

## NAKHEEL SUPER TALL TOWER BREAKING THE RECORD?

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### INTRODUCTION

The Nakheel Tower is part of the Nakheel Harbour & Tower development in Dubai, United Arab Emirates. The record breaking 1 kilometer plus tall tower follows many other bold initiatives taken in developing real estate in the Emirate. It is intended to be a central focal point of the numerous large scale developments (some constructed, some planned) that the quasi-government owned Nakheel has implemented.



Figure 1. Nakheel Harbour & Tower

The sheer size of the tower, over 10 million square feet, logically leads to a mixed-use development containing residential, office, hotel, and accompanying retail and

amenity spaces. It is to be situated adjacent to the proposed Arabian Canal, and be the center of a 270 hectare development home to 55,000 people, and a workplace for 45,000 more.

The tower's record breaking height and gross area necessitated a unique approach to super-tall building design from standpoint of functionality, structural design and constructability. Influenced by historical Islamic patterns, Woods Bagot, the project architect conceptualized a symmetric cylindrical tower that is accented by 16 points formed by the perimeter columns.

The diameter of the building is nearly 100m in order to limit the height-to-width aspect ratio, (1:10+). As such, the central area of the building footprint becomes impractical in terms of its usability because it is so far from any natural light at the perimeter. This led to the creation of a central void which then created the opportunity to place large slots through the tower. The slots are a means of mitigating the biggest hindrance to building tall, wind.

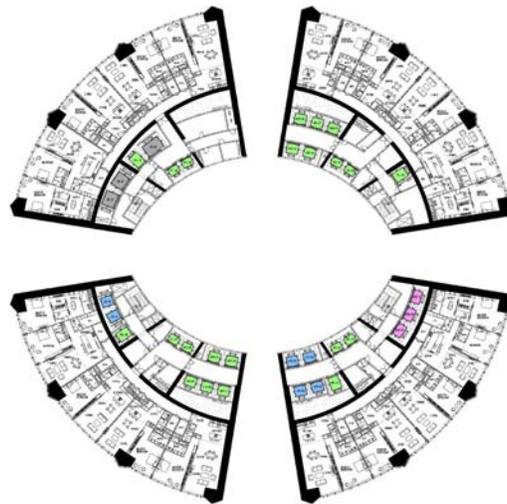


Figure 2. Typical Floor Plan

One of the main tenets of the design brief is to maximize the most valuable real estate, i.e. the usable areas at the top of the building. This led to an almost uniform cylindrical shape for the tower from the ground up. This is contrary to traditional tall buildings that tend to taper as they reach greater heights. While this works to reduce the wind sail of the building, it also reduces the most valuable real estate. However, by creating the means for wind to pass directly through the center of the tower by introducing slots, the building essentially tapers from the inside out.

The slots break the building into halves or four quadrants over approximately 25 floors which are then linked together by 3-story “skybridges”. This effectively results in several 25 story buildings stacked one upon the next – creating a vertical city. Each skybridge serves as a transfer point from shuttle lifts to local lifts, and provides amenity and retail spaces for the 25 floors above. In addition, these levels provide spaces for plant rooms, emergency medical facilities as well as alternate means of egress.

## **STRUCTURAL FORM**

In order to create an efficient structure in super tall buildings, early on we had to established the “First Principles” that would guide us throughout the design process. Whereas with conventional buildings the design is not highly sensitive to these principles and they can easily be overlooked, in super tall buildings, they will have a significant effect.

- Architectural and Structural concepts need to merge and complement each other like body and soul.
- Structural components and systems need to follow a utilitarian rationale for their existence thus reinforcing the entire fabric of the structure and architecture.
- Robust and intrinsic load paths and symmetry are critical virtues.
- All vertical structural elements need to participate in supporting vertical and lateral load effects, no ounce of structure will be left under-utilized.
- Constructability issues need to be addressed and embedded early on into the concept design.
- Understanding the wind aerodynamics, aero-elastic effects and approaches to mitigating those effects are the key to a successful design.

Beyond its constant form from top to bottom, the tower is also characterized by its symmetry. This provides two very important benefits for the structure. First, there are no transfers of vertical elements through the main body of the tower. Second, 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.

Differential axial shortening becomes a greater and greater concern with each additional story in a building. 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 due to elastic, creep and shrinkage effects. However, the structural characteristics that address this issue are one in the same as those that address the core issues of efficiency, economy, and redundancy.

The vertical structure is organized in such a way that the elements are all sized based on strength considerations while at the same time are all engaged to provide sufficient lateral stiffness. Every element of the structure is interconnected as will be described below. This creates an extremely efficient structure where the materials perform dual roles; it provides for multiple alternative load paths for added redundancy and redistribution of loads; and by placing material only where it is required for strength it 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, the building functions as a single entity. The main body of the tower is comprised of 6 basic structural components.

