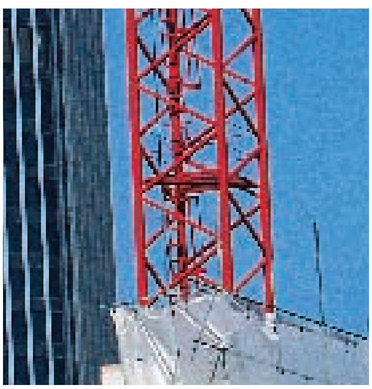
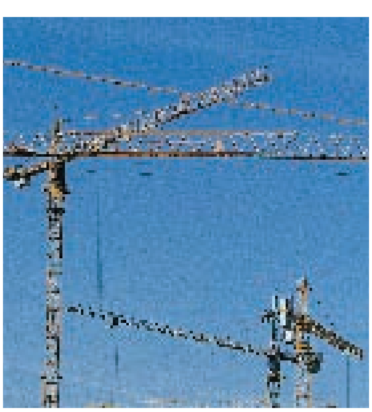


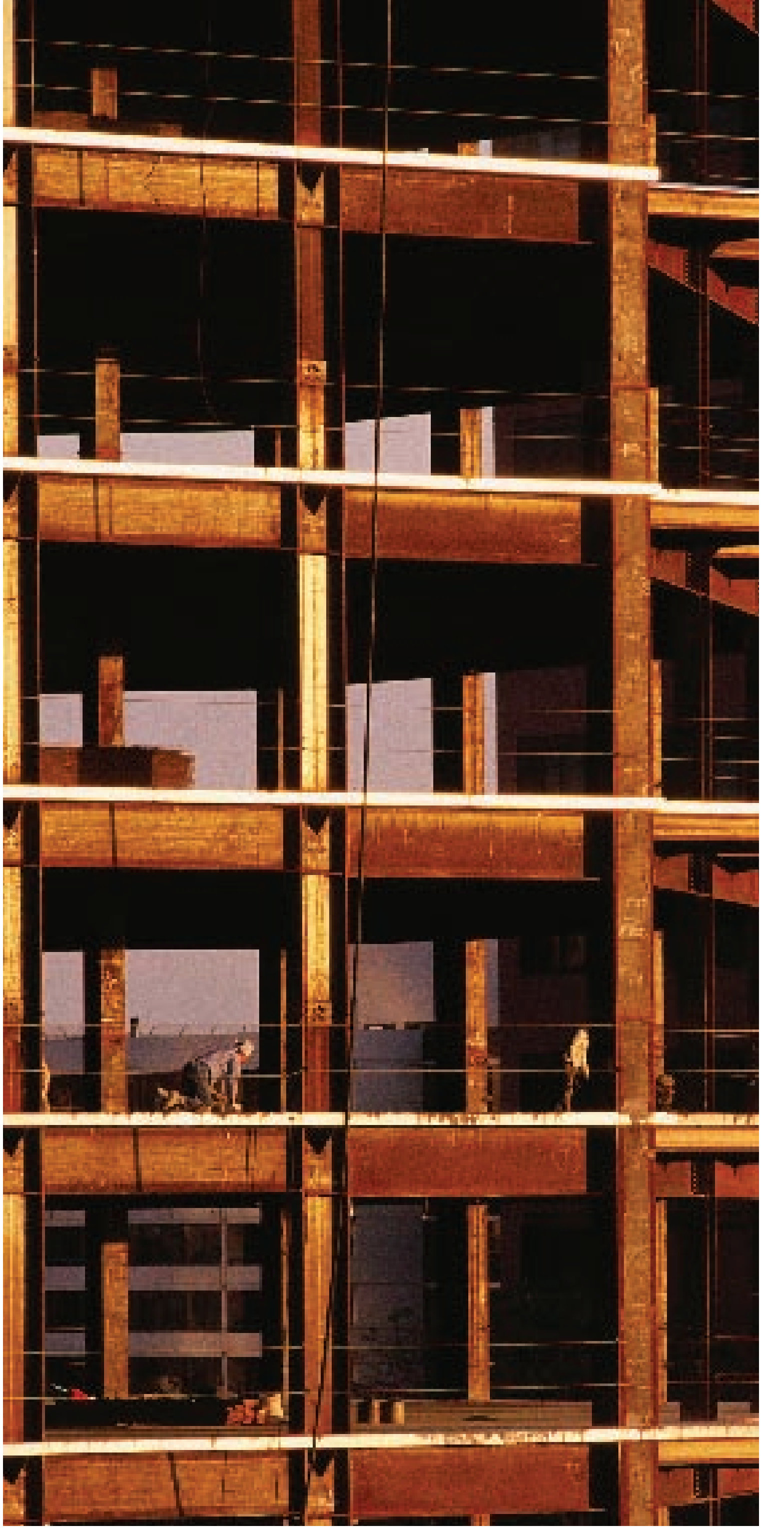


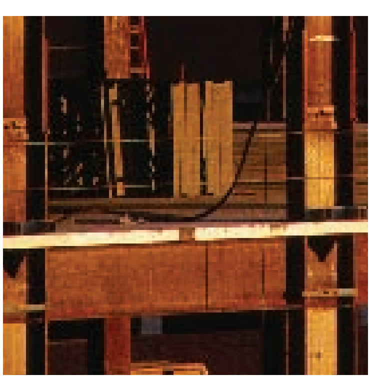
The Sky's the Limit

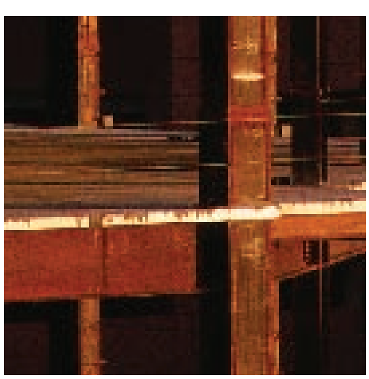
For more than a century, skyscrapers have climbed farther into the sky thanks to advancements in engineering and the ever-present desire to be the tallest. By Virginia Hughes

Today's skyscrapers stand, in every major city in the world, as breathtaking reminders of the scope of human engineering. The 1,053-foot-tall Burj al Arab Hotel, in Dubai, United Arab Emirates, takes the shape of an enormous sail, seemingly floating on the sandy soil of an artificial island 985 feet from the coast. The 1,667-foot Taipei Financial Center (Taipei 101), currently the tallest building in the world, stands steady in a region that sees 6-point earthquakes and 155-mph typhoon winds.

But it was economics, not technology, that spurred the construction of the first skyscraper. On October 8, 1871, a fire of unknown origin raged through downtown Chicago, leaving 300 people dead, 90,000 homeless,







and $200 million (more than $3 billion in today's U.S. dollars) in property damages. The subsequent demand for office space, coupled with the high cost of downtown real estate, left only one way to build: up.

Thus, in 1885, Chicago produced the 10-story, 138-foot Home Insurance Co. Building that, though since torn down, was said to look like a Renaissance palace. Cast and wrought iron made up most of its inner core, but also—unlike previous buildings—steel. This led most historians to deem the building the first "real" skyscraper. It weighed just one-third as much as a similarly sized stone building.

Before this iron-and-steel innovation, tall buildings stood only thanks to strong masonry walls—sometimes as much as 6 feet thick. "The walls supported all of the weight," explains Donald Friedman, seasoned structural engineer and expert in the preservation of historic buildings. "They got to be sort of ridiculous." Thick walls meant that windows had to be set deep within the walls, often creating ugly, dark recesses across the building's façade.

