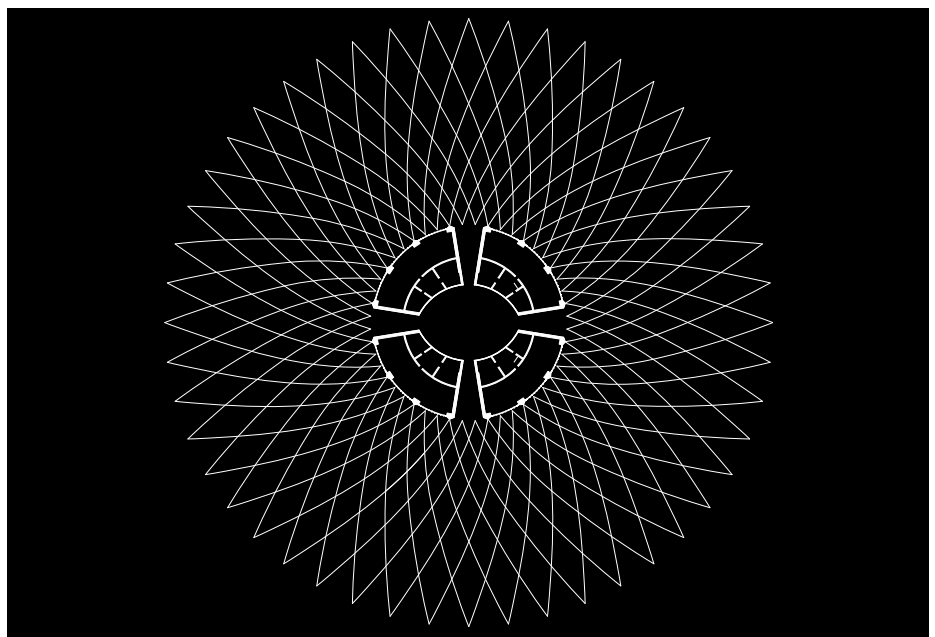


Figure 5. Pattern informing tower plan

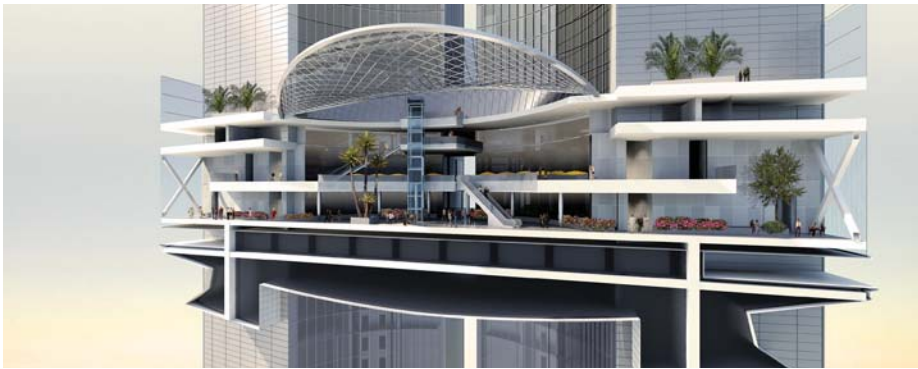


Figure 6a. Skybridge section

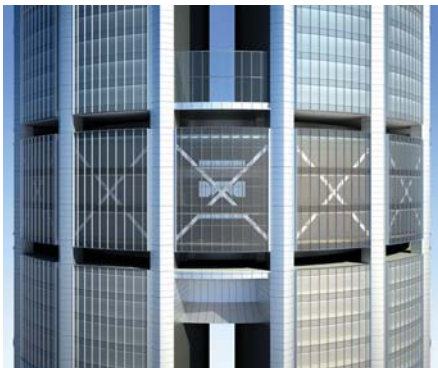


Figure 6b. Skybridge link

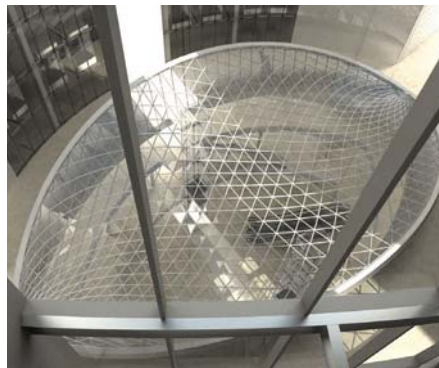


Figure 6c. View to Skybridge dome from glass elevator



Figure 7. Diagram of the planning and stacking of the 156 tower lifts

functionally as the transfer point between lifts, the refuge zones in an emergency, and the structural link between the four tower legs, acting as a 'belt truss' that binds the tower together (see Figure 6a-c).