### **PRIMARY STRUCTURAL ELEMENTS**

The first element is the wall system. All of the vertical elements of the building are cast-in-place reinforced concrete. The wall system consists of a drum wall, acting as the main spine of the tower, 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 gravity loads of the core area.

The hammer walls connect to the second primary element, the mega-columns. Sixteen mega-columns are situated at the perimeter of the tower. Like all of the vertical elements of the building, they perform double duty in supporting gravity and lateral loads.

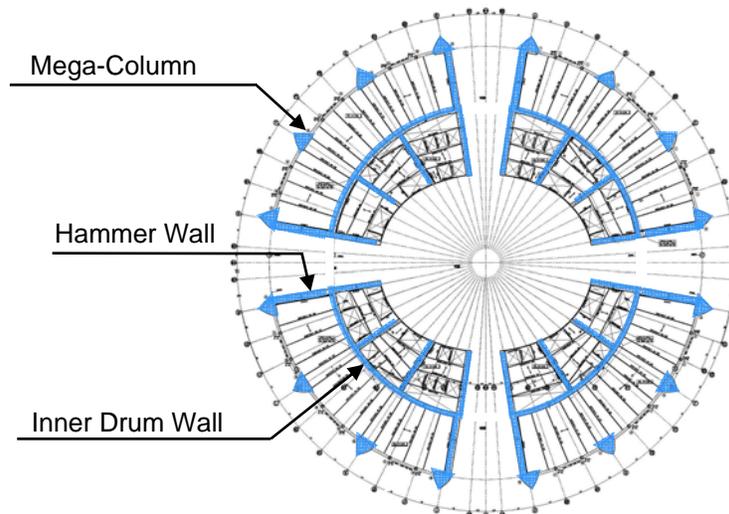


Figure 3. Typical Wall Layout

At each skybridge, the mega-columns are interconnected by a 3 story perimeter belt truss. These 3 story high steel trusses provide a means of engaging the mega-columns to further increase the lateral stiffness of the building.

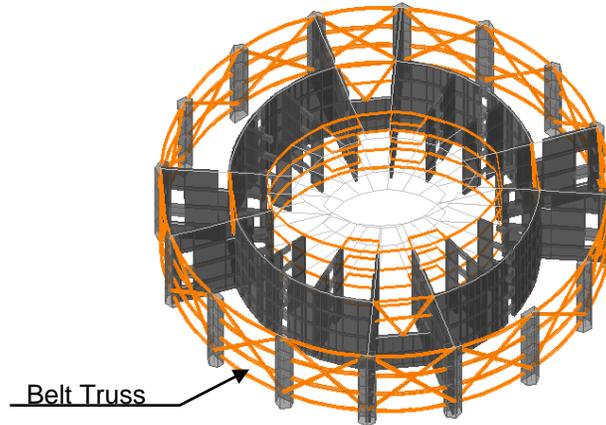


Figure 4. Isometric View of Skybridge Belt Trusses

The composite link walls extend over several floors, occurring at every skybridge. The walls serve to link the drum walls of each quadrant. This produces an interconnected structural system that behaves as a single tower rather than separate quadrants. This consists of steel plate shear walls encased with up to 1300mm of reinforced concrete. Structural bracing is also extended from the link in order to provide added strength while allowing circulation through the skybridge.

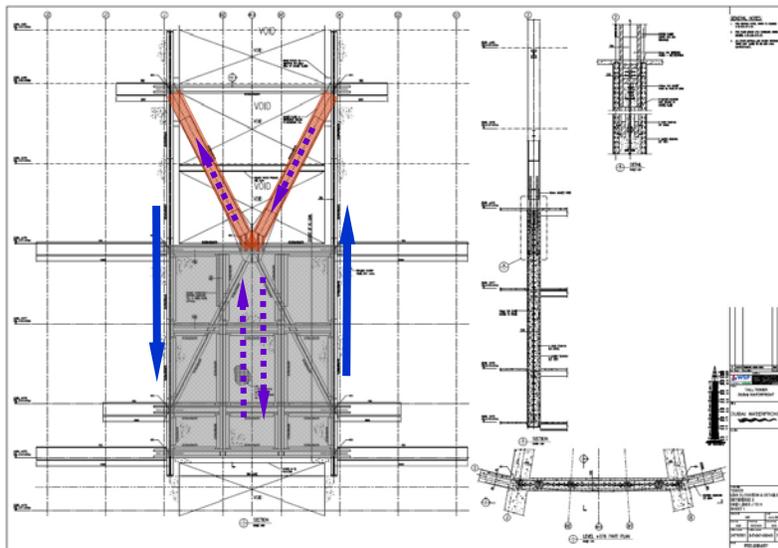


Figure 5. Elevation of Composite Link Wall

Spanning across the internal void at each skybridge are a series of steel trusses, the fifth element. The trusses' primary elements span the void in one direction with a series of secondary trusses in the perpendicular direction to create added redundancy with alternate load paths. Each truss is supported by an embedded connection to the concrete fin walls.

