650-Plus Meters Skyward, Crews Are Already Out of this World. (cover story)

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Abstract: The article reports on the status of the construction of the $1.1 billion Burj Dubai skyscraper as of May 2008. The lead structural designer for the project is Skidmore, Owings & Merrill (SOM). William F. Baker, the structural partner of SOM for the job, does not underplay the amount of effort poured into the design of the vertical cantilver to keep it as simple and repetitive as possible.

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Tall Buildings

August topping-out expected for record-tall supertower in Dubai

Skidmore, Owings & Merrill's lead structural designer for the $1.1-billion Burj Dubai--already a 668-meter concrete- and-steel giant--is blasé about the complexity of construction, even at the upper reaches of the desert "cloudbuster." But for most others on the unprecedented vertical expedition, the trek to the top--a rumored 800-plus meters--is as exciting as a trip to outer space.

William F. Baker, SOM's structural partner for the job, does not underplay the amount of effort poured into the design of the 479,830-sq-m vertical cantilever to keep it as simple and repetitive as possible. "You wouldn't believe the amount of time it took [just] to get the core right," he says.

But Baker is somewhat understated about the sophisticated design's realization: "Construction is uneventful because the structure is not complicated."

That is easy for Baker to say. He did not have to work out the nitty gritty of "extruding" the record-breaker on its way to superseding the 509-m-tall Taipei 101 by a whopping 300 m (if rumors of the final height are true). The difference is equivalent to a 70-story-plus tower--no mean feat in itself.

The engineer does not have to organize and lead the vertical wagon train of up to 8,000 workers--moving them up and down and providing for their daily needs for five years.

It was not on Baker's shoulders to pump concrete 600 m up, keeping it fluid for the 30 minute ride to the top. (That is 152 m higher than the record set at Taipei 101, the tallest occupied high-rise.)

Baker did not have to maintain a vertical frame to extremely tight tolerances, nor did he have to jump the three tower cranes at extreme heights. He also does not have to operate the luffing-boom cranes, with cable as long as 805 m, or lift steel as high up as 740 m.

And the engineer did not have to cope with environmental plagues. In Dubai, summer temperatures can hit 130° F. In winter, high winds reduce crane and hoist efficiency to 50% because of safety shutdowns for days at a time.

On the 162-story Burj Dubai, the nuts and bolts of construction were largely left to Samsung Corp., the Seoul-based leader of the pack that is building the tower, and its army of subcontractors (ENR 11/6/06 p. 28). The general contractor, which includes Belhasa Six Construct LLC, Brussels, and the local Arabtec Construction LLC, tells tales of traveling to unchartered territory to put the United Arab Emirates boomtown on the supertall-building map.

"As the building got taller and the tapered structure became more slender, working at extreme heights was very challenging," says Ahmad Abdelrazaq, Samsung's executive vice president for high-rise and structural engineering.

Taking concrete to such heights is only possible thanks to advances in materials technologies, structural-engineering theories, wind-and-seismic engineering, construction methods and computers, says Abdelrazaq. Still, "there are not many analysis programs available to do the construction sequence that includes the effects of creep and shrinkage [over] time at those heights, especially for concrete," he says.

To help keep the 585-m-tall structural-concrete portion vertical, Abdelrazaq prepared a "very detailed" construction sequence analysis and ran it monthly. He says most contractors do not do that.

Samsung also implemented the most extensive structural-behavior monitoring program in the history of building construction. The research, which measures load distribution throughout the frame as it is built, allows Samsung to correlate design with reality. "It gave us more confidence," says Abdelrazaq. "To see actual data demonstrate what you dreamed about is very special," he adds. The data will likely be shared with others, he says.

In the end, Samsung and its team produced a concrete superstructure very close to design assumptions, investigated in creep and shrinkage tests carried out three years ago, says Kyung-Jun Kim, Samsung's project director.

Abdelrazaq attributes the positive outcome in part to the sequencing analyses. "It was more sophisticated than what was done during design," he says.