Fire and life safety design is paramount in tall building design. The design team made a priority of incorporating multiple levels of in-built redundancy within the Nakheel Tower's design. The concept of four legs means that there are four separate towers that offer four distinct means of exiting in an emergency. For example, if one of the tower cores were disabled due to an emergency, it is possible to travel either up or down to the nearest sky bridge and safely cross to an unaffected tower and exit from there.

The logistics of servicing a population of over 15,000 people vertically requires innovative design solutions. The tower is serviced by 156 lifts using the latest technology of double-deck and express lifts - the equivalent of a vertical mass transit system.

The express lifts use the highest lift technology available to reach the 560m high sky lobby and transfer floors. From the sky bridges, residents, tenants and guests can commute in local lifts for the 25-level community above. All 156 lifts can be used for fire evacuation to refuge zones on sky bridges or complete evacuation. Delivery to the tower is also via remote loading and docking with a logistics handling system not unlike an airport terminal (see Figure 7).

Due to the sheer scale of the Nakheel Tower and the time projected to build it, a key consideration during the design process has been to maximise the repetition of façade elements, to keep construction time and cost down as much as possible. The curtain wall and titanium cladding follow a modulation that panelises the entire façade - essentially making the panels used on every level exactly the same (see Figure 8).

The façade incorporates the very latest in glass technology, including advanced nanotechnology, to allow maximum light transmission



Figure 8. Façade Panelisation

whilst providing shading co-efficiencies and U-Values to withstand direct sunlight and high humidity levels. The Titanium panels proposed are 100% recyclable - including all fixing plates and connections. The panels are manufactured in a process similar to that utilised by the aerospace industry.

In a region such as the Middle East with its harsh climate, sustainability is of the upmost importance. The design teams are working

to achieve LEED Gold rating for the Nakheel Tower. Also, original and forward-thinking sustainability initiatives are being developed and incorporated in parallel to contemporary standards to ensure that it is 'future proofed'. When holistically considered, all these efforts will offer 'green' capability above and beyond the existing advisory standards. The current sustainability model for super tall buildings is being challenged at every level on a continuous basis, the physical example becoming the Nakheel Tower. Many forms of environmental strategies have been applied to the building design. These include everything from the use of high-performance facades to low energy-use servicing.

### Structure

WSP Group has been appointed as structural consultant for the Tall tower. Structural engineering of the Tall Tower were managed by WSP Cantor Seinuk as lead structural engineer in collaboration with LERA and VDM Group.

### Building Form

The building form steps forward beyond the traditional approach to high-rise construction, and does so in a holistic way that harmonizes the structure and architecture. For any high-rise building, a broad footprint gives the structure the stability that it needs; and

## ...super-talls

“The primary difference between a super-tall tower and two towers half its size is not the cost per square meter – it is the time it takes to build the tall one versus two shorter ones, and the loss of revenue through lost rent. This makes most super-tall buildings financially unfeasible.”

*Adrian Smith, Principal, Adrian Smith + Gordon Gill Architecture on why most super-tall buildings are financially unfeasible for developers. From 'The Sky's the Limit' Cityscape. February/March 2009*

traditionally that broad footprint would taper and narrow at higher elevations. Generally, this approach has the beneficial effect of reducing the lateral wind and seismic loads on the building. Unfortunately, the tapering reduces the most valuable real estate that the building possesses – the area towards the top.

To gain an adequate footprint for stability, the tower extends to nearly 100m in diameter, resulting in an approximately 10:1 aspect ratio. Still, despite being quite a slender tower, the central area of such a floor plate cannot be reasonably utilized as lettable area, as it is too far from the natural light of the façade.

This fact led to creating a central void space in the tower, which pushed all of the usable area to the perimeter. This in turn afforded the opportunity to create vertical slots in the tower, allowing wind to pass directly through

the center of the building. In effect, the tower essentially tapers from the inside out to dramatically reduce the overturning wind forces on the structure.

The 4 quadrant approach also provided the opportunity for independent and redundant building

systems of all kinds – structural, mechanical, electrical, fire egress, life safety, etc...

And of course, this design maximizes the most valuable real estate at the top of the building.

