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Tower in the Sky

Bill Baker

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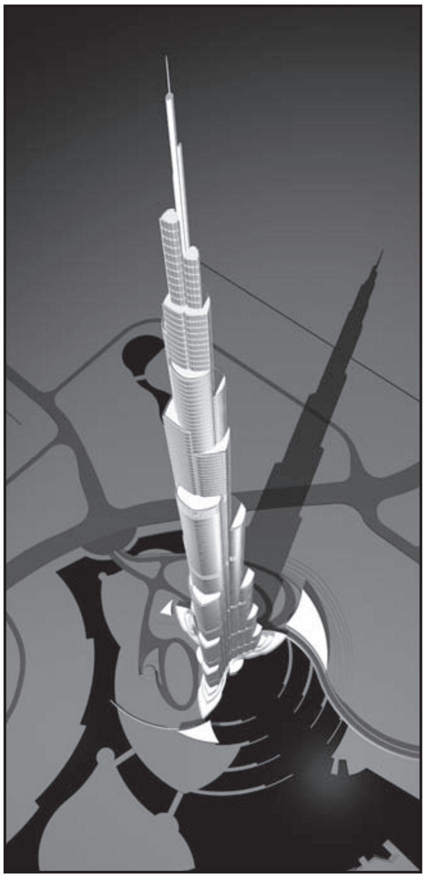
Key Concepts from Previous Chapters

- 11 Loads
- 11 Bending, Compression, Tension
- 11 Foundation
- 11 Construction Materials—Characteristics

People have always wanted to build to the sky. More than 5,000 years ago, people pushed the available technology to its limits to build the monumental Pyramids of Egypt. Ancient towers and minarets dot the landscapes of Europe, the Middle East, and Asia. Today, the skyline of any modern city in America proves that we're still using the most advanced technologies to construct buildings that scrape the sky.

I'm Bill Baker, and I've made a career of designing super-tall structures. I'm a structural engineer at Skidmore, Owings, and Merrill LLP (SOM), a Chicago-based architecture and engineering firm. We are famous for our award-winning skyscraper designs. I'm currently working on plans for the Burj Dubai, a multi-use skyscraper in Dubai, a city in the United Arab Emirates, a small nation northeast of Saudi Arabia on the Arabian Gulf.



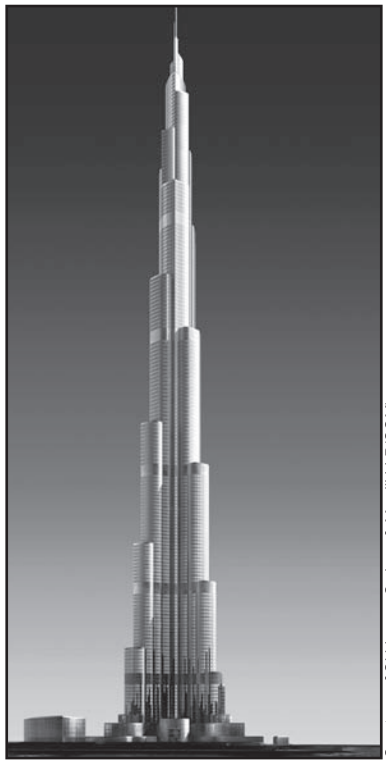
A perspective drawing of the proposed building design for the Burj Dubai

The Burj Dubai will be the tallest building in the world, with over 3,000,000 square feet of residential and commercial space. I can't tell you exactly how tall it will be—that's a closely guarded secret until the building is unveiled to the public in 2008. I can only tell you that the Burj Dubai will surpass the world's current tallest building, Taiwan's Taipei 100, which was completed in 2004, and is 1,671 feet. That's about one and a half times as tall as the Eiffel Tower in Paris.

Growing up in a small town in Missouri, I wouldn't have guessed that my job would take me across the world to nations such as China, Malaysia, or the United Arab Emirates. I didn't know any engineers when I was younger and I didn't really know what engineering was. In high school, I took an aptitude test to help me decide what I should do after graduation. I scored well in the math and science portions of the test, and my responses indicated that I enjoyed applying my math and science knowledge to create things. My guidance counselor told me the test results showed that engineering would be a good career choice. When I told my mother, she informed me that both of my grandfathers had been engineers. They had passed away before I was born, so I had never known them. I felt honored to be starting down a similar path to the ones they had taken.

In college and graduate school I became interested in large structures such as aircraft hangars and convention centers. Building big structures involves a complex and interesting set of constraints that I find challenging and exciting. First off, big structures have enormous live and dead loads, so they must support a lot of weight. Secondly, the skyscrapers must stand up during storms—and believe me, the higher you build, the stronger the force of the wind! Finally, these buildings are very expensive to build and require vast quantities of materials. So structural engineers must choose construction materials very carefully, balancing strength and cost.

