

Higher and Higher: The Evolution of the Buttressed Core

The development of the buttressed core structural system led to a paradigm shift in tall building design that brought a dramatic increase in the height of buildings. In the 32 years between the completion of 1 World Trade Center (1972) and Taipei 101 (2004), there was only a 22 percent increase in the height of the world's tallest building. In 2010, the Burj Khalifa claimed the title at 828 m, eclipsing Taipei 101 by more than 60 percent. With its innovative buttressed core, the tower represents a major leap in structural design, elicited by a change in the approach to the tall building problem through an examination of scale.



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FIGURE 5

THROUGHOUT THE HISTORY of tall buildings, structural engineers have invented the means to go higher. In the 1970s Fazlur R. Khan's tube concept was a dramatic shift from the traditional portal frame system used on such structures as the Empire State Building. Later developments, including the core plus outrigger system, also provided architects with the tools to design taller, more efficient buildings. However, the resulting growth was gradual, each innovation marking a point on the progressive scale of the tall building.

The buttressed core is a different species. Permitting a dramatic increase in height, its design employs conventional materials and construction techniques and was not precipitated by a change in materials or construction technology. The essence of the system is a tripod-shaped structure in which a strong central core anchors three building wings. It is an inherently stable system in that each wing is buttressed by the other two. The central core provides the torsional resistance for the building, while the wings provide the shear resistance and increased moment of inertia (see figure 1, typical floor plan of the Burj Khalifa). The buttressed core represents a conceptual change in structural design whose evolutionary development began with Tower Palace III, designed by Chicago-based Skidmore, Owings & Merrill LLP (SOM).

Completed in 2004, Tower Palace III, located in Seoul, South Korea, promoted a new standard in high-rise residential development (see figure 2). Its tripartite arrangement provides 120 degrees between wings, affording maximum views and privacy. Although Chicago's Lake Point Tower set the architectural precedent

for the residential high-rise, the design of Tower Palace III revealed a new structural solution for the supertall residential tower.

Tower Palace III was originally designed at more than 90 stories, its height supported by a Y-shaped floor plan. Because its architectural design called for elevators within the oval floor plate of each wing, SOM engineers opted to connect the elevators via a central cluster of cores (parts a and b of figure 3). In doing so, the "hub" became the primary lateral system of the building. At the two upper mechanical floors, the perimeter columns also were engaged to assist in resisting lateral loads by means of virtual outriggers (floor plates above and below in conjunction with a perimeter belt wall). While not as effective as direct connections, these virtual outriggers spared the builders the numerous connection and construction problems typically associated with direct outriggers (see figure 4).

Throughout the design process, the building exhibited very good structural behavior and performed well in the wind tunnel, and it became obvious to the engineering team that the structure could go much higher. However, because of zoning issues, the design of the tower's tallest wing was cut from 93 to 73 stories (the other wings were then elevated to compensate for the loss of area). Despite the decrease in height, the project provided the SOM team with the opportunity to explore a new approach to the tall building problem. Given Tower Palace III's efficiency, the structural design team inferred that, if a project had a sufficiently large parcel, this system could be used in building at extreme heights.

In early 2003, soon after completing the design of Tower Palace III, SOM was contacted about a potential supertall building in Dubai (Dubai), part of the United Arab Emirates. (See "The