### Structural Form

Beyond practically a constant form from top to bottom, the tower is also characterized by its symmetry. This provides two very important benefits for the structure. Firstly, there are no transfers of vertical elements through the main body of the tower. Secondly, it allows for a uniform distribution of gravity forces through the structure. These characteristics allow for a more efficient structure. Further, they address an important design consideration for super-tall buildings – axial shortening.

Maintaining a uniform distribution of load throughout the structure was one of the driving forces in developing the structural systems, given that the building would likely shorten more than 400mm at its observation level. However, the structural characteristics that address this issue are one in the same as those that address the core issues of efficiency, redundancy, and economy.

There is no separation between the gravity system and the lateral system, as can often be the case in high-rises. The vertical structure is organized in such a way that the elements are all sized based on strength considerations, while at the same time providing sufficient lateral stiffness. Every element of the structure is interconnected as will be described below. This creates an extremely efficient structure

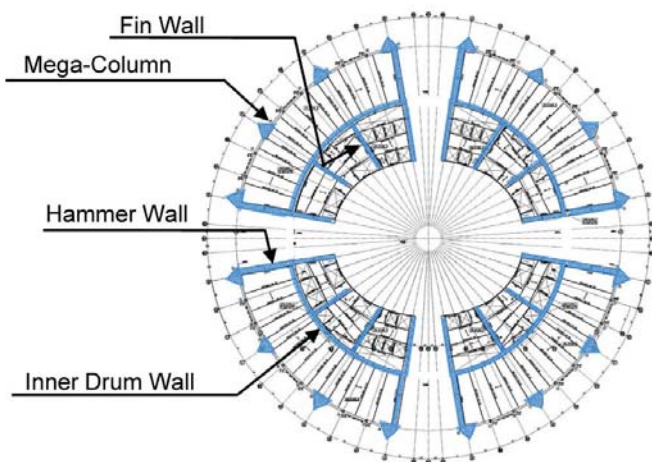


Figure 9. Typical Wall Layout

where the materials perform double-duty (gravity and lateral support). Multiple load paths are created to give added redundancy and by placing material only where it is required for strength. This structure creates a uniform distribution of load, so as not to have differential shortening.

Though the building may function architecturally as several groups of 25-story buildings, structurally it functions as a single entity.

### Primary Structural Elements

All of the vertical elements of the building are cast-in-place reinforced concrete. The wall system consists of a Drum Wall, which is essentially analogous with a typical building's central core wall. From the Drum, Hammer Walls spring outwards to engage the structure at the perimeter of the building and Fin Walls spring inward primarily to support the core area (see Figure 9).

The Hammer Walls connect directly to eight Mega-Columns situated at the perimeter.

At each skybridge, the balance of the Mega-Columns are interconnected to the Hammers by means of the 3 story high steel Belt Trusses (see Figure 10). In addition to increased lateral stiffness, the Belt provides a level of redundancy and added robustness to the structure by creating alternate load paths.

Also at each skybridge are Link Walls, which tie the Drum Wall segments together. This produces a completely interconnected structural system that behaves as a single tower rather than separate quadrants. To transfer the tremendous shear forces, steel plate shear walls, up to 80mm thick encased with up to 1300mm of concrete, are used.

The top of the building is characterized by a series of 8 arches that extend upward to a center spire that supports several special function levels (see Figure 11). To put this portion of the tower in perspective, the arches are taller than the Eiffel Tower.

The spire itself is a cylindrical concrete form that is supported from the 7th skybridge with a series of concrete walls. The arches are to

be constructed with structural steel. Outrigger trusses at the special function levels will provide support to the floor systems as well as stabilize the spire by engaging the arch elements.

The last main element is the floor system, which is a conventional concrete on metal deck supported by composite steel beams. With 10 million square feet of area, the floor designs are meant to reduce complication. Given that there is a tremendous amount of repetition and that its erection can run independently of the concrete operation, the system is easily erected.

### Structural Materials

As important as the simplicity of the floor framing is, its weight is equally as important. Reducing the overall weight of super-tall buildings is always a principal goal, since the weight and costs tend to compound themselves in the vertical elements. In this case, nearly half of the vertical structure's capacity went towards simply supporting its own self-weight. Therefore, a lightweight floor system is key.

Of course high strength concrete is imperative in achieving a building of such unprecedented height. Although there is a ready supply of concrete in Dubai, placing concrete above an 80MPa strength is not believed to have been attempted. For the Nakheel Tower, concrete in excess of 100MPa strength is required with Young's Modulus of nearly 50,000MPa.