He should know. From 1987 through 2004, Abdelrazaq, a structural engineer, was working at SOM's Chicago office. His spent his last year designing the tower he now is helping to build (see p. 31).

Abdelrazaq's former colleagues at SOM, which is providing architectural, interior, structural and mechanical-electrical-plumbing design, agree the job is height- and climate-challenged. "If it were easy, everyone would do it," says Roger E. Frechette, SOM's MEP partner for the tower. "You can't approach the project in a conventional way," he adds.

Dubai's windy, sandy, corrosive, hot and humid climate complicated materials selection "down to the smallest intake air louver," says Frechette.

On the tower, all louvers are aluminum or stainless steel. If they were steel, they would rust in a year, he says. Special traps and filters are required to keep superfine sand out of building systems.

Architect Peter A. Weismantle, an SOM associate director, says some of the job's demands resulted from changes in program and height--the original concept was for a 550-m tower. Many changes happened after the late 2003 start of construction. For example, in the fall of 2004, the developer switched the program: The uppermost occupied floors would be offices, not residences.

The skyscraper consists of a 585-m-tall, structural-concrete superstructure topped by a 200-m-plus structural steel spire, concentrically braced and 400 sq m at its base. The spire will be topped by a steel-pipe pinnacle, which tapers in diameter from 2.1 m to 1.5 m. Baker likes to joke that the burj--Arabic for "tower"--is "the world's tallest steel building on a very strong concrete base."

The largely residential but mixed-use burj is the centerpiece of the $20-billion Burj Dubai Downtown. The development is owned by the local Emaar Properties PJSC (see p. 28).

Emaar is keeping people guessing about the burj's final height, only admitting to more than 700 m. "We don't know when we will announce the height," said Mohamed Ali Alabbar, Emaar's chairman, at a conference of the Council on Tall Buildings and Urban Habitat held in Dubai on March 3-5. "Should we?" he asked rhetorically, implying he may keep the global guessing game going forever.

Also at the meeting, Alabbar announced an opening delay of about four months. The push to next spring from this year's end is in part caused by a decision made last summer to upgrade residence finishes and by "project" delays, says Emaar, declining to be more specific.

Emaar may be silent on the tower's final height, but it is almost a broken record about the project's record-breakers. The tower is currently the world's tallest structure, having last month surpassed the 628.8-m KVLY-TV mast in Blanchard, N.D. The burj also grabbed the title for the tallest freestanding structure from Toronto's 553.3-m CN Tower.

The burj's 310,000 cu m of reinforced concrete is equivalent to a solid cube of the material 61 m on a side, a sidewalk 1,900 kilometers long, or the weight of 100,000 elephants, says Emaar. Reinforcing steel weighs 55,000 tons. Emaar says the rebar, if laid end to end, would extend a quarter of the way around the globe.

The silvery metal-and-glass curtain wall covers 140,000 sq m, equivalent to 25 (American) football fields. Emaar says it will take three to four months to clean all the windows.

The burj's MEP numbers are also chilling. In the hottest days, the tower will require some 10,000 tons of cooling per hour, which is equivalent to the capacity of 10.2 million kilograms of ice melting in one day. The water system will supply on average about 946,000 liters of water daily. The tower's peak electrical demand is equivalent to about 360,000 100-W lightbulbs, all aglow.

The tower will have the highest almost everything, including lifts (see p. 32). The 123rd-level observatory's elevator will have the world's fastest double-deck cabs. They will travel at 10 m per second, up and down.

Project organization was a challenge, as well. SOM alone had 90 people on the project at the peak of design, representing a third of its Chicago office. It is managing 50 consultants (see sidebar, left). "It takes a village to do a tower like this," says Adrian Smith. Smith, currently with Adrian Smith + Gordon Gill Architecture, Chicago, was SOM's burj design partner.