The Tallest Tower

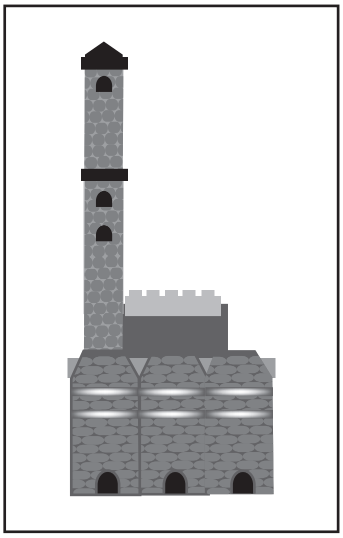


Courtesy of Skidmore, Owings & Merrill LLP(SOM)

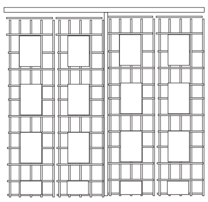
To understand why we're building the world's tallest tower in Dubai, you need to know something about the place. In recent years, Dubai has experienced a period of unprecedented growth. New laws and regulations make it very easy and inexpensive for international companies to do business there. The city was transformed into an international melting pot. People from the Arab world, Asia, Africa, Europe, Australia, and the United States have moved there in recent years as a result of the booming economy. With luxury resorts, plenty of fine dining, and bustling shopping districts, the city has also become a popular tourist destination of wealthy Europeans and Americans. In fact, a "celebrity culture" like one you might find in Miami or Hollywood has started to take shape.

In 2003, EMAAR Properties, a real estate development company in Dubai, asked my company to submit a proposal for a super-tall building. The company wanted a structure that would serve as an emblem of the city's prestige, something that would raise the stature of Dubai as a global tourist destination. Years ago, this is what the Eiffel Tower did for Paris and the Golden Gate Bridge did for San Francisco. A number of firms submitted designs, but we were chosen to design the new skyscraper.

Our design was inspired by a flower that is native to the region. The base of the Burj Dubai blossoms upward in a series of steps to give the tower a graceful transition from the ground. The design offers impressive views and protection against high winds. When complete, the tower's 160-plus stories will house a world-class hotel, luxury condominiums, and office spaces. The top stories will be used by telecommunications companies for satellite and radio transmissions. Whole floors will be reserved for building maintenance, where several cranes and drop baskets will be used for window cleaning and outside maintenance. The window-washing equipment alone will occupy several stories. The "skin," or outer covering, of the building will be made almost entirely of glass to allow for breath-taking views of the Arabian Gulf and the desert.



Windows make the walls of stone towers weaker and less structurally sound.



The steel frames of this metal-framed building carry the load.

Shear

is a force that results in the deformation of an object such that the object's parallel planes move past one another.

Rising Higher

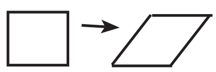
Humans can only build as high as current technology permits. During the Middle Ages, massive stone walls supported towers and spires. The walls were very thick in order to support the dead load of the structure. Building a taller tower required that the lower walls be thicker to support the load of the walls above them. The Leaning Tower of Pisa, for example, has walls as wide as thirteen feet on the lower floors. There is a limit to how high you can build just by making the walls thicker. In towers above a certain height, the walls must be so thick that little open space remains inside. In addition, stone towers rarely have many windows, because they weaken the walls and the structural integrity of the buildings.

During the Industrial Revolution, engineers began experimenting with new ways to manufacture long beams of iron and steel. By the late 1800s, engineers designed buildings with metal frames. In these buildings, the steel frame, not the outer walls, carries the load of the structure. In these designs, the outer walls could have plenty of windows. In fact, the skyscrapers of the 20th century often had glass walls to allow for great views and plenty of natural light. And because steel is much lighter and stronger than stone, brick, or mortar, steel-frame buildings can rise much higher than earlier buildings, which seldom extended past ten stories.

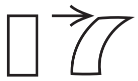
A Matter of Geometry

The frame of the building—its skeletal bones—keeps the structure standing despite very high loads. The shape of a building's frame can minimize the amount of tension or compression that every individual beam and column bears. How is this possible?

Let's look at a very simple frame with four joints, or corners, pictured below. If a force, perhaps wind, acts on this frame from the side, the top and bottom would slide past each other, causing shear. ***Shear*** is a force that results in the deformation of an object in which its parallel planes remain parallel but move past one another.



A tall structure such as a skyscraper may start to bend as shear increases. Remember, bending occurs when one side of an object experiences tension and the other side experiences compression. When bending becomes too great, the structure is in danger of toppling to the ground.