Again, beyond simply the strength of the material, constructability is at the forefront of the design approach. The concrete must be workable in a very hot environment, pumpable to great heights, and above all reliable.

To this end the design team worked together with concrete technologists, Ancon Beton of Australia, developing design mixes. This was seen as a crucial element in the structural design of the building and work on the concrete design was undertaken during schematic design. ↗

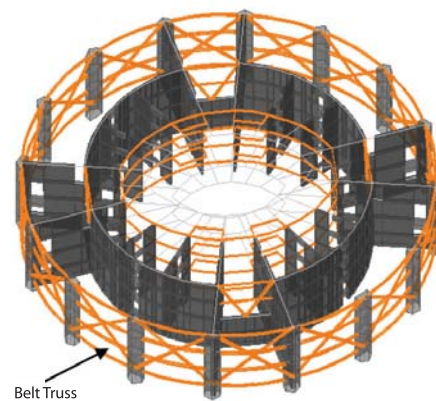


Figure 10. Isometric View of Belt Trusses



Figure 11. Finite Element Model of Spire and Crown

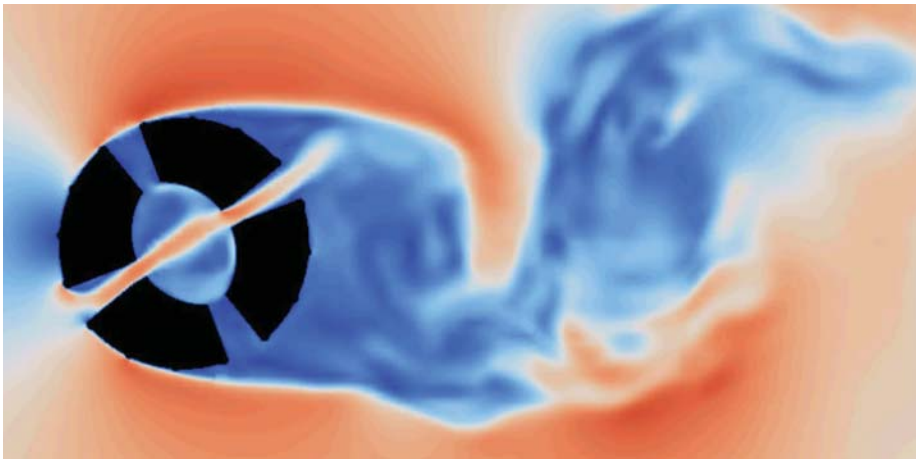


Figure 12. CFD Analysis

### Wind Engineering

Wind was perhaps the single greatest adversary for the engineers on this project. Rowan Davies Williams & Irwin (RWDI) are the wind engineers for the project with peer review work being performed by the Alan G. Davenport Wind Engineering Group of the University of Western Ontario and MEL Consultants. The wind engineering, structural engineering and the architecture of the tower were very closely intertwined in the development of the project. Numerous building forms were studied throughout the tower's development. Ultimately, many of the refinements to the tower's architectural concept were driven by aerodynamics.

With a constant cylindrical form, the tower was susceptible to vortex shedding, which is why the slots are such a crucial design element. The slots serve to mitigate the vortex-shedding phenomenon and reduce the overall wind load on the building by three fold. One lesson learned in the design was that very subtle changes in the slot or internal void geometry can substantially impact the aerodynamic behavior.

Computational fluid dynamics (CFD) were used to study many small variations in geometry (see Figure 12) together with dozens of high frequency force balance (HFFB) tests (see Figure 13). However, the CFD modeling and HFFB tests were only initial indicators as to the building's response

to wind. Aeroelastic model testing, high frequency pressure integration studies, and large-scale tests at high Reynolds Number (Re) were also performed to provide additional pieces to the puzzle (see Figure 14).

The strategy for addressing lateral accelerations of the tower was always to look for an aerodynamic solution first. This required a very good understanding of the wind behavior and extensive testing (as intimated above). The wind engineering is substantially completed at present. The building's performance in terms of lateral accelerations is good and no supplemental damping is necessary. However, provisions for a liquid mass damper has been included in the design to account for possible variations in the building's as-built stiffness and inherent damping.

### Building Services

Norman Disney & Young has been appointed to design Mechanical, Electrical, Hydraulic and Fire Services for the Nakheel Harbour Tower. A significant amount of research and development has been undertaken for this project. The product of this effort has significant implications for the engineering of other tall towers.