SOM is not licensed in Dubai. It helped Emaar select local consultants, which adopted and stamped

SOM's documents for permitting. Hyder Consulting Middle East Ltd. is the designer of record. Hyder also designed foundations and is supervising construction.

Turner International, New York City, is Emaar's project manager. The firm was involved during design to advise on constructibility.

About the only one with the same sangfroid as Baker is Emaar's project director, Greg Sang. The "nuts and bolts of construction are not that different from a 30-story building," he says. For the high-level concrete work, the critical part is "maintaining pumps," he says, adding that "it went pretty smoothly."

Through level 156, the burj is a high-performance concrete tower with a Y-shaped plan. A hexagonal, shear-wall core is at the nexus of the Y's wings. A typical perimeter column is a long, wall-like rectangular column that matches the thickness of adjacent walls, typically 60 cm thick. At wing tips, there are round columns. Outrigger shear walls for stability are in three-floor mechanical levels, every 30 stories or so.

Instead of SOM's rebar-congested outrigger walls, Samsung suggested more constructible, composite-concrete shear walls with embedded steel members. SOM approved the change.

At the base, there is 41.1 m from the core's center to each nose, which is four bays long. Every seven floors, an outer bay "peels away," creating a taper and 27 different floor plate sizes. Slabs are generally two-way, reinforced-concrete flat plates. Core slabs have beams. The tower is founded on a high-performance, reinforced-concrete raft on piles.

With the concrete tower's morphing shape, "it is a challenge as you build [higher] to know which way [the concrete structure] is going to sway and how you bring it back to the center," says Abdelrazaq. "Verticality was very critical" to maintain a straight path for elevators, he says. For the first 100 stories, Samsung kept tolerances within 25 millimeters.

To keep core and wall alignments, workers had to "recenter" the climbing formwork, supplied by Austria's Doka Schalungstechnik GmbH. If movement was within 10 mm, the adjustment would be made immediately on the floor above; otherwise, it would be done over a series of floors. Workers adjusted formwork several times, says Samsung.

For monitoring, workers installed strain gauges on columns every 24 floors. Gauges measure load distribution and flow of forces. Data from critical areas, such as outriggers, was of special interest to Samsung. Vertical and horizontal movement was also monitored using traditional optical techniques and global positioning-system survey technologies.

SOM says there were issues in the beginning related to camber in the slab, which is 200 to 250 mm thick. "They got resolved," says SOM's Baker. "On tall buildings, you always learn on the floor working the hardest," he says.

The tower has settled 40 mm, much less than the predicted 60 to 75 mm, says Baker. Mute on specifics, he says tower accelerations are within design criteria.

For construction, the contractor used three high-pressure concrete pumps at ground level. A secondary pump was installed at level 124, in case of an emergency. It was not used, says Samsung.

Spire work started after concrete construction was completed last November. Samsung pumped concrete for the spire's composite decks to level 158, two levels above the top of structural concrete at 585 m. "We went to 600 m to make it a record," says Samsung's Abdelrazaq.

Above that, the floor plates got too small for efficient pumping. "We did it the old way, using a hopper, because the pipe starting getting in our way," he says.

For the concrete tower, crews first cast the core. Wing walls and their slabs followed several floors behind. "Nose" columns at the wing tips came next, with slabs. Three high-capacity, self-climbing tower cranes with luffing booms, located within the core, were used to lift rebar cages and other components.

Above level 43, workers achieved a three-day-per-floor construction cycle. However, the outrigger levels and floors above and below them took seven days because of their complex construction, says Samsung. This slowed the noses.

To get outrigger levels off the critical path, Samsung devised a so-called up-up sequence for the noses. The resequencing allowed nose casting to proceed concurrently at different levels. This required introducing structural-steel formwork for platforms for concrete formwork.