In the early 19th century, England's industrial revolution led to the development of the iron frame building—rigid iron column supports upon which outer, non-structural "curtain" walls hang. French architect Gustave Eiffel brought this technology to the United States, literally, in 1885, with the riveted iron internal structure of the Statue of Liberty. Most European cities of the 19th century had strict building ordinances that set height limits on all new buildings. "The Paris skyline was a level plateau of shorter buildings, punctuated by spires of the great cathedrals," says Lee Gray, associate dean of the College of Architecture at the University of North Carolina-Charlotte. American engineers, limited by no such rules, quickly mimicked Eiffel's innovation, experimenting first with iron and then with mass-produced steel.

After the Home Insurance Co. Building, the "Chicago School" of architects built a few other skyscrapers within a decade. By the turn of the century, every major city wanted the world's tallest building for its skyline.

For most of the 20th century, the architectural spotlight oscillated between Chicago and New York, as each churned out building after building of unusual design and epic proportions. New York's Woolworth Building, built in 1913, and the Chicago Tribune Building, built in 1925, looked like skinny Gothic cathedrals. In 1930, New York's art deco chrome-top Chrysler Building, at 1,046 feet, claimed to be the tallest in the world—but not for long. Just one year later (and nine blocks south), the spire of the General Motors-backed Empire State Building edged higher, to 1,250 feet. The Empire State Building maintained the title of world's tallest for 41 more years.

In 1972, the twin towers of the World Trade Center took the lead, with 110 floors and 1,368 feet of glass façade. (See sidebar on page 14 for more about the collapse of the WTC.) Not to be outdone, two years later, Chicago's Sears Tower, with its signature black bands and 110 floors, reached 1,451 feet.

The most-talked-about skyscrapers, once classically American, are now constructed on the other side of the globe. The United States now claims only four of the 20 tallest buildings in the world. (See sidebar on page 15 for the complete list.) "It's a funny thing," Friedman says, "but non-architects would have a hard time naming the tallest building in the world today."

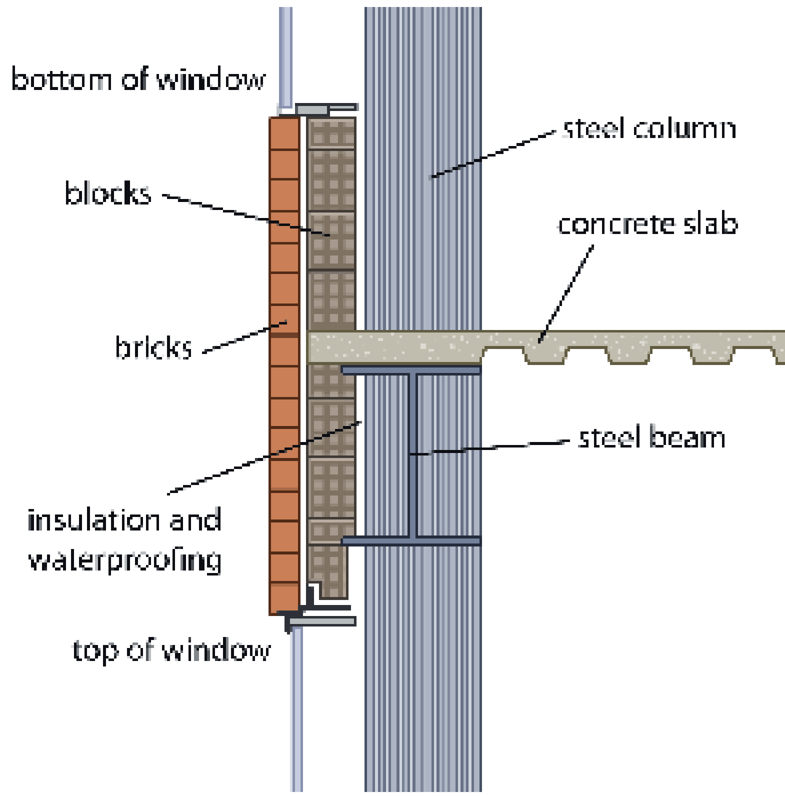
BUILDING TALL

"There's no hard and fast definition of what a skyscraper is," Friedman says. From an engineer's perspective, he explains, it's just a building tall and skinny enough that wind forces factor heavily into the design.

