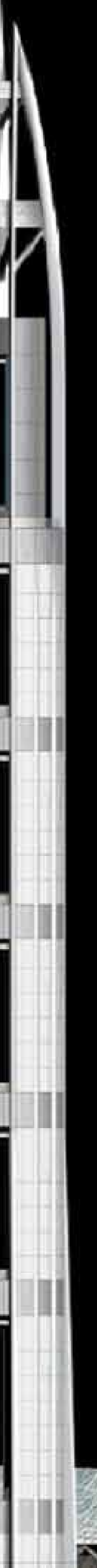
Nakheel Super Tall Tower

By Ahmad Rahimian, Ph.D., S.E., P.E., Kamran Moazami, P.E., M. ASCE and Bart Sullivan, P.E.



The Nakheel Tower is part of the Nakheel Harbour & Tower Development in Dubai, United Arab Emirates. The record breaking design of the Tall Tower, with a height of more than 3,300 feet (1 kilometer), 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.

The shear size of the tower, over 10 million square feet (1 million square meters), will be a mixed-use development containing residential, office, hotel, and accompanying retail and amenity spaces. It will be situated adjacent to the proposed Arabian Canal, and will be the center of a 667 acre (270 hectare) development, home to 55,000 people and to 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 the standpoint of functionality, structural design and constructability. Influenced by historical Islamic patterns, the project architect, Woods Bagot, Dubai, UAE, conceptualized a symmetric cylindrical tower that is accented by 16 points formed by perimeter columns.

The diameter of the building was set at nearly 330 feet (100 meters) in order to limit the height-to-width aspect ratio to approximately 1:10. Without any mitigating strategy, this would have created a very large floor plan with central areas far from natural light. This led to the creation of a central void which then created the opportunity to place large vertical slots through the tower. These slots are an essential means of improving the building's aerodynamics.

One of the main tenets of tall building design 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 tapering is effective to reduce the wind sail of the building, it also reduces the most valuable real estate. However, by allowing wind to pass directly through the center of the tower, an effective reduction in wind forces would be provided.

Nakheel Harbour and Tower. Courtesy of Woods Bagot Architects.

The slots typically divide the building into four quadrants over approximately 25 floors, which are then linked together by three-story "skybridges". This effectively results in several stacked 25 story buildings – 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, "First Principles", as described below, have to be established early on that provide guidance throughout the design process. With conventional buildings the design is not highly sensitive to many of these principles; overlooking them in super tall buildings would 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 presence, 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 both vertical and lateral load effects, leaving no ounce of structure under-utilized.
- Constructability issues need to be addressed and embedded within the early stages of the design concept.
- Understanding the wind aerodynamics, aero-elastic effects and approaches to mitigating those effects are the key to a successful design.

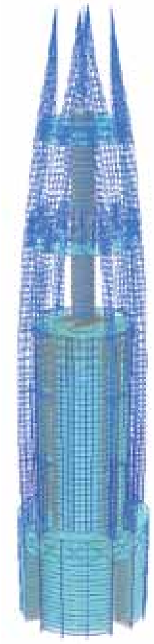
Beyond its constant form from top to bottom, the tower is also characterized by its symmetry. This provides two very important benefits for the structure. First, there are no transfers of vertical elements in the main body of the tower. Second, it allows for a uniform distribution of gravity forces throughout 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 16 inches (400 millimeters) at its observation level due to elastic, creep and shrinkage effects.

Every element of the structure is interconnected. This creates an extremely efficient structure where the materials perform dual roles; they provide for multiple alternative load paths for added redundancy and redistribution of loads and, by placing materials only where they are required for strength, they create a uniform distribution of loads so as not to have differential shortening.

Structural System

The floor system 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. The vertical load carrying system is primarily reinforced concrete, comprised of mega columns at the perimeter, interconnected to a series of internal walls.



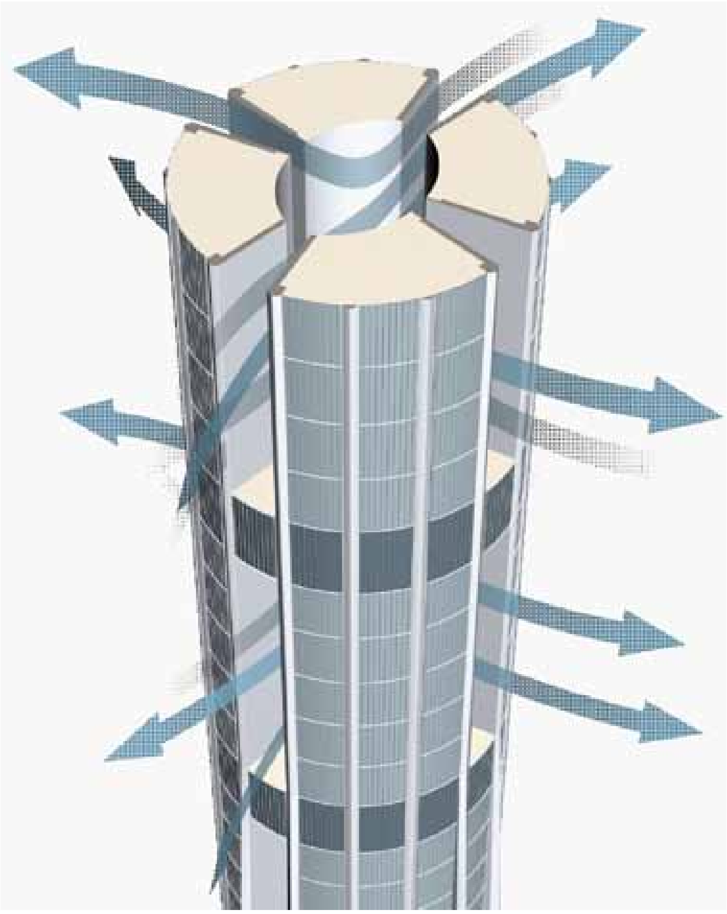
Finite Element Analysis Model of Spire and Crown.

The wall system consists of a drum wall acting as the main spine of the tower, which is essentially analogous to a typical building's central core wall. The drum walls are connected to a series of fin walls, both inward and outward of the drum walls, to provide gravity support.

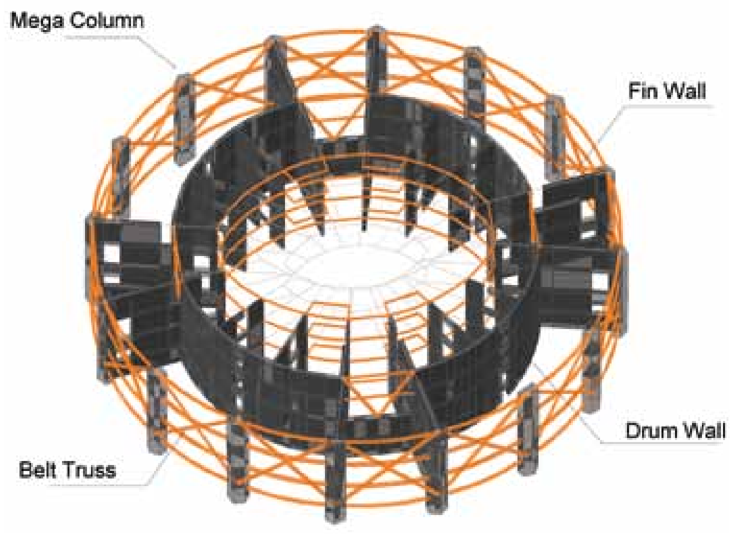
The fin walls provide connections to the eight corner mega-columns at the perimeter. The mega-columns are interconnected by a three-story perimeter belt truss at each skybridge. These three-story high steel trusses provide a means of engaging the mega-columns to further increase the lateral stiffness of the building.

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. These walls consist of steel plate shear walls encased with up to 50 inches (1300 millimeters) of reinforced concrete. Structural bracing is also extended from the link in order to provide added strength while allowing circulation through the skybridge.

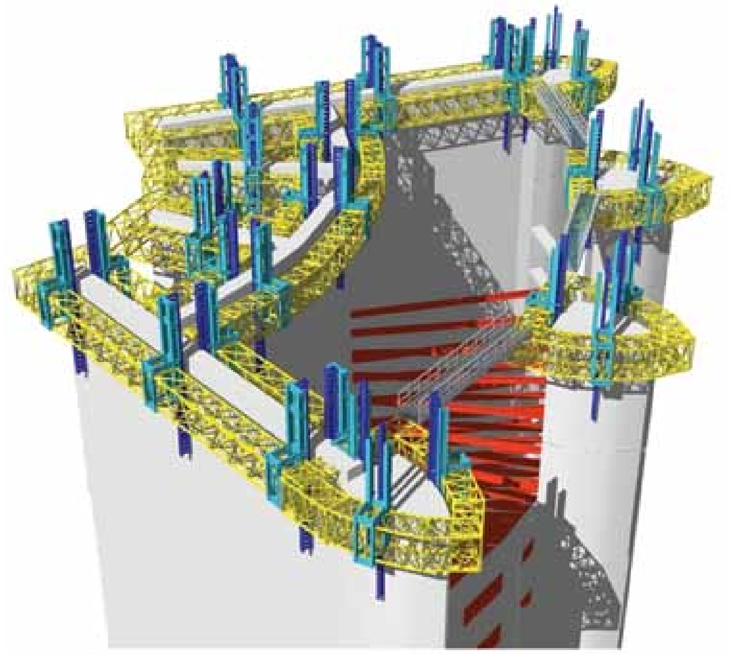
continued on the next page



Wind Flow through the Slots. Courtesy of Woods Bagot Architects.



Isometric View of Skybridge Belt Trusses.



Conceptual Slip-Form System. Courtesy of Taisei Corporation.

Spanning across the internal void at each sky bridge is a series of steel trusses. The primary floor trusses span the void in one direction, with a series of secondary trusses in the perpendicular direction to create added redundancy with alternate load paths.

Spire and Crown Structure

The top of the building is characterized by a series of eight arches that extend upward to a center spire that supports several special function floors. The arch structure itself is taller than the Eiffel Tower.

The spire itself is a cylindrical concrete form that is supported from the upper skybridge by a series of concrete walls. The special function 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 are designed as trussed space frames to be architecturally clad.

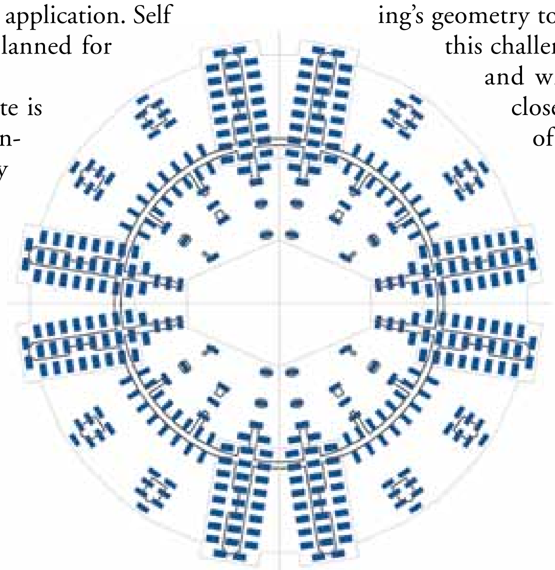
Constructability

Constructability was the paramount issue in creating an efficient structural design for such a project. Reinforced concrete was chosen as the basic structural material because of its structural design and constructability efficiency in this tall building application. Self climbing slip form construction has been planned for the erection of the wall system.

The utilization of high performance concrete is imperative in achieving a building of such unprecedented height. Although there is a ready supply of concrete in Dubai, concrete beyond 11,500 psi (80 MPa) is believed to not have been attempted. For the Nakheel Tower, concrete in excess of 14,500 psi (100 MPa) has been specified.

To this end, the design team collaborated with concrete technologists Ancon Beton, Australia, to develop special design mixes. This was seen as a crucial element in the structural design of the building, and work on the concrete mix design was undertaken before completion of the schematic design.

The geotechnical investigation and foundation design were advanced in parallel tracks to the superstructure design. Fugor Consultants provided the geotechnical investigation services and Golder Associates provided the geotechnical consulting services. The tower foundation is a combination of raft and deep foundations using closely spaced barrettes, capped with a reinforced concrete raft system whose thickness ranges between 13 feet (4 meters) and 26 feet (8 meters). Barrettes are deep foundations similar to drilled cast-in-place piles that are constructed in a rectangular shape. Normally Grab-Bucket or Hydrofraise drilling tools are use. Soletanche-Bachy, the foundation contractor, has already installed almost one half of the deep foundations for the tower.



Foundation Barrette Plan.

Wind Tunnel Testing

The wind phenomenon is perhaps the single greatest challenge in the design of super tall buildings. Establishing the wind climate, understanding wind's behavior at different strata, direction and frequency of occurrence, understanding the building's aerodynamic and aeroelastic response, and making subsequent adjustments to the building's geometry to mitigate wind effects was key to addressing this challenge. The structural engineering, architecture and wind tunnel testing of the tower were very closely intertwined throughout the development of the project.

Numerous alternates for the building's 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) was also used to study 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 that is typical of slender round structures. These 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.

HFFB Test at RWDI.

Summary

The design has progressed into Design Development with most of the project's challenging design issues resolved. 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.▪

Ahmad Rahimian, Ph.D., P.E., S.E is the President of WSP Cantor Seinuk, based in New York and part of WSP Group PLC. Dr. Rahimian was the recipient of 2007 AISC Special Achievement Award, 2005 ASCE-CERF Charles Pankow Award for innovation and the ENR Excellence Award as one of the Top 25 Newsmakers of 2003.

Kamran Moazami, P.E., M. ASCE, is Senior Vice President and Director of WSP Cantor Seinuk in London, UK.

Bart Sullivan, P.E. is a Vice President and Director of the Middle East with WSP Cantor Seinuk.

This article is a modified version of a keynote speech given at the fib Symposium in London in June 2009, which was published in the fib Symposium Proceedings. It is reprinted with permission.

Credit

This project was the result of intense collaborative efforts between various international design and construction team members under the guidance of the ownership, in particular with the project architect, Woods Bagot. WSP Group has been appointed as structural consultant; managed by its specialty high-rise group, WSP Cantor Seinuk, as the lead structural engineer in collaboration with Leslie E. Robertson Associates, New York, and VDM Group, Australia. Winward Structures, Melbourne, Australia, was assigned as the structural peer reviewer. RWDI, Ontario, Canada was assigned as the wind engineer in collaboration with Boundary Layer Wind Tunnel Laboratory at University of Western Ontario, Canada and Mel Consultants, Melbourne, Australia as wind tunnel peer reviewers.