Crews from Kuala Lumpur-based structural-steel contractor Eversendai Corp. continue to erect, piece by piece using the cranes, about 0.5-million tonnes of structural steel in the spire. The geometry was initially set by locating columns on top of the concrete tower's core walls, says SOM. From these columns, the remaining steel-braced frame and spire-structure work points are resolved into a series of intersecting equilateral triangles that rotate and decrease in size with the progression in height, ultimately culminating in the pinnacle. The geometry was the result of a rigorous exercise to ensure all spire work points were symmetrically aligned within the building envelope, says the engineer.

There are three primary pinnacle support columns and three secondary pinnacle columns, says SOM. Their work lines form two equilateral triangles, with the pinnacle located in the center of each. As such, the primary pinnacle columns are located to the side of the pinnacle and directly support the pinnacle. The secondary pinnacle support columns are offset farther away from the pinnacle itself and support the primary pinnacle support columns.

Early in its erection, the frame drifted 150 mm from the geometric center. "It became very difficult to bring the steel structure back," says Abdelrazaq.

But the cagelike spire did not have to align with the tower's geometric center because it has its own, short-run maintenance elevator. Instead of recentering, crews are erecting the steel straight up after initially centering it to level 156. The straight-up approach represents a change in methodology, says Samsung.

The pinnacle will be jacked into place, up through the spire, off the 156th floor. In preparation, workers are installing a support beam at level 156. This will be followed by the lifting block and assemblies. Next, crews will install lifting equipment and assemblies. Crews will jack the pinnacle in a three-step process, says Samsung. After each lift, cladding is installed. Connections are also completed. After the lifting is done, workers will fill holes left in the center of the spire's floors. Completion is expected in August.

The burj is designed to meet the local energy code. One of the novel MEP systems that crews from the local ETA-Voltas-Hitachi Plant joint venture are installing will reduce the tower's use of desalinated city water. The system captures condensate off the cooling coils, created from taking in humid fresh air, and recycles it as gray water. "Most buildings in the U.S. and the world dump that water into drainage systems," says SOM's Frechette.

The system of holding tanks, pumps and pipes will capture 946,000 liters of water daily, or 60 days of water use annually. "This could fill 20 Olympic-size swimming pools," says Frechette.

Building water cannot be pumped in a straight shot because of static pressure on pipes and fittings. Instead, it is pumped to tanks and heat exchangers on mechanical floors. The devices separate the pumping circuits and "break" the pressure, allowing water to be pumped to the next-higher mechanical level. To minimize the number of breaks, SOM specified above-standard, high-pressure pipe fittings. Standard fittings would have required another mechanical floor, says Frechette.

Height has also had an impact on power. There would be too great a voltage drop if low-voltage power were vertically distributed, as was the code during design. Instead, allaying official concerns about safety and security, the design team convinced the power authority to allow medium-voltage power up the building to transformers in mechanical levels. There, it is turned into low-voltage power for distribution.

The structure is complete at the tower's base. Cladding is at level 141. Workers will begin using tower building elevators this month. The multifaceted fit-up remains. "The toughest part is coming," says George J. Efstathiou, SOM's managing partner for the project. "There are so many contractors involved, and not all are the best quality," he says.

Developer Rises From the Desert Dust To Alter the Landscape

Emaar Properties PJSC seemed to rise out of nowhere, much like the Burj Dubai--the superskyscraper it is building in the desert city on the Persian Gulf peninsula it calls home (see p. 26). The developer is only 11 years young, yet it reports an international project portfolio of more than $65 billon, which it says does not include the company's largest-ever international project in Libya, near Tripoli.

The company has six business segments and more than 60 active companies operating in 36 markets in the Middle East, North Africa, Pan-Asia, Europe and North America. Of its 600 employees, 100 are outside Dubai.

Emaar International was started in 2004. Recently, Emaar signed a memo of understanding with the Shanghai China-News Development Ltd., a government entity, to development projects and infrastructure in China. In the U.S., Emaar acquired John Laing Homes, which is the second-largest private homebuilder in the U.S. Two years ago, Emaar and the Dallas-based Turner Corp., the parent of Turner International and the Burj Dubai's project manager, formed Turner International Middle East Ltd., to pursue projects in the Persian Gulf. Emaar will say only that it has "substantial" equity in the company. Emaar's chairman, Mohamed Ali Alabbar, also chairs the joint venture.