When a building engineer isn't worried about building tall—say, for buildings under 20 stories—then only one force affects structural design: gravity. Friedman uses the example of building a 10-story steel-frame building on a lot that's 100 feet by 100 feet. Because it's so short, the architect could create all kinds of unusual structures: "If you wanted to have masonry on the top five floors and glass below that," he jokes, "it'd be ugly, but you could do it."

Consider using the same 100-by-100-foot lot to build a 50-story building. Gravity is no longer the engineer's chief concern. "All of a sudden you're worried about earthquakes, or keeping that building from swaying in the wind," Friedman says.

Indeed, today's skyscraper engineers consider, first and foremost, these "Big Three" forces: gravity, earthquakes and wind. The tallest buildings today—at almost 1,700 feet



Cutaway section of steel and concrete skyscraper construction

Fighting Fire at the Top

The prospect of being 1,000 feet from the ground when a fire breaks out is frightening.

But how do you ensure fire protection in a skyscraper?

Just like any other building, every floor of a skyscraper contains a sprinkler system. "The big challenge in a skyscraper is moving that water to the upper floors," explains Craig French, plant manager of Dixon Powhatan, which specializes in manufacturing fire protection equipment. When a fire breaks out, a massive hydraulic basement pump fights against gravity to get water to the upper floors. The water travels up from the basement in large-diameter, steel standpipes, then branches from the standpipes into small-diameter sprinkler pipes on each floor. Pressure-reducing valves allow the water to flow safely from the standpipe, which French says can withstand water pressures up to several hundred pounds per square inch (psi), into the sprinkler pipes, which can only handle about 175 psi.

Another challenge: In a tall building, firefighters can't use an outside fire hydrant. "If you're 50 stories up, that'd take a heck of a ladder truck," French jokes. Instead, they connect their hoses directly to the building's standpipes, using its own water pump to fight the fire.

Some of the world's tallest buildings: (from the left) are Burj al Arab Hotel, Dubai, United Arab Emirates; Sears Tower, Chicago; Taipei 101, Taipei, Taiwan; Empire State Building, New York.

tall—must be about 50 times stronger against wind forces, in fact, than the 200-foot buildings of a century ago.

A wide margin of safety is built into modern building codes, so that if standard materials are used with standard construction methods, the chances of a skyscraper's collapse are extremely slim. The biggest challenge for structural engineers, then, isn't keeping a building standing—it's keeping it standing steady. "All skyscrapers move, because to make them not move would be totally economically unfeasible," says Vicki Arbitrio, of New York's Gilsanz, Murray, Steficek firm, who's been a structural engineer for 24 years. "But people don't like to know that they're moving."

To make a skyscraper's sway as imperceptible as possible, engineers first consider its drift, or "deflection ratio"—the ratio of lateral sway to building height. The top of the World Trade Center towers, for instance, used to sway about 2 feet. "But that's 2 feet in 1,200 feet of height," Arbitrio explains, "so that ratio was actually pretty small." In addition to drift, an engineer must also consider acceleration, or how fast a building sways from side to side.

The acceptable degree of sway also depends on the tenants. Office workers, often on their feet or working intently at their desks, won't notice a building's movements nearly as much as someone sleeping in a high-rise apartment. These criteria could even vary from floor to floor.

A skyscraper's total design demands a massive coordination effort between three principal players: the architect (and leader of the team), the structural engineer and the mechanical engineer.

One of the architect's first tasks is to analyze the geological makeup of the building site, to determine the depth of the bedrock and to make sure it is void of any archaeological remains. The next step is to dig a hole, generally 30 or 40 feet deep, and to fill the hole with concrete foundations. Steel base plates are embedded in the concrete to support steel and concrete columns that will form the backbone of the structural skeleton.