As you can imagine, engineers want to minimize the effects of bending as much as possible, because it reduces the stability of the frame. We can do this by adding diagonal members, forming a truss. A ***truss*** is a triangular arrangement of structural members that increases a structure's rigidity (shown on the right). When a shearing force pushes on the side of the frame, the truss holds the joints in place so they cannot slide apart. The entire structure resists the force, not just each individual column.

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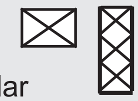
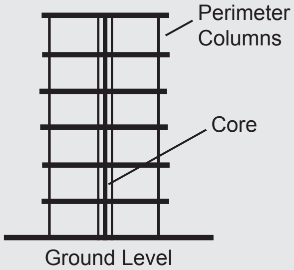
> 

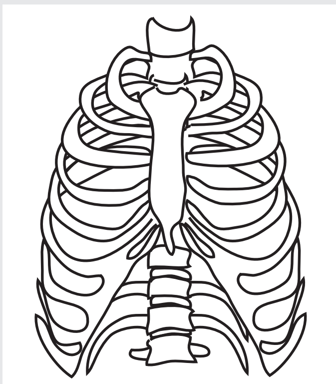
The Empire State Building, constructed with a steel frame in 1931, is a good example. The Empire State Building's strong frame allowed it to rise 1,250 feet into the air, making it the tallest building in the world until 1972. Its impressive height along with its beautiful design made the building an internationally celebrated landmark. But the building's steel skeleton, a three-dimensional grid of columns and beams, restricted its indoor space. In fact, most of floors are chopped up into small rectangular rooms, and the interior rooms get very little daylight.

Steel frames and truss systems are quite strong, but they are not the only way to make tall buildings stand up to the forces of nature. Nowadays, many buildings are constructed around a strong central core that supports the structure like a spine. This spine acts like a tall, wide column held together with trusses or walls. In many buildings the core is constructed around the elevator shafts, because they must be very straight.

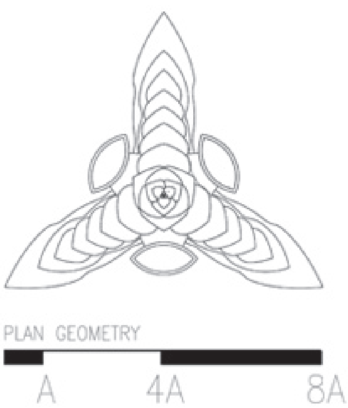
Very tall structures are often designed with multiple elevators, requiring a wide core composed of many solid vertical columns. The floors of the building then span from the core to the columns at its sides. This allows for nice, open floor plans, large rooms, and plenty of natural light throughout the building.

Tall Building Constructed Around a Central Core





How is the central core of the building like a human spine?



Courtesy of Skidmore, Owings & Merrill LLP(SOM)

Today, durable reinforced concrete is often used instead of steel for the columns and core walls. Concrete is a hard substance made from cement, crushed rock or sand, and water, which performs very well under compression forces. Modern concrete also uses fly ash from coal-fired power plants, ground up blast furnace slag from steel manufacturing, and silica dust from computer chip manufacturing as substitutes for some of the cement.

These waste products from other industries actually make concrete stronger and contribute to recycling. While concrete is very strong in compression, it doesn't resist tension forces very well. To make it perform better under tension or bending, concrete is reinforced with steel bars (called rebar). The reinforced concrete works just as well as steel for many purposes, and for compression elements such as columns, it is hard to beat.

While engineering the Burj Dubai, I've thought a lot about how to distribute the load while maintaining an open floor plan. After all, its dead load will be approximately a half-million tons. That's one billion pounds!

In our design, the central core and the perimeter columns are supported from deep underground. The underground portions of the columns are called piles. These piles act like the roots of a tree, adding even more stability. Each pile carries about 3,000 tons.

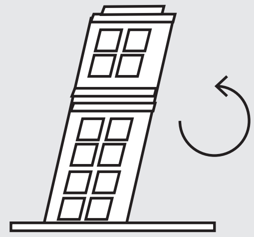
The central core of the Burj Dubai resembles the hub of a wheel with three spokes, which spread out into the three wings of the structure, so that the immense weight is distributed over all three wings of the building. In turn, each wing has its own walls along the corridors and perimeter columns. Each wing was designed to be a stable structure in and of itself. This wing design bolsters the support of the central core, allowing the Burj Dubai to reach its towering height.

Confusing the Wind

The enormous load of a structure like the Burj Dubai actually comes in handy when battling the largest force that the building will have to withstand: the wind. Wind gusts can reach up to 160 miles per hour at the top of the spire. The mere weight of the building helps brace the structure against the wind. You can get a sense of this by placing two soda cans, one empty and one full, on a table top and aim a fan directly at them. Which soda can is more likely to remain standing? The full one, of course! That's because the full can's weight pushes the can onto the surface of the desk, stabilizing it.