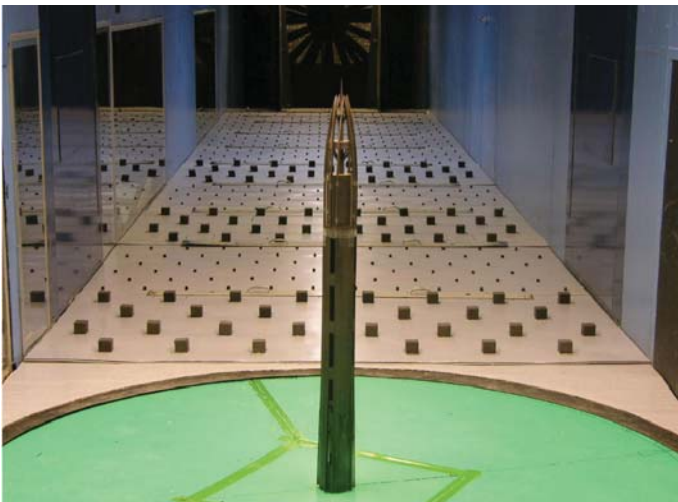


Figure 13. High Frequency Force Balance Test



Figure 14. Large Scale High Re Test

## Stack Effect

Stack effect is one of the main difficulties associated with tall tower design. The problem has traditionally been encountered in cold climates in North America, during winter, where temperature differences approaching 40°C are common. Many of the world's early tall towers were constructed there.

A warm building in a cold climate behaves like a chimney, with warm air rising to the top of the building. This results in the internal pressure at high level becoming well above atmospheric and at low level becoming well below atmospheric. Somewhere near the middle of the building there will be a neutral point, where the internal and external pressures are equal.

In the past decade, the world's new breed of high rise towers has been built in the hotter climates of Asia and the Middle East. Problems occur during hot weather, with the pressure gradient operating in reverse. The result is high pressures at ground level and low pressures at high level. The tallest towers in Asia have been approximately 500m high. Temperature differences tend to be no more than 15°C (say 36°C ambient and 21°C internal). The Nakheel Harbour Tower is over 1,000m high and the temperature difference in summer is 25°C (46°C ambient less 21°C internal). This results in a pressure difference between the top and bottom of an open shaft of 780 Pa. This is expected to result in a positive pressure on the order of 390Pa at the ground and a negative pressure of 390 Pa at the high level. To put this into perspective, most fire codes limit the pressure difference across a fire escape door, due to stair pressurisation, to 50 Pa. This is due to the force needed to open the door.

The pressure created by stack effect causes air infiltration into the building at the high level, resulting in energy loss and loss of capacity of HVAC systems. At the bottom of the tower, the high pressure will cause high loss of conditioned air to the outside.

The pressures will result in high air velocities across doors connecting to the outside. This will cause lift doors to jam and subsequent loss of lift service. It will make doors either

impossible or dangerous to open.

Measures being considered to mitigate the problems created by stack effect include:

- Use of revolving doors at pedestrian entries.
- Providing multiple stages to entries.
- Isolating loading docks from goods lifts.
- Providing an anti-room with sequenced operation of doors and pressure control for goods access.

A similar use of anti-rooms is proposed for maintenance access at the top of the building.

In general, stair shafts serve from skybridge to skybridge only, opening onto safe havens at each skybridge. Likewise, lifts serving limited parts of the tower do not present major problems.

High rise lift shafts will be temperature controlled to align pressure differentials to those existing elsewhere in the building. Shafts will be required to be warmer in summer than the general space temperature, to provide the same pressure gradient.

## Pressure Staging

Tall buildings create the need to pump water in stages up the building, to limit the pressure in any part of the pipework to the pressure rating of the available pipework, valves and equipment.

In the case of chilled water, this issue becomes more complicated. The number of stages is limited by the practicalities of permissible temperature rise in the chilled water to the top of the tower.

Two broad options presented themselves. Option 1 had a pressure stage at each skybridge. This kept the pressure ratings low but resulted in unacceptably high chilled water temperatures at the top of the tower. Air-cooled chillers would be required at high levels in the tower.

Option 2 had a pressure stage at every second skybridge. This limited the stages to 5 (including a stage at the basement chiller level) and eliminated the need for chillers in

## ...retrofit

“They’re showing the rest of the city that existing buildings, no matter how tall they are, no matter how old they are, can take steps to significantly reduce their energy consumption.”