Think of a skyscraper as a human body: its construction flows from the inside out, starting with the skeleton, or structural frame. The earliest skyscrapers used cast iron as the primary frame material. Though iron can bear strong loads under compression—that is, when pressed down by gravity—it becomes brittle when stretched by tensile forces, such as high winds. Steel, strong under both compression and tension, became the material of choice when inventor Henry Bessemer found an inexpensive way to remove impurities from iron to create it. His "Bessemer process" allowed for the inexpensive mass production of steel.

The skeleton of modern skyscrapers is made of columns of steel and reinforced concrete, in varying proportions. Steel structures, like the Empire State Building, are made of huge steel I-beams, but have concrete floor slabs.

Concrete structures, like the Trump Tower, are made of concrete columns that are reinforced every few feet with small steel bars, called rebar. It is fortuitous that the two materials are chemically compatible; if you added a metal like aluminum to concrete, for instance, it would set off a dangerous chemical reaction.

Concrete and steel each have advantages and disadvantages, depending on the intended function of the building. In essence, a steel building is light, flexible and easier to build tall. Concrete buildings, on the other hand, are heavy, stiff and sway at much lower accelerations than steel. "If you believe there will be a lot of change [made inside the building] in the future, steel is better," Friedman explains. Internal staircases for tenants occupying multiple floors, for instance, are more easily added to steel structures. "But if you want to minimize floor to floor height, like in an apartment house, concrete is better."

The new Time Warner Center in New York shows how the two materials can be used in tandem. The lower levels, comprised of office and retail space, are made of steel. The higher towers, one of which is an apartment building and the other a hotel, are made of concrete all the way up to the top.

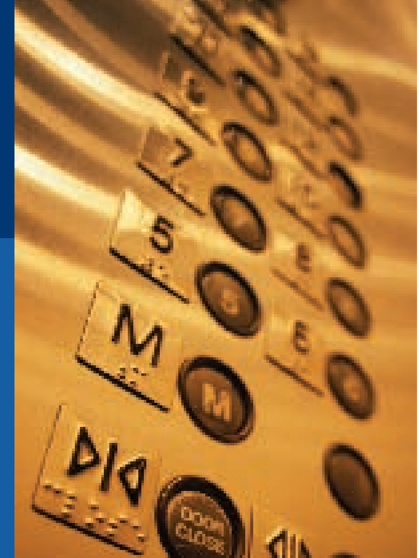
Once a building's skeleton falls into place, the building team turns next to the emerging skyscraper's veins. Mechanical contractors install elevator shafts, plumbing pipes, electrical systems, air conditioners and computer networking wires as soon as the metal decks go down on each floor.

Finally, with the strong steel core and all the pipes installed, comes the most visible component: the skin, sometimes called the building envelope. Though the façade is generally critiqued mostly for its aesthetic qualities, its practical purpose is to keep the elements out. The windows and roof must be watertight, and windows are often treated with coatings that will keep too much sun (and thus heat) from shining through.

To figure out how strong a building must be to resist earthquakes or windstorms, the writers of building codes look to several decades of historical weather data. For a specific region, Friedman explains, "you have a certain size storm that, on average, will show up once every 100 years. That's called a 100-year storm. There's also 500-year storms, and 100-year earthquakes and 500-year earthquakes." Those statistics will help give a rough estimate of what weather a geographic region can expect over time. But what about differences in, say, wind patterns from one block to the next?

For these micro-level estimates, engineers send their skyscraper design to a lab that specializes in wind tunnel simulations. One of the most famous labs is Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario. There they use tiny scale models of the world's major cities to test a proposed building's outer shell, sway and structural load, as well as what kind of winds it will produce for nearby pedestrians.

Going Up?