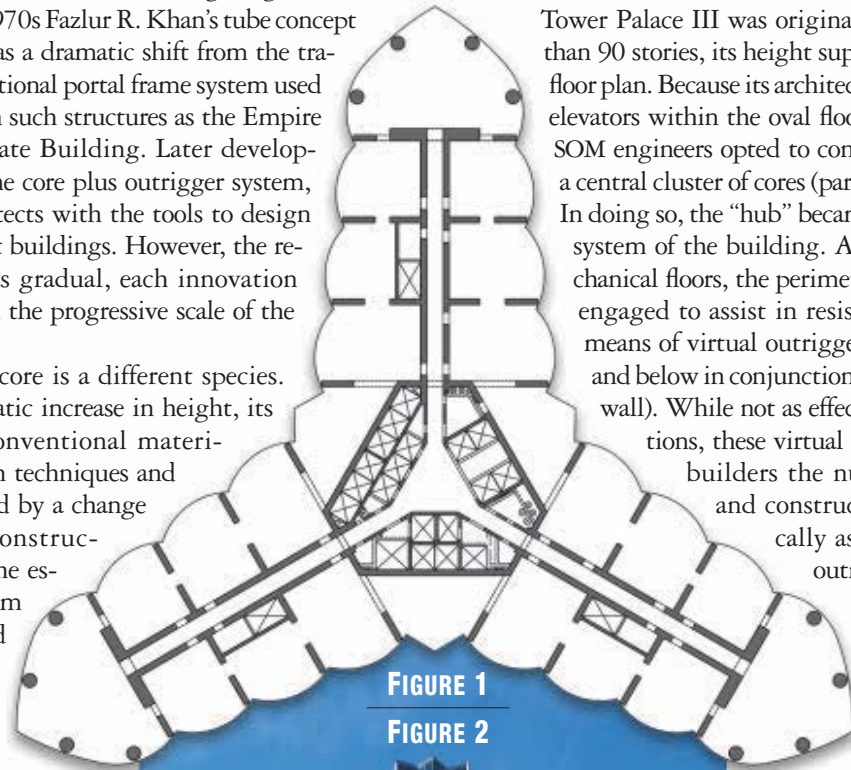


FIGURE 1
FIGURE 2



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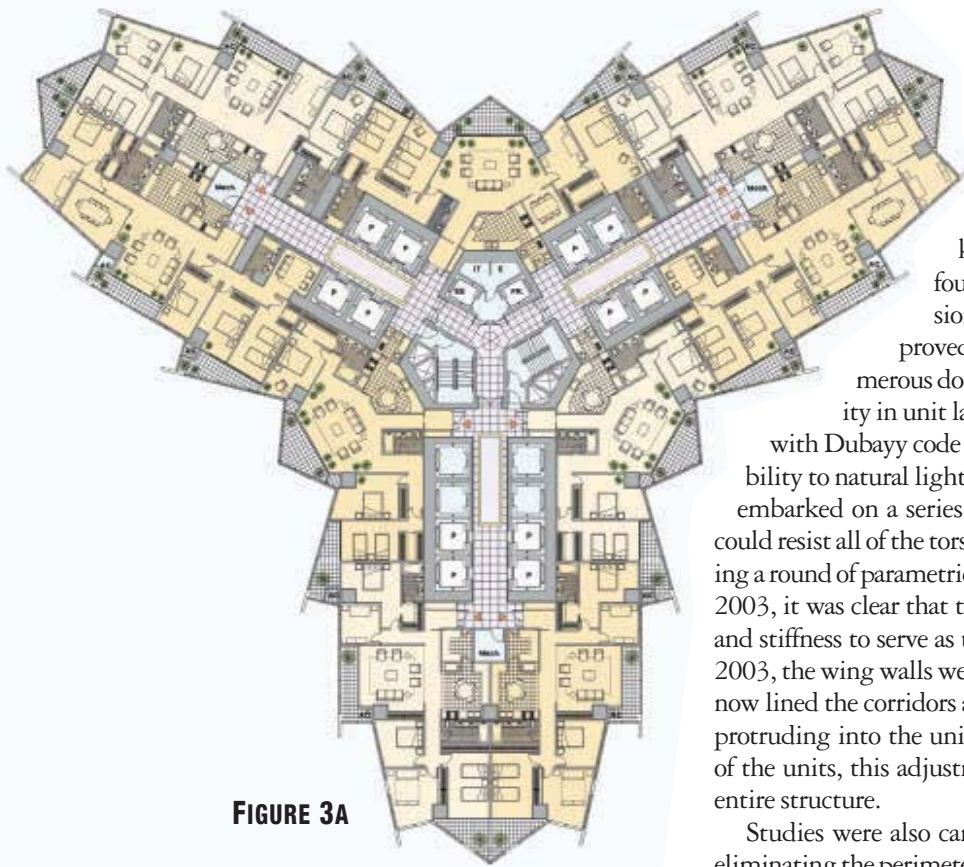


FIGURE 3A

buttressed core is on a 9 m module. As in Tower Palace III, the walls in each wing of the Burj Khalifa were initially spread apart in such a way as to separate the living components from the bath and kitchen components. This provided four interlocking tubes, but the dimensions were much greater. This plan later proved problematic because there were numerous doors in the structure and little flexibility in unit layout. It was thus difficult to comply with Dubai code requirements, which dictate accessibility to natural light in the kitchen. As a result, the team embarked on a series of studies to see if the central core could resist all of the torsional effects of the building. Following a round of parametric studies carried out in the autumn of 2003, it was clear that the central core had enough strength and stiffness to serve as the building's torsional hub. Also in 2003, the wing walls were adjusted so that the primary walls now lined the corridors at the center of each wing, instead of protruding into the units. Besides improving the efficiency of the units, this adjustment improved the efficiency of the entire structure.

Studies were also carried out to assess the possibility of eliminating the perimeter columns by using cantilever beams from the core walls. After SOM was selected to design the Burj

Burj Khalifa Triumphs” by William F. Baker, P.E., S.E., FASCE, *Civil Engineering*, March 2010, pages 44–55.) On March 1 of that year, the team went to New York to be interviewed for the project, and it was agreed there that a brief idea competition would be held involving SOM and various other invited teams. Given the success of Tower Palace III and its potential to be developed to even greater heights, the SOM team elected to use this structural system for what would later become the Burj Khalifa (see figure 5).

Throughout the design process, SOM engineers made critical changes to the Tower Palace III design that were essential to the evolution of the Burj Khalifa's buttressed core. The design of the tower's central core relied upon close collaboration on the part of SOM architects and engineers, and that multidisciplinary approach successfully fit all of the tower's elevators and operating systems within the core while maintaining good structural behavior. In contrast to the case of Tower Palace III, Burj Khalifa's central core houses all vertical transportation with the exception of egress stairs within each of the wings (see figure 6).

Each of the three wings forming the Burj Khalifa's

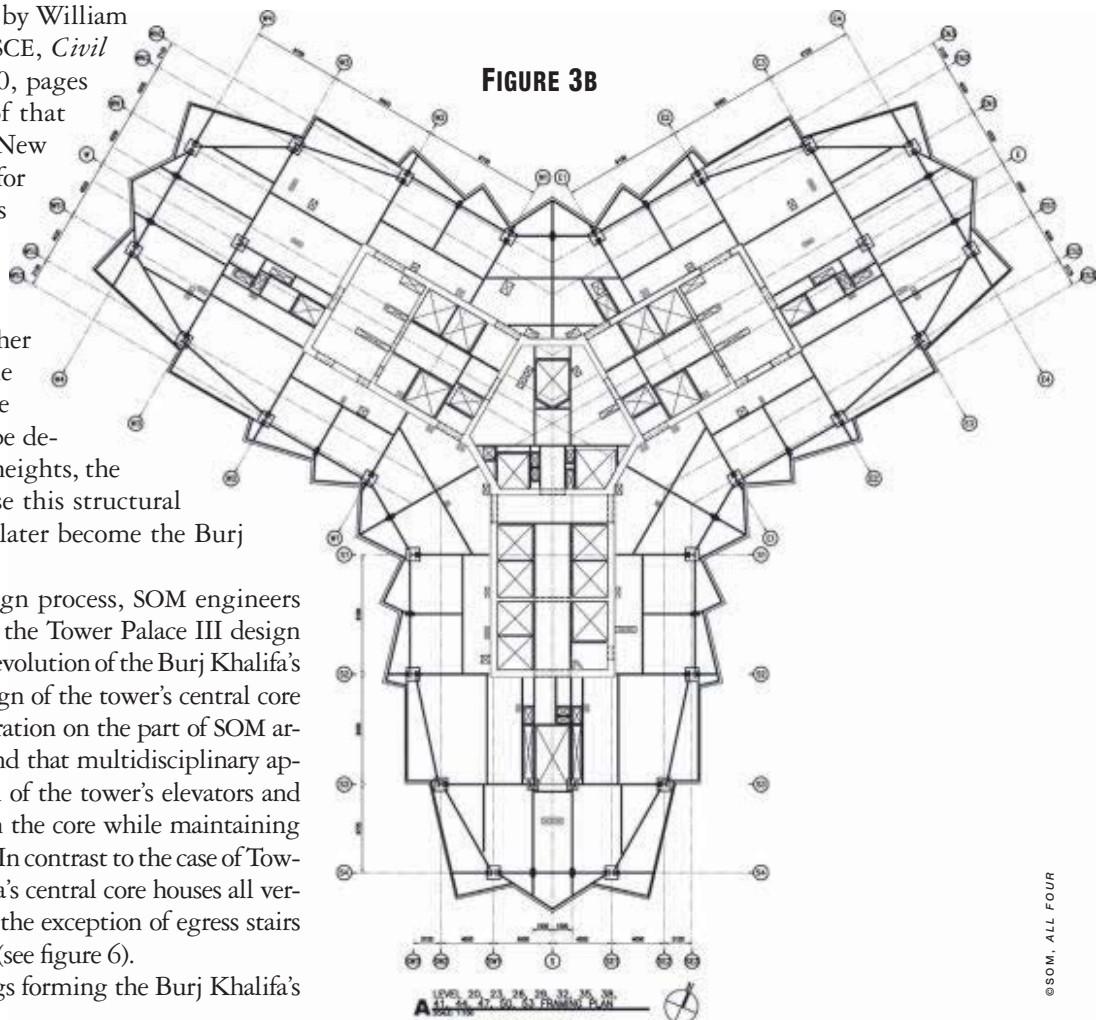


FIGURE 3B

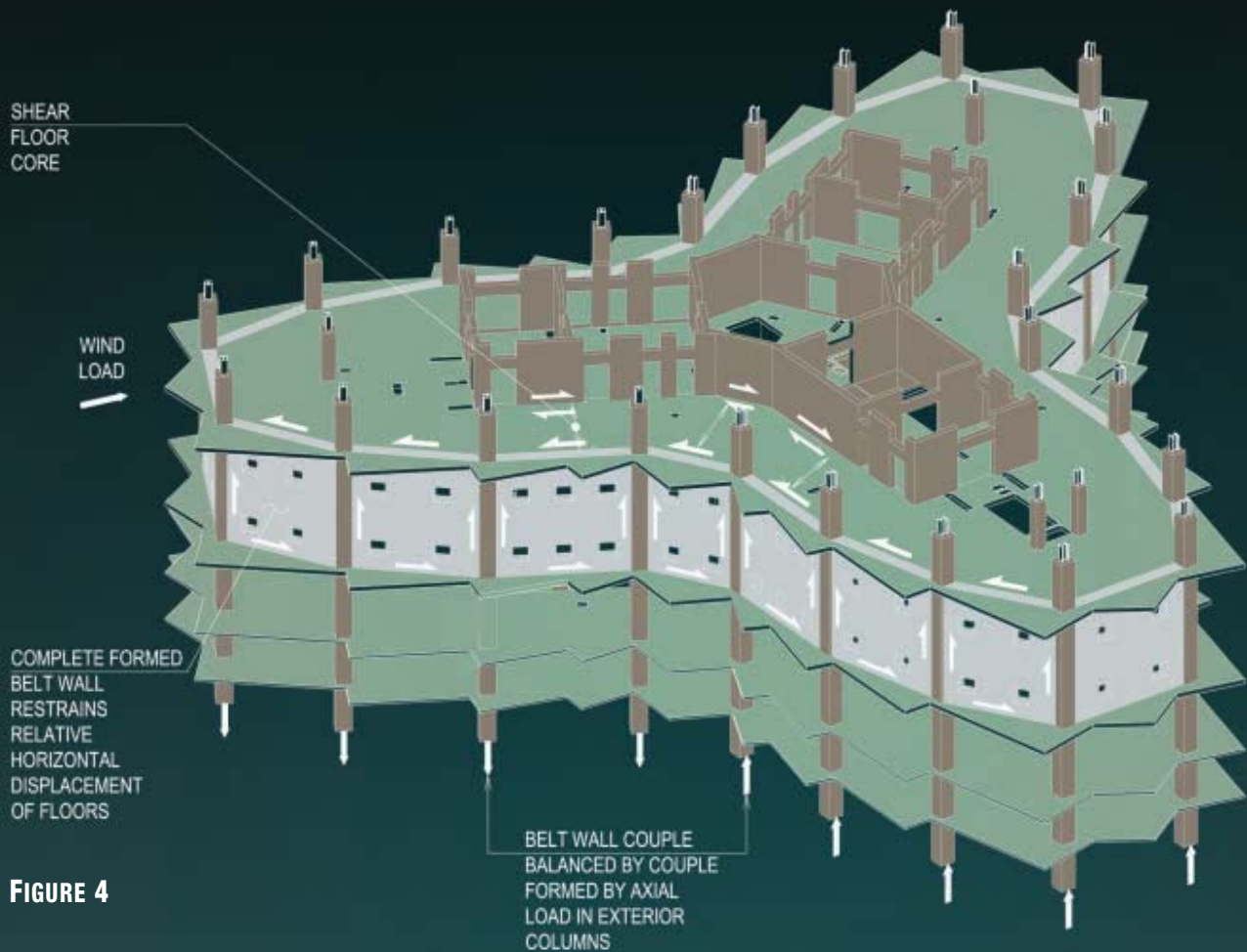


FIGURE 4

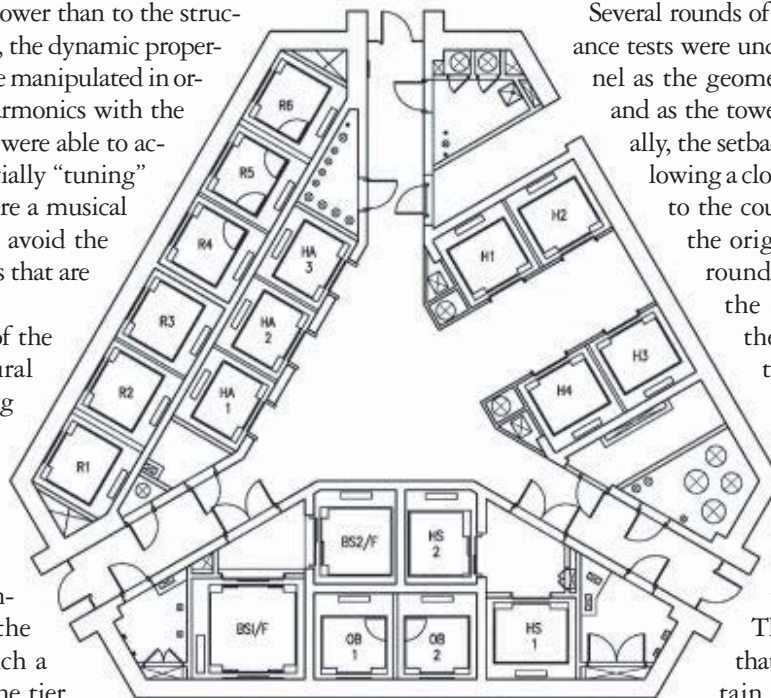
Khalifa, the engineering team immediately tested the tower's initial geometry in the wind tunnel, only to discover that it had large movements and base moments.

Upon further analysis, it was discovered that the results were more closely related to the geometry and orientation of the tower than to the structural system. Therefore, the dynamic properties of the structure were manipulated in order to minimize the harmonics with the wind forces. Engineers were able to accomplish this by essentially "tuning" the building as if it were a musical instrument in order to avoid the aerodynamic harmonics that are residual in the wind.

A key component of the Burj Khalifa's structural design was "managing gravity." This meant moving the gravity loads to where they would be most useful in resisting the lateral loads. Structural engineers manipulated the tower's setbacks in such a way that the nose of the tier

above sat on the cross-walls of the tier below, yielding great benefits for both tower strength and economy. Engineers also employed a series of "rules" to simplify load paths and construction. These included a rigorous 9 m module and a philosophy of no transfers (figure 7).

FIGURE 6



Several rounds of high-frequency force balance tests were undertaken in the wind tunnel as the geometry of the tower evolved and as the tower was refined architecturally, the setbacks in the three wings following a clockwise pattern (in contrast to the counterclockwise pattern in the original scheme). After each round of wind tunnel testing, the data were analyzed and the building was reshaped to minimize the wind effects and accommodate unrelated changes in the client's program.

In general, the number and spacing of the setbacks changed, as did the shape of the wings. The designers also noticed that the force spectra for certain wind directions showed

less excitation in the important frequency range when winds impacted the pointed, or nose, end of a wing than when they impacted the tails between the wings.

This was kept in mind when selecting the orientation of the tower relative to the most frequent directions of strong wind in Dubai, which are from the northwest, south, and east. The careful selection of the tower's orientation, along with its variant setbacks, resulted in substantial reduction of wind forces. By "confusing" the wind, the design encourages disorganized vortex shedding over the height of the tower (see figure 8).

In order to have an efficient supertall building, it is best to use all the vertical elements for both gravity and wind loads. In order to achieve this on the Burj Khalifa, it was necessary to engage all of the perimeter columns of the structure. Because of the tower's extreme height, the virtual outrigger used on Tower Palace III was replaced by a direct outrigger. In addition to engaging the perimeter for lateral load resistance, the outriggers allow the columns and walls to redistribute loads several times throughout the building's height. This helps control any differential shortening between the columns and the core. By the time the building meets the ground, the loads in the walls are somewhat ordinary, and in contrast to the case of many buildings in which the columns at the base are massive, most of the Burj Khalifa's base columns are relatively thin and only slightly thicker than those at the top.

The Burj Khalifa's structural system was created with a conscious effort to conform to and

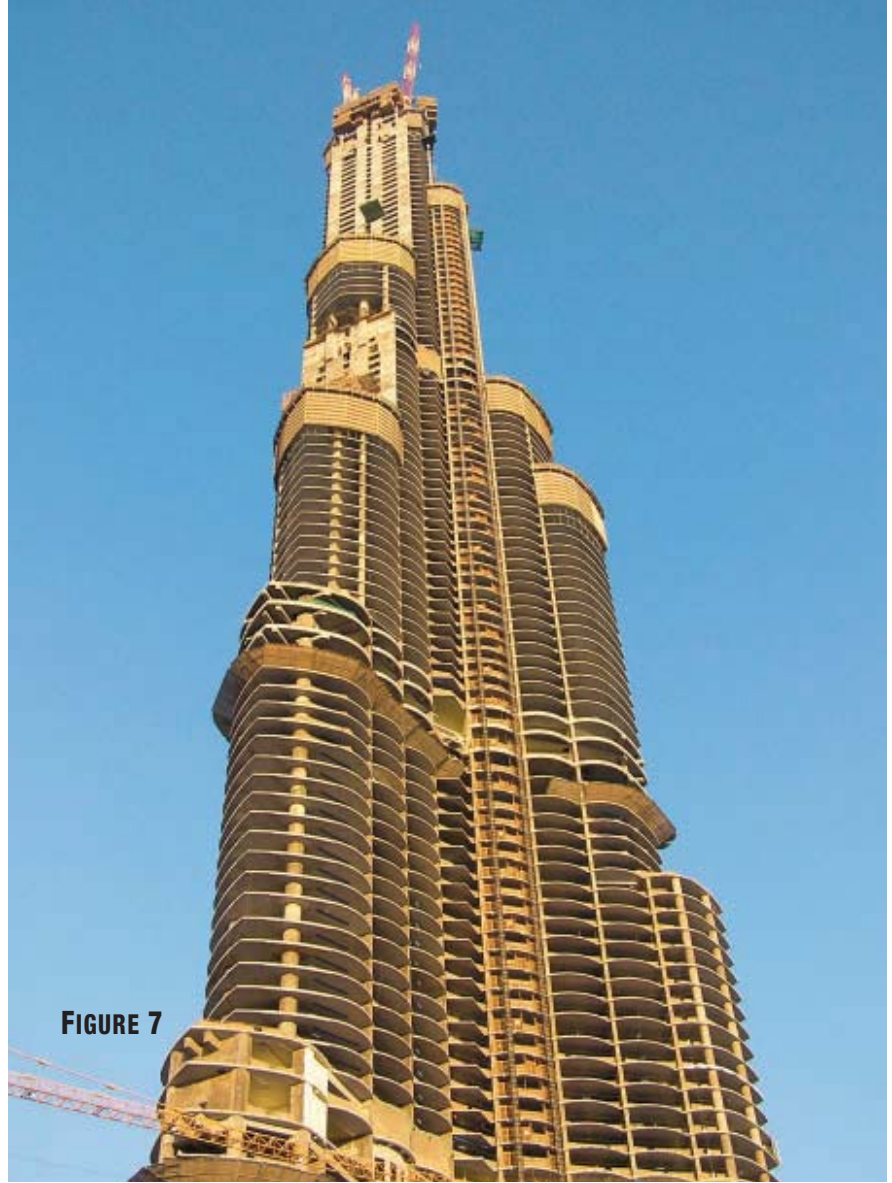
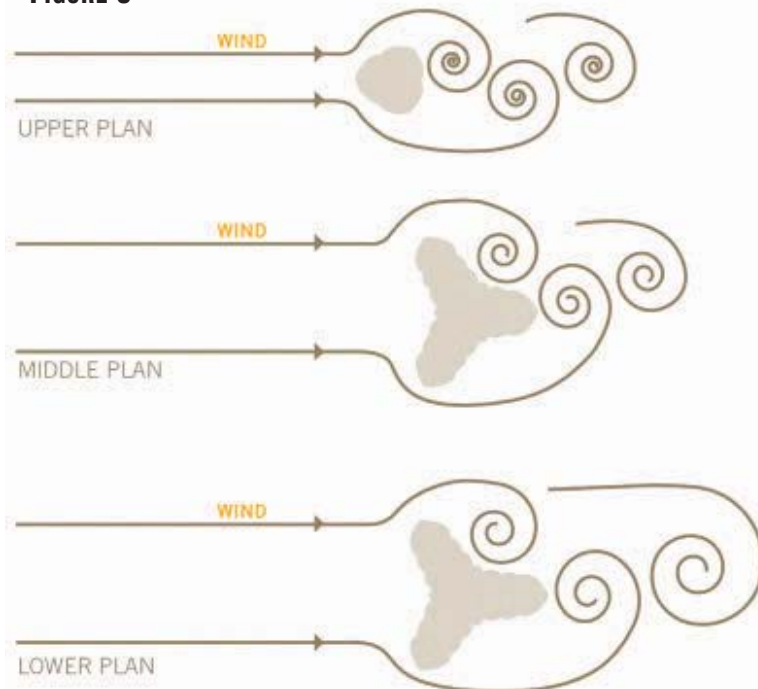


FIGURE 7

FIGURE 8



The Burj Khalifa's structural system was created with a conscious effort to conform to and complement current construction technology.

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However, rather than stepped setbacks, Las Vegas Tower has a shape that changes in elevation, causing the tower's width to continually vary.

complement current construction technology. The goal was to use a highly organized system with conventional elements that would provide a high repetition of formwork. Initially the team contemplated a composite floor framing system, as well as an all-concrete floor framing scheme. It was later decided that the all-concrete scheme was more appropriate and economical. Although the tower's floor plate changes as the structure ascends, the segments near the core repeat themselves for as much as 160 levels. As the loads accumulate from the top down, the sizes of the structural elements are relatively constant since walls were added as the loads accumulated.

The design of Las Vegas Tower (Crown Las Vegas) marked the next step in the evolution of the buttressed core. In early 2006, SOM began working on the design of a 575 m hotel



FIGURE 9

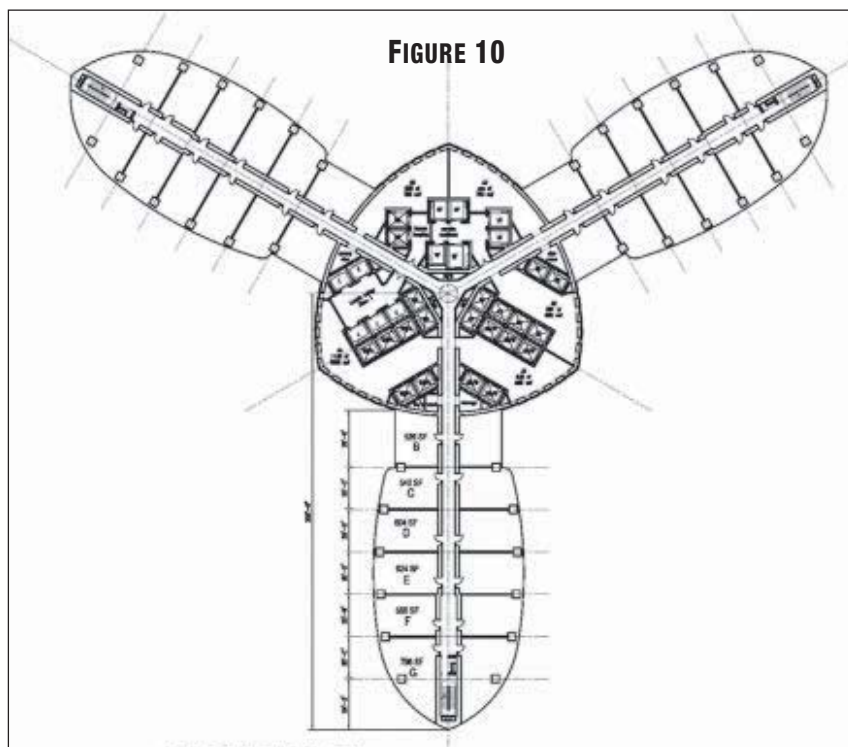


FIGURE 10

tower located on the Las Vegas Strip (see figure 9). As in its predecessors, each of the tower's three wings buttresses the other via a central core.

However, rather than stepped setbacks, Las Vegas Tower has a shape that changes in elevation, causing the tower's width to continually vary. In this way, wind vortices never get organized. Furthermore, continual changes in the tower's footprint required the loads to be moved to other elements besides the wing walls. This was accomplished by locating the stair at the end of the corridor (see figure 10). The concrete around the stair, somewhat like the chord of a truss, acts as a major structural element but moves toward the center of the building as it tapers at the top. In this way it does not require the stair transfers that were necessary in the Burj Khalifa and permits a much smoother load transfer than a solution that relies

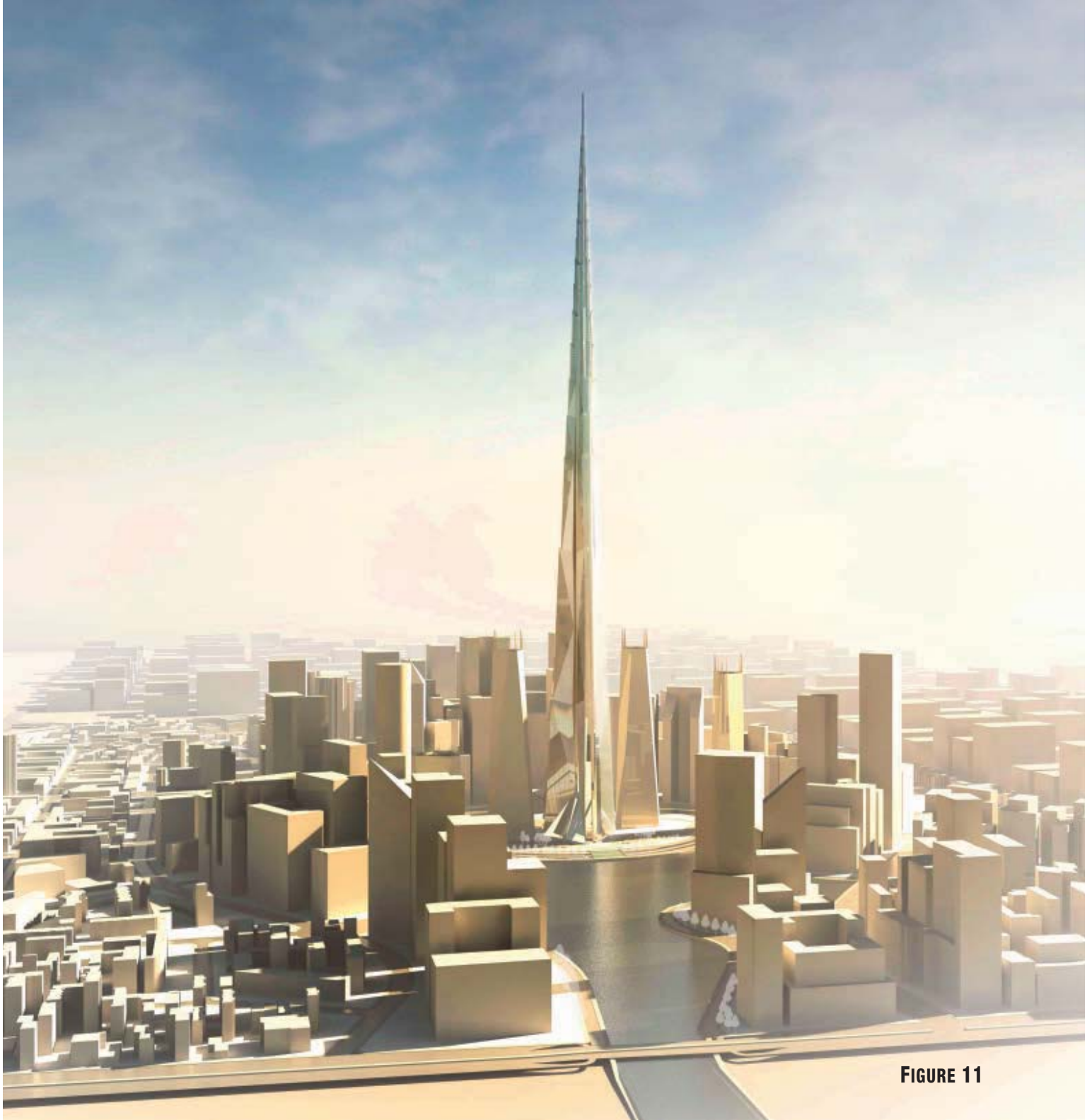


FIGURE 11

on setbacks. The stair core also provides for a large amount of structure placed near the end of each wing, thereby significantly increasing the tower's moment of inertia. However, the system is similar to the Burj Khalifa in that it employs direct outriggers connecting the perimeter columns to the interior core walls at each mechanical floor. (The project was ultimately never built.)

In 2009 SOM embarked on a design competition for what is set to be the next world's tallest building, Kingdom Tower, in Jeddah, Saudi Arabia. At more than 1,000 m, the mixed-use tower's elongated, triangular shape is a direct descendant

of the Tower Palace III, Burj Khalifa, and Las Vegas Tower paradigm and is derived from an optimized structural form for strength and wind performance (see figure 11). Referred to as the stayed buttressed core, this structural system was developed from an extensive analysis of the construction history of its predecessors and of the methods that were employed.

SOM proposed two schemes for this tower, one with columns and one without. The scheme with columns is similar to that used for the Burj Khalifa: columns of the perimeter blade type located in line with interior transverse core wall elements. Like their predecessors, these columns required

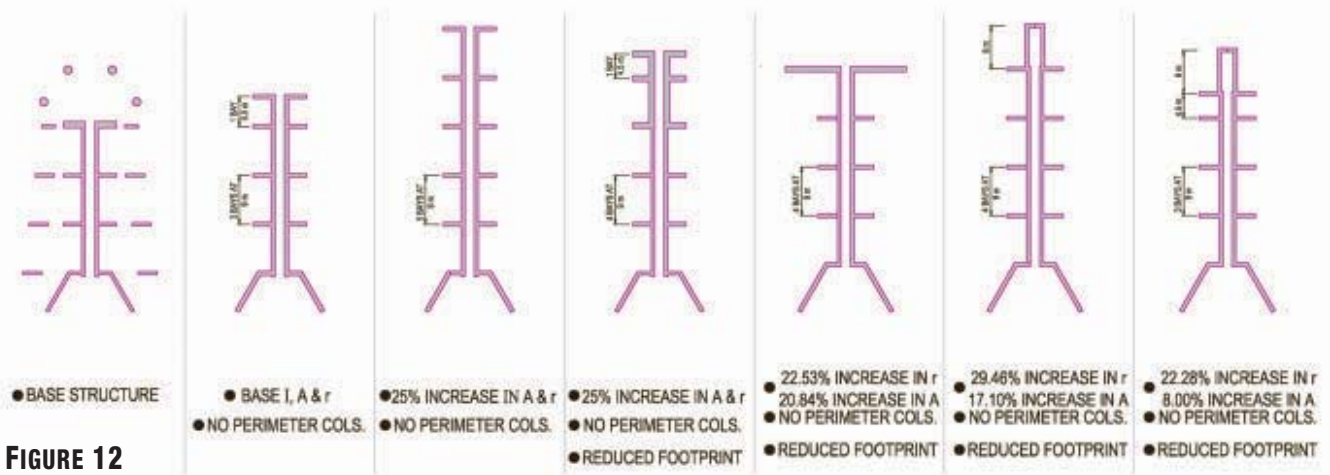


FIGURE 12

A rigorous study was conducted to determine the optimum wall geometry with respect to system efficiency and stiffness. Thus, the column-free scheme was born.

linkage to the core via direct outriggers, although distributed link beams also were considered. Early in the design process, it was realized that there was an opportunity to create the next generation of the buttressed core and to eliminate these columns and, with them, the outriggers, thereby facilitating construction and increasing efficiency. A rigorous study was conducted to determine the optimum wall geometry with respect to system efficiency and stiffness (see figure 12). Thus, the column-free scheme was born. Like the system considered in 2003 for the Burj Khalifa, this system used a central structural core with short transverse walls that continue into each of the three wings, supporting cantilevered floors and a column-free perimeter (figure 13). Stairs with surrounding walls are located at the end of each wing and scale back a nominal amount at each level to establish the building's taper, thereby eliminating any setbacks. The tripartite floor geometry, in combination with a shallow lease span, produces a breathtaking structure of unencumbered space that in its height and panoramic views realizes the full potential of the buttressed core concept.

Because of the amazing stiffness of this refined structural system, SOM engineers were able to scale the system to achieve a much taller building using virtually the same concrete quanti-

ties per square meter as in the Burj Khalifa, which is already very efficient. This new structural system also eliminates the need for outriggers and perimeter columns and is easily constructed within a standardized formwork system, thus greatly simplifying and accelerating construction. Tapering as they rise, the symmetrical internal core elements are sized to maximize their footprint and allow the building to move loads efficiently to the ground while shortening the construction schedule through the elimination of perimeter columns, complex outrigger trusses, and similar transfer elements.

The evolution of the buttressed core traces the development of a simple yet powerful structural idea. This idea was developed into an appropriate and successful system for each of the buildings described here. With each building, this system was further refined, reflecting both its flexibility and its potential. The buttressed core

has evolved into a system that truly incorporates the ideals of structural efficiency, constructability, and architectural function and makes it possible to produce buildings of great height. **CE**

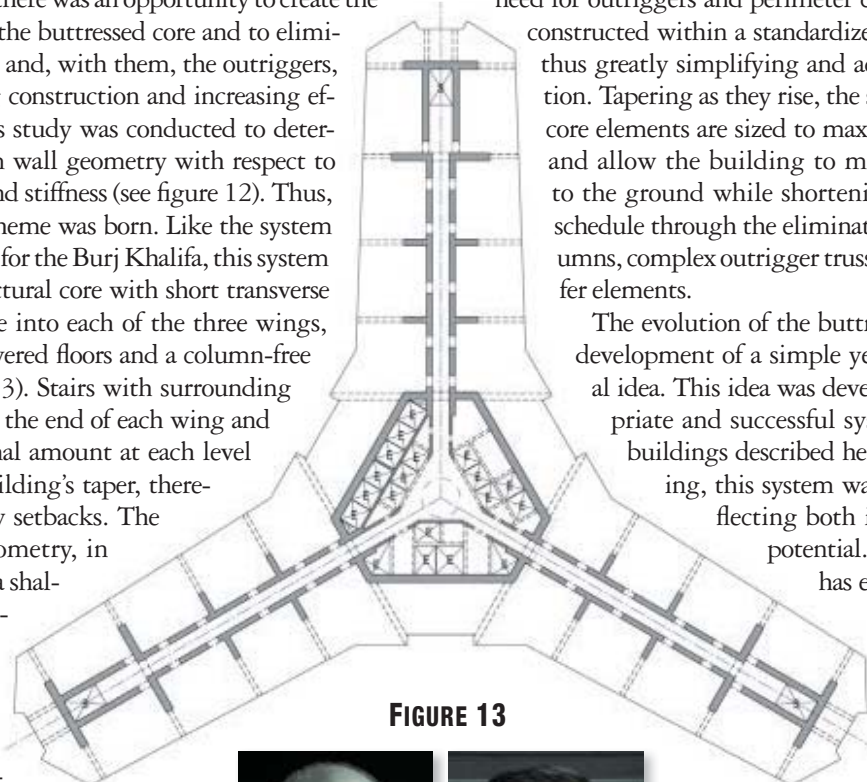


FIGURE 13



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