The sixth main element is the floor system which is a conventional steel framed composite concrete on metal deck system. Reducing the overall weight of super-tall buildings is always a principal goal since the weight tends to compound itself in the vertical elements. This system also provides a simple erection process that can run independent of the vertical concrete construction.

Reinforced concrete makes for an efficient construction material for the vertical elements since it offers a high level of stiffness in addition to its compressive strength. Efficiency is the goal in any structural engineering effort, but not necessarily always achieved.

### **SPIRE AND CROWN STRUCTURE:**

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 level. To put this portion of tower in perspective, the arch structure itself is taller than the Eiffel Tower.



Figure 6. Finite Element Analysis Model of Spire and Crown

The spire itself is a cylindrical concrete form that is supported from the 7<sup>th</sup> skybridge with a series of concrete walls. The cantilevered floors and the arches are to be constructed with structural steel. Outrigger trusses at the special function levels

would serve to support the floor systems as well as stabilize the spire by engaging the arch elements. The arch elements themselves being a trussed space frame and architecturally clad.

## **CONSTRUCTABILITY**

Constructability is the paramount issue in creating an efficient structural design for such a project. Reinforced concrete is the basic structural material for many reasons beyond the structural design. First, it can be erected to great heights while limiting the use of cranes. Only specially constructed cranes have the ability to lift at such great heights. Moreover, the time involved with simply lifting pieces to such a height becomes prohibitive when attempting to maintain an expeditious construction schedule.

Thus, a self climbing slip form is planned for the erection of the wall system. Crane time is then limited mainly to lifting prefabricated reinforcing cages. This leaves time for erection of the floor framing steel which can follow at its own pace.

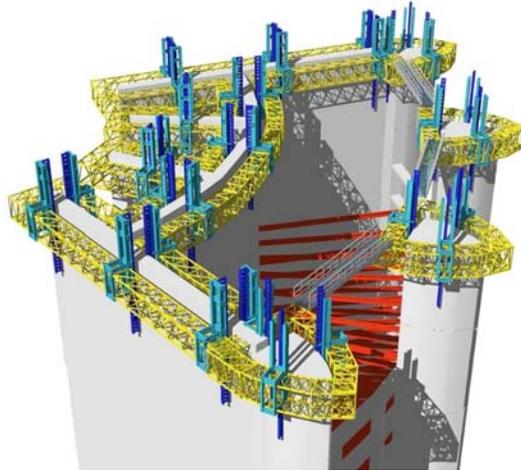


Figure 7. Conceptual Slip-Form System (*courtesy of Taisei Corporation*)

Concrete is also readily available in the local market which has a large contingent of ready-mix suppliers.

## **CONCRETE**

Of course high performance concrete is imperative in achieving a building of such unprecedented height. Though, there is a ready supply of concrete in Dubai, concrete beyond 80MPa is not believed to have been attempted. For the Nakheel Tower, concrete in excess of 100MPa with Young's Modulus of about 50,000MPa is

required. Also, the concrete must be workable in a very hot environment, it must be pumpable to great heights, and it must be reliable.

To this end the design team collaborated 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 before completion of the schematic design.

The process focused on the foundations and the superstructure separately. The foundation consists of closely spaced barrettes capped with a raft element between 4m to 8m thick. For the barrettes, beyond the importance of achieving a very fluid concrete with a long set time that could be placed with confidence, an extremely durable concrete was necessary. The soil in Dubai is particularly aggressive in terms of chloride attack with the ground water possessing more salinity than the nearby Gulf waters.

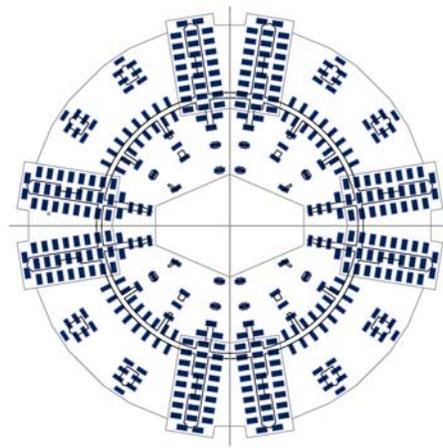


Figure 8. Foundation Barrette Plan

A tri-mix made up of ground granulated blast furnace slag (GGBS) and silica fume was developed. In combination with a maximum water/cement ratio of 0.34 and additional concrete cover for reinforcing to ensure durability.

The dominating concern for the raft construction is heat. Raft requires a minimum high strength concrete simply to support the bearing pressures of the superstructure walls above. With such a deep concrete element, adiabatic conditions result throughout. A variety of design mixes were tested to determine peak hydrating temperatures and final compressive strengths. The final raft design must find a balance between the raft depth and the design strength where the in-situ strength can be confidently relied upon. In all likelihood, the final raft design will likely require an internal cooling system in order to maintain temperatures to a manageable level.

Further testing is also planned to establish the thermal effects as the raft cools. This is vital to determining the location of and the behavior at construction joints.

There are several focal points for the superstructure concrete. First, it must have a strength never before achieved in the country. It must have a high stiffness. The concrete must not be characterized as sticky in order to have the form system work efficiently. It must be flowable so as to be pumped and placed easily, and must not have a tendency to segregate. Finally, it must be able to be sourced and mixed reliably.

The concrete mix design program is still not yet complete, and has been undertaken in several stages. At present the designs for the highest strengths would likely include some amount of fine aggregate sourced from overseas, but otherwise the mix is largely made of local constituents. This is a major concern for the project since it will need to rely on tremendous quantities of raw materials in order to maintain progress in construction.

Thus far, the record height for pumping concrete in a single lift is about 600m. For the construction of the Nakheel Tower, work has commenced on exceeding this height by a considerable margin. Current new technology is considered capable of achieving greater heights and in the years that follow it is likely to improve. Pumping tests are planned in future stages of the concrete design program. Thus far, the mixes have been designed with limited chemical content and show signs of good stability. The concrete is extremely fluid, but not self-compacting.

## **WIND TUNNEL TESTING**

One of the major challenges was not only establishing the Wind climate, and its behavior at different strata, direction and frequency of occurrence but understanding building aerodynamic and aero-elastic response and making adjustment to the building geometry to mitigate the wind effects. In other words the wind phenomenon was perhaps the single greatest challenge in the design of this project. The structural engineering, architecture and wind tunnel testing of the tower were very closely intertwined in the development of the project.

Numerous alternates for the building shape were studied throughout the tower's development to address programming, functionality and response to wind effects. Ultimately, many of the refinements to the tower's architectural concept were driven by aerodynamics.

Where it was more appropriate computational fluid dynamics (CFD) were also used to study many variations in geometry together with dozens of high frequency force balance (HFFB) tests. The slots through the building were employed to mitigate the vortex shedding phenomenon which is typical of slender round structures. The slots serve to 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.

Aeroelastic model testing and high frequency pressure integration studies were also performed to provide additional pieces to the puzzle.

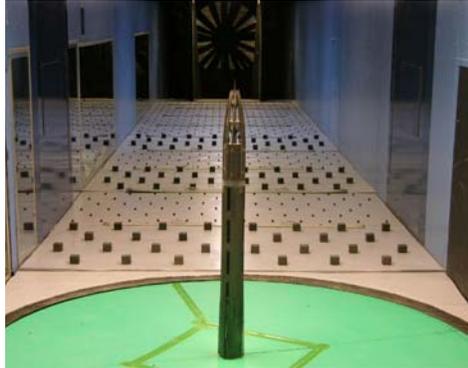


Figure 9. HFFB Test

The wind engineering is substantially completed at present. The strategy for addressing lateral accelerations of the tower was always to look for an aerodynamic solution first. The building's performance in terms of lateral accelerations is good and no supplemental damping is necessary. However, provision for a liquid mass damper has been included in the design to account for possible variations in the building's as-built mechanical properties.

## **CONCLUDING REMARK**

The design has progressed into Design Development and resolved most of the project's challenging design issues. Currently, more than half of the foundation barrettes have been placed successfully however, the project is on hold due to the current market downturn and at the moment the future construction schedule is unknown.

## **CREDIT**

This project was the result of intense collaborative effort between various design and construction team members under the guidance of the ownership.

Developer: Nakheel PJSC

Architect: Woods Bagot

Structural Engineer:	WSP Consortium: WSP Cantor Seinuk Leslie E. Robertson Associates VDM
Geotechnical Engineer:	Golder Associates
Soil Investigation Engineers:	Fugro Middle East
MEP Engineer:	Norman Disney & Young
Elevator Consultant:	Barker Mohandas
Wind Tunnel Laboratory:	RWDI
Construction Advisor:	Taisei Corporation
Fire/Life Safety Consultant:	Schirmer Engineering
Security Consultant:	Olive Group
Foundation Contractor:	Soletanche-Bachy / Intrafor JV
Wind Tunnel Peer Review: MEL Consultants	BLWTL-UWO
Structural Peer Review:	Winward Structures
Geotechnical Peer Review:	Coffey Geosciences