Using a machine to lift goods is not modern technology. In ancient Greece, Archimedes used hoisting ropes attached to a pulley; and the Roman gladiators rode elevators up to the top arena of the Colosseum. But the engine-controlled elevator didn't come about until the mid-19th century, where it was used mostly by workers in factories, mines and warehouses.

In 1853, American Elisha Otis invented a safety device that, in case a cable should break, prevented a freight elevator from falling down the shaft. With this assurance of safety, so grew the idea of elevators to carry people. Big cities of the early 19th century saw the construction of large and luxurious hotels that "always showcased the latest in technology," says Lee Gray, associate dean of the College of Architecture at the University of North Carolina-Charlotte and elevator historian.

When the first passenger elevator was installed in a New York Fifth Avenue hotel in the late 1850s, it was described as a "movable room," complete with benches and a chandelier. Although its ascent was painfully slow, "the idea wasn't speed," Gray explains, "it was gracious living."

In the 1870s, the passenger elevator moved to the office building. "And that's where our modern concept of the elevator comes from," Gray says. "When you're in an office building, it's about speed and fast-paced business."

The old hotel elevators were powered by steam, as were the first office elevators—but not for long.

Steam-powered elevators were soon replaced by cheaper, quieter hydraulic elevators. The hydraulic elevator car sits atop a heavy piston, moving in a cylinder. The piston moves up and down by water pressure produced by pumps.

Though a few hydraulic elevators are still in use today, their speed is ultimately limited by how fast you can move the piston. To be of practical use in an office building of 10, 20 or 50 stories, elevators had to be much faster. The need for speed led to the development of the electric elevator, first built by German inventor Werner von Siemens in 1880.

Though many historians say the skyscraper would never have been possible without the invention of the elevator, Gray says this perspective "oversimplifies what is a really wonderful story of technology." The steam elevator allowed buildings to grow taller. But the subsequent demand for even taller buildings spurred the technology of faster elevators. "I think of it as a technological dance," he says. "Yes, the elevator made the skyscraper possible. But without the skyscraper we wouldn't have the modern elevator."

THEN AND NOW

Advances in computer technology in the last 20 years have certainly changed the way skyscrapers are designed and constructed. After she graduated from engineering school in 1983, Arbitrio recalls that nobody really knew how to use CAD (computer-aided design). She shared a phone line with three other co-workers. "The whole pace was just much slower," she recalls. "Nobody has that luxury anymore. Between e-mail and faxes and phones, we're all connected to each other all the time."

Has the modern age also changed the skyscraper's cultural and economic significance? The first skyscrapers, Friedman says, "represented the high technology of that era." But in the hustle-bustle pace of the 21st century, these past technological marvels, perhaps, are no longer so breathtaking. "Every little city … now has its own group of skyscrapers," he adds. "People used to come from all over to see them, go look out of a window at the top, and be faint. That doesn't really happen anymore."

Many historians have argued that skyscraper technology began with an economic push, and that all subsequent skyscrapers were built for the same reason: to make money. The cost of a skyscraper is astronomical—the 4.25 million square-foot Petronas Towers, built in Kuala Lumpur, Malaysia, in 1998, cost $1.6 billion—but owners expect to make back their initial investment, and more, from high-rent tenants. "It's certainly true that no one's going to invest in a skyscraper without the expectation of making money," Friedman says. "But if that's all there was to it, we would never have gotten past the cookie-cutter box buildings of the 1960s."

Indeed, no one who's ever seen a skyscraper up close, even in fast-paced 2007, could doubt its significance. The 9/11 attack on the World Trade Center, after all, was meant as a symbolic blow to America's identity. And the Empire State Building, old and rundown as it is inside, gets 4 million tourists each year. Now, with almost half of the world's population living in urban centers, there's little doubt that skyscraper technology will continue to evolve. And in that sense, the sky's the limit.

