The Sky's the Limit

Citicorp Center
(New York City;
915 ft; 1977)

Empire State Building
(New York City;
1,250 ft; 1931)

World Trade Center
(New York City;
1,368 and 1,362 ft; 1972 and 1973)

Sears Tower
(Chicago;
1,450 ft; 1974)

Future skyscrapers will lift high-rise technology to new heights. But the economic challenges are daunting

by Alden M. Hayashi

They stretch toward the sky, piercing clouds as they soar to spectacular heights, majestically mocking gravity and humbling everything on the ground below. The Empire State Building, the Sears Tower, the Petronas Twin Towers. These heavenly high-rises, surging well past 1,000 feet (300 meters), have been a striking testament to humankind's technological strength throughout the 20th century.

And the progression skyward promises to continue. The São Paulo Tower, the Shanghai World Financial Center and 7 South Dearborn in Chicago are among the proposed structures looking to join this elite group of the supertall. The new superskyscrapers, representing a variety of daring structural concepts, will test the limits of high-rise

Central Plaza
(Hong Kong;
1,227 ft; 1992)

Bank of China Tower
(Hong Kong;
1,209 ft; 1989)

Jin Mao Building
(Shanghai;
1,380 ft; 1999)

Petronas Twin Towers
(Kuala Lumpur;
both 1,483 ft; 1997)

Jakarta Tower
(Jakarta;
1,830 ft; proposed)

Shanghai World Financial Center
(Shanghai;
1,509 ft; planned)

technology. Space frames, aerodynamic tuning, intelligent elevators and computerized damping systems are but a few of the innovations pushing building heights toward 2,000 feet.

But whether any of these structures makes it from the drawing board to reality is, more than anything else, a financial issue. "If you had enough real estate, you could build a building to the moon," declares Leslie E. Robertson, one of the world's leading structural engineers. Understanding the crucial economics of superskyscrapers requires a quick lesson in engineering and some basic arithmetic.

For millennia, buildings have waged an ongoing battle with the implacable forces of nature. As high-rises stretch higher, the advantage increasingly goes to nature. First, there is gravity. In a high-rise, a typical column at street level must support not only the nearby area on the second floor but also the cumulative weight of each respective portion of every story above that.

But the real test of a building is its ability to withstand hurricanes and earthquakes. To prevent those lateral forces from toppling a structure, its base must be sufficiently wide. For stability, the height of a skyscraper divided by its width typically must be between six and eight. This so-called aspect ratio for the Sears Tower in Chicago, for example, is 6.5 (the building's height of 1,450 feet divided by its width of 225 feet). So a 2,000-foot high-rise might need to be about 330 feet wide. Thus, the footprint of a superskyscraper could easily consume multiple city blocks. Obviously, finding the necessary real estate is a difficult—and expensive—proposition,

São Paulo Tower
(São Paulo; 1,624 ft;
proposed)

7 South Dearborn
(Chicago; 1,537 ft;
proposed)

Landmark Tower
(Hong Kong; 1,883 ft;
proposed)

Citygate Ecotower
(London; 1,509 ft;
proposed)

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particularly in congested areas like Tokyo and Manhattan.

To finance such extravagance, developers need rentable space—and lots of it. “Rentable” for an office building in the U.S. means that the maximum distance to a window should be less than about 50 feet. Meeting that requirement in a high-rise hundreds of feet wide is no simple matter.

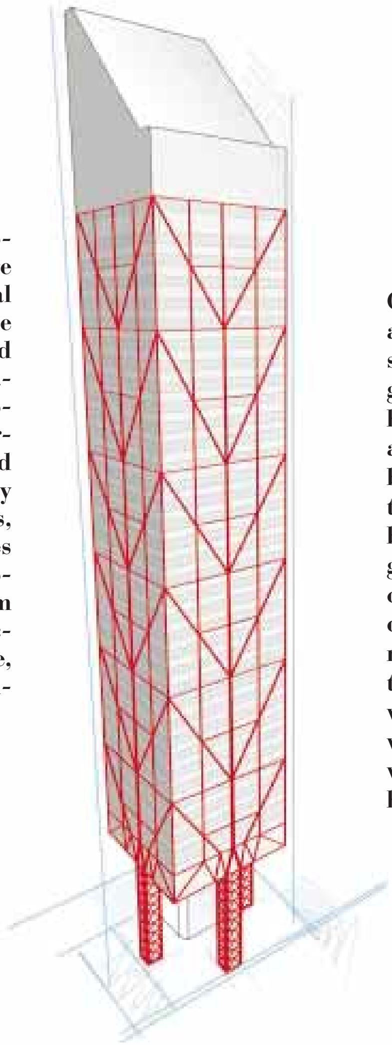
Consequently, many experts contend that constructing taller buildings is not merely a matter of simple scaling. “There will have to be changes in the way people think about supertall structures: they have to become more efficient, otherwise they’ll be too costly,” asserts Robertson, who is the director of design for Leslie E. Robertson Associates in New York City.

Already structural engineers have been rethinking their strategies for combating the wind, perhaps the single most important factor in the design of supertall structures. Consider that as a building’s height rises, the wind effects increase dramatically. Wind speeds are greater at higher elevations, and the wind pressure is related to the square of the velocity. Taller buildings also have a larger surface area for the wind to push against, and their additional height gives the wind a longer lever to topple them. For a 100-story skyscraper, the wind is the primary factor dictating much of the building’s structure, even in earthquake