But the building's load is not enough to withstand the extremely high forces that wind can produce. Wind acts on the building's surface in two different ways. It pushes directly on the side of the building to produce a force called "drag." Wind also swirls around the edges of the building, creating small "vortices," or whirlpools, of spinning air.

Though drag can get quite strong, it's really the force of the vortices that give us the greatest concern. When these forces develop at opposite sides of a building, they can actually push the building from side to side. If the vortices spin at exactly the right speed, they can intensify the building's natural swaying motion, causing it to rock back and forth dramatically.



Even relatively small forces of the vortices may cause a building to start rocking dangerously to and fro.

If you have ever been to the top of a skyscraper, then you may have felt it swaying. To solve the wind problem, we purposely design skyscrapers so that they are flexible. They move a little with the wind and with the movements of the Earth. That's because even very small movements at the base are translated to larger movements at the top. If you hold a long fishing rod in your hand, you'll notice that the tip of it sways back and forth no matter how steadily you try to hold it.

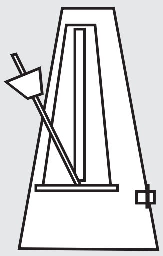
Courtesy of Skidmore, Owings & Merrill LLP(SOM)

A skyscraper's flexibility also makes it better able to withstand earthquakes. In an earthquake, a skyscraper rides the waves of the shaking Earth almost like a surfer. Even a smaller, more rigid structure that does not sway is more likely to fracture and collapse. It may seem unlikely, but you might be better off in a well-designed skyscraper than in a two-story building during an earthquake.

Every tall building sways from one side to the other and back again in a set number of seconds. The time it takes for one full cycle is called a ***period.*** The Sears Tower in Chicago, for instance, has a period of 7 and 3/4 seconds. The Burj Dubai will have a period of eleven seconds.

If the vortices at the edges of the building begin pulling the structure from side to side in rhythm with the natural period of the building, the building will began to sway a greater and greater distance from its vertical position. To understand how this happens, think of how you move back and forth on a swing. When you kick your feet in rhythm with the motion of the swing, each kick propels the swing higher and higher. When timed correctly, the relatively small force of kicking results in increasingly higher swings. Similarly, at certain speeds, the small forces of the vortices may cause a building to start rocking violently.

All skyscrapers are designed to compensate for these forces. For the Burj Dubai, the design team varied the width of the building and the shape of the floors. Every section that has a different width or a different-shaped floor will have vortices occurring at different spinning rates. We changed the shape of the building 24 times in order to confuse the wind. It's as if you sat on your swing and kicked your left foot at one rate and your right foot at another. If you do that, the swing won't go very high. We tested each design by placing a scale model in a wind tunnel and observing how it behaved during a range of wind speeds. From wind-tunnel tests, we were able to identify the areas affected by vortices, and modify the design to reduce these forces.



Tuning the skyscraper's period is not unlike the way you adjust the period of a mechanical metronome.

Engineers can also "tune" a building to make sure that it has a period that is unlikely to become synchronized with the side-to-side pushing of the vortices. By analyzing data about storms and wind currents at the construction site, we determined the safest period for the structure. Engineers can "tune" a skyscraper by moving the weight of the structure higher or lower, not unlike the way you would adjust the period of a mechanical metronome—the higher the weight, the longer the building's period. We determined the eleven-second period for the Burj Dubai based on estimates of wind vortices in the worst possible storm that is ever likely to strike the building.

As you can see, every square inch of a super-tall building is painstakingly engineered for the safety and comfort of its occupants. But these structures still possess awe-inspiring mystery, even for me—and I spend my days engineering them! I often say that skyscrapers are dreams rendered in steel and concrete. Whether they reflect the dreams of a young boy growing up in Missouri or the dreams of entire cities and nations, these structures are at the very cutting edge of current construction technologies and of our own imaginations.

What's the Story?

1. Why do people in Dubai want to build a super-tall structure in their city?
2. What limited the height of structures in the Middle Ages?
3. What manufacturing breakthrough led to the development of taller structures in the 1800s?

Designing with Math and Science

4. What is shear?
5. What is a truss and how does it minimize the effects of a shearing force?
6. Why is it necessary for Bill to design the Burj Dubai so that it "confuses" the wind?
7. Is concrete better at minimizing the effects of compression or tension? What is special about the concrete that Bill is using as construction material for the Burj Dubai?
8. How does the Burj Dubai reflect a New Urbanist's approach to city planning?

What Do You Think?

9. Name a structure that is emblematic to your city, town, or region. Find out when it was built and what materials were used in its construction. What do you think would have been different if it had been built more recently?
10. What do you think superstructures of the future will be constructed of? What is special about those materials?