Why the World Trade Center Fell

After two jets crashed into the World Trade Center on September 11, 2001, the slow collapse of its 1,368-foot-tall twin towers changed forever the skyline of New York City and the political dynamic of the world. The first tower to be hit, the north, stood for an hour and 40 minutes after impact, while the south tower lasted for 2 hours and 59 minutes—saving the lives of thousands of tenants working on the floors below.

Immediately after the tragedy, the American Society of Civil Engineers (ASCE) began a study to investigate the structural cause of collapse. (Completed in May 2002, its report served as the foundation for the three-year investigation later done by the National Institute of Standards and Technology.)

"We started just like any other forensic job," says structural engineer W. Gene Corley, team leader of the ASCE report, who also was the principal investigator for the Federal Emergency Management Agency's (FEMA) study of the bombing of the Murrah Building, in Oklahoma City. The team first assembled as much raw data as it could, including the towers' original design plans; the weight, fuel loads and speed of the planes; and the distribution of fireproofing on each floor. "Then we did as many calculations as we could in the short time we had to try and figure out why this happened," Corley says.

Though newspaper reports following the attacks described them as explosions, "there wasn't really an explosion in the normal sense," Corley says. "The fireball that occurred with each crash is really what's called deflagration"—the rapid burning of very fine particles of fuel. "It'll break windows, do minor things like that, but won't cause any damage to the structure."

The structure fell because of the heat. The fire produced by the crashes was so immense, Corley says, "that there was no hope of ever putting it out. It just had to burn out on its own." With any structural material, including steel, heating it up makes it lose strength. In the meantime, the impact had jarred loose much of the fireproofing from the columns and the floors. Corley says this was most likely the trigger of the final collapse: "the sagging of the floors pulled the exterior columns in so far, that finally they just couldn't carry the load."

Still, Corley finds it amazing that the towers stood as long as they did, especially considering that two-thirds of the exterior columns were either gutted completely or incurred significant damage. "That engineering certainly saved lives. Ninety-nine percent of the people below where the plane hit got out alive. Most other buildings would have collapsed much sooner."

The 20 Tallest Buildings of Today (and Tomorrow)

Rank	Name, Place, Year Built	Stories	Height (ft.)
1	Taipei 101,Taipei, Taiwan, 2004	101	1,667
2	Petronas Towers, Kuala Lumpur, Malaysia, 1998	88	1,483
3	Sears Tower, Chicago, 1974	110	1,451
4	Jin Mao Building, Shanghai, China, 1999	88	1,381
5	Two International Finance Centre, Hong Kong, 2003	88	1,362
6	CITIC Plaza, Guangzhou, China, 1996	80	1,283
7	Shun Hing Square, Shenzhen, China, 1996	69	1,260
8	Empire State Building, New York, 1931	102	1,250
9	Central Plaza, Hong Kong, 1992	78	1,227
10	Bank of China, Hong Kong, 1989	70	1,205
11	Emirates Tower One, Dubai, UAE, 1999	54	1,165
12	Tuntex Sky Tower, Kaohsiung, Taiwan, 1997	85	1,140
13	Aon Center, Chicago, 1973	80	1,136
14	The Center, Hong Kong, 1998	87	1,135
15	John Hancock Center, Chicago, 1969	100	1,127
16	Shimao International Plaza, Shanghai, China, 2005	60	1,093
17	Minsheng Bank Building, Wuhan, China, 2006	68	1,087
18	Ryugyong Hotel, Pyongyang, North Korea, 1995	105	1,083
19	Q1, Gold Coast, Australia, 2005	78	1,058
20	Burj al Arab Hotel, Dubai, UAE, 1999	60	1,053

In development …

The Burj Dubai, in Dubai: Scheduled to be completed by 2009, the exact height of this pointy tower of glass is secret. Rumor has it it's supposed to be at least 162 floors and 2,651 feet high, making it the tallest building in the world.

The Shanghai World Financial Center: With a distinctive square hole at the top of its 101 floors, this building is rumored to be 1,614 feet tall and also is scheduled for completion in 2009.