*Mayor Michael R. Bloomberg, New York City, who has made sustainability a theme of his administration, quoted on the environmental retrofit plans for the Empire State Building. From 'Empire State Building Plans Environmental Retrofit' The New York Times, April 6, 2009*

the tower. The concern with this arrangement is the very high pressures in the system.

Option 1 is favoured, with the most significant concern being the potential for a leak in the heat exchangers between stages. This would result in a doubling of pressure in the lower parts of the stages and subsequent failure of all heat exchangers below these stages. Resultant damage would be enormous, and the potential for injury significant.

This is likely to be overcome by the use of an oversized venting system. Whilst this seems likely to prevent a rapid pressure build up, computer modeling is to be undertaken to ensure the design can cope with any transient pressures due to a sudden failure.

## Environmental Initiatives

The project brief requires high standards of environmental performance. Most initiatives, which are widely considered best practice in modern buildings, are being incorporated as a matter of course and are not covered in this paper.

The project has a high component of residential and hotel space and therefore a high need for hot water on a continual basis. The Dubai climate creates the need for cooling, even during the winter months. ↗



Several alternative cogeneration strategies are being considered.

The project requires its own District Cooling Plant. This provides the opportunity to gain the advantages of efficient operation from a large chiller plant. It also enables the design of the load side (air handling plant) to be optimised to increase chiller efficiency and reduce pumping needs.

Water conservation is by means of black water treatment, storm water harvesting, and reuse of fire test water.

Phase change material is being considered for thermal storage in chilled water and hot water systems as well as in building construction, where an increase in thermal mass can contribute to either energy savings or reduction in peak demand.

The use of high voltage power distribution enables reduced transmission losses.

### Logistics

During construction, the time taken to hoist equipment to such heights is considerable. The time taken for labour to go to and from the upper parts of the building is also considerable. This dictates the need to look closely at prefabrication offsite.

Internal lift shafts are to be used for construction lifts, to reduce the reliance on external cranes. Therefore, components that fit in the lift shaft and can be quickly assembled onsite are preferred.

Examples of preassembly include prewired electrical and communication systems with plug-in connections, fan coil units and air

handlers complete with mounting frames, valves, electrical panels and control panels. All will be pretested offsite and will use proprietary-bolted assembly pipework.

Replacement of system components, during the life of the building, includes equipment that can be broken down to components and catered for in a goods lift. Where this is not feasible, the dimensions of the component must be within the dimensions of the lift shaft, which can be temporarily used for hoisting.

Services risers must be planned, to allow replacement and additional services to be run. This requires spatial planning not only for the riser but also for access during installation.

### Facing the Future

In order to develop a tower of this scale and distinction, the design team has had to project its design strategies forward into the future by using the latest design techniques of today and creating flexibility to embrace the trends and technology of the future. Children of the Emirates will see this tower constructed and will be the future occupiers, tenants and guests of the building. The team has been designing this tower for future generations and future vertical communities. Future-proofing the thoughts and innovations behind the design involves

becoming a futurist and not accepting current norms. Research into future trends and means of providing for them has been an important part of the design teams' approach.

In these uncertain financial times, Dubai and the Nakheel Tower have not been immune to the effects of the Global Financial Crisis. Currently, the design team have completed a substantial portion of the project design and documentation, enabling extensive foundation work to be completed at the site. The decision by the developer to temporarily suspend site-work has not impacted the enthusiasm of the team, who are still excited about the day this boundary-pushing tower will rise out of the sand. ■

*Naming all the professionals involved and instrumental in advancing a project of this scale requires more space than available here.*

*However, this article will not be complete without acknowledging the contribution and dedication of the following individuals:*

*Cris Johansen, Peter Read and Neil Woodcock, Nakheel. Alf Seeling, Garry Marshall, Richard Marshall, Nik Karalis, Peter Miglis and Matthew Gaal, Woods Bagot; Kamran Moazami, Bart Sullivan, Samer Wattar, Andy Veall and Patrick Chan WSP cantor Seinuk; Leslie Robertson and SawTeen See, LERA; Anil Hira, VDM; Kevin Winward, Winward Structure; Peter Irwin and Derek Kelly, RWDI; Nick Isyumov and Peter Case, BLWTL; Bill Melbourne, MEL Consultant. Max Ervin & Chris Haberfield, Golder Associates; Ian Ullah, Fugro; Harry Poulos, Coffey Geotechnics. Soletanche-Bachy / Intrafor JV Michel Percak Khalil Ibrahim.*



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