The list goes on. Emaar and Giorgio Armani S.p.A. are planning to build and manage 10 hotels and resorts around the world, including the one in the Burj Dubai.

Emaar is a public company. The Dubai government owns 32%. It also holds equity in Dubai Bank and three other lenders in the United Arab Emirates.

Emaar announced record revenue of $4.78 billion and net profits of $1.79 billion in 2007. The numbers represent a 25% increase in annual revenue and a 3% increase in net profits, says Emaar.

Modesty is not one of the characteristics of Emaar's corporate culture. It describes itself as "en route to becoming one of the most valuable companies in the world by 2010." It continues: "Emaar has highlighted the remarkable growth of the company by debuting on the 2007 Financial Times Global 500 ranking."

In Dubai, the developer completed 15,713 homes in seven years. "Our innovative offering of self-contained, amenities-rich communities created lifestyle options that were the first choice for many Dubai residents," it brags.

At the Burj Dubai, where residences sold out in a matter of days, excess isn't enough. The tower will contain some 600 luxury condominiums, including two spas and meeting facilities, 200 hotel rooms, 350 hotel-serviced condominiums, 50,000 sq m of luxury office space, a grand spa and health club, seven restaurants, the world's highest public observatory and 3,000 parking spaces. If residents get bored, they can "run" across the street to the 4-million-sq-ft mall, also touted as the world's largest, which is part of Emaar's $20-billion Burj Dubai Downtown. Condo owners can even start shopping before they move in. Unlike the tower, which opens next spring, the mall is scheduled to open in August.

Sealing a Big Deal With a Handshake

The place was a bar called Vu in Dubai. The date was April 3, 2003. There, George J. Efstathiou, a managing partner in the Chicago office of Skidmore, Owings & Merrill, and Mark Amirault and Robert

Booth, executives of Emaar Properties PJSC, Dubai, shook hands to seal the deal for SOM to design a 550-meter-tall skyscraper that would be the icon of a $20-billion development in Dubai (see p. 26). Nothing was put on paper. "We cemented the deal and a three-way friendship," says Efstathiou.

The deal had been a whirlwind. Only a couple of months before, Emaar had asked SOM to participate in a two-week design competition. The main concept has not changed much since, but the height has. "Before we knew it, we were being asked if we could make the building taller," says Efstathiou.

Emaar asked SOM the question more than once. Ultimately, SOM found itself designing the world's tallest building by a long shot. But no one at SOM will reveal the final height of the tower, rumored to be more than 800 meters.

At the time of the handshake, SOM had been asked to provide only architecture. Soon, the architect-engineer convinced Emaar to add not only structural and mechanical-electrical-plumbing design but construction documents, public interiors and coordination of the 500-piece art program.

Last summer, after Emaar decided to upgrade the interior finishes of the residences, SOM took on that job as well.

At the job's peak, SOM had 90 people working on the tower. It is also managing 50 specialty consultants. "We're used to dealing with complex teams," says Efstathiou. "This one was just bigger than usual."

Engineer Got To Wear Two Hats for World's Tallest Structure

Some may have considered Ahmad Abdelrazaq's late 2004 move from architect-engineer Skidmore, Owings & Merrill to contractor Samsung Corp. a missed opportunity. SOM had just issued the foundation package for the supertall Burj Dubai--and Abdelrazaq had been working on the design for a year. Why give up the chance to help engineer what was touted as being the world's tallest building?

Perhaps because Samsung finally made Abdelrazaq an offer he could not refuse; to lead the Seoul-based contractor's high-rise building and structural engineering group. "I had helped them expedite construction, through design, on a 93-story Seoul project, which went up very fast," he says.

Abdelrazaq moved to Seoul not knowing he would end up working on the Burj Dubai from the other side of the fence. "I joined Samsung, and then we started bidding the burj," says the engineer.

Samsung, which also built one of the 452-m-tall Petronas Towers in Kuala Lumpur, won the Dubai job on technical merit, say sources. It is not a surprise, considering the input of a 17-year veteran of SOM's Chicago office. "The client knew me, the designer knew me, and Samsung knew me," he says.

During construction, Abdelrazaq functions as a liaison of sorts, bridging the two firms. It has turned out well. "I got the chance to wear both hats," he says. "It was very good for the project, to make sure it was delivered to the highest technical quality."

With Abdelrazaq's input, Samsung made several suggestions to expedite construction on the burj, including switching the outriggers from reinforced-concrete walls to concrete walls with embedded steel (see p. 26). And Abdelrazaq convinced Samsung to install a building monitoring system that he says is more comprehensive than any in the world.

Having his former colleague at Samsung increased the level of trust between SOM and the general contractor, says William F. Baker, SOM's structural partner. "It was helpful because Ahmad knows both corporate cultures," he adds, calling Samsung a "pretty straight-up group."

At Samsung, Abdelrazaq's team of 20 develops construction methodology for Samsung's tall-building projects. He currently spends one week each month in Dubai and supports the burj project daily from Seoul.

Elevator Man Takes On Only Long Rides

Veteran elevator consultant James W. Fortune says he used to hear about a supertall tower like the Burj Dubai once every five years. These days, he hears about one a month. "And one out of 10 is built," he adds.

When Fortune started working on the vertical transportation system for the supertower in Dubai, he was president and CEO of Lerch Bates & Associates, Little, Colo. He subsequently retired--for two weeks--and hung out a sign in Galveston, Texas. "All I do is design elevators for mega-high-rises," says the president of Fortune Elevator Consultants.

For the Burj Dubai, Fortune designed the vertical transportation coming and going. After he left Lerch Bates, the firm hired him to come back and do a peer review on his own design.

The system for the 162-story Burj Dubai is more complicated than for previous supertall buildings because the others are office towers. The burj--Arabic for "tower"--is mainly residential but multi-use (see p. 28), which means multiple-type elevators, multiple sky lobbies, different entry levels and separated security are needed to suit those uses.

Putting the elevator puzzle together was a huge effort, says SOM. To save space, the elevator pits for the upper runs stack above elevator machine rooms in mechanical levels.

Otis Elevator Co., Bloomington, Ind., is installing the elevators. The $32-million contract is a record size, says Fortune.

Height for any one elevator run is limited to 525 meters because of cable crowding and weight, says Fortune. The elevator code requires a 10:1 safety factor, which means any one hoist cable must be able to support the total load.

Even the separate lift for emergencies could not have a full run. The cab goes straight to level 134. To go higher, emergency responders will have to transfer to another cab.

GRAPH: World's Tallest Buildings

DIAGRAM: Formwork

DIAGRAM: Up, up. To recoup time lost, contractor cast noses concurrently at different elevations.

DIAGRAM: Straight. Unlike concrete tower, which was recentered for elevator runs, spire was built plumb after centering on top concrete floor.

PHOTO (COLOR): Desert Climb. Dubai's high winds and heat put demands on Burj Dubai's building team.

PHOTO (COLOR): On High. More than 200-m-tall steel spire sprouts from tower's 585-m-tall concrete base.

PHOTO (COLOR): ALABBAR

PHOTO (COLOR): Many Forms. 156-level concrete tower has 27 floor sizes.

PHOTO (COLOR): Nose cast out of sequence to save time (right).

PHOTO (COLOR): Scrubbed. 140,000-sq-m curtain wall will take three to four months to clean.

PHOTO (COLOR): SOM team was led by Efstathiou (left, at right) with designers Adrian Smith (far left) and William F. Baker.

PHOTO (COLOR): ABDELRAZAQ

PHOTO (COLOR): FORTUNE

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By Nadine M. Post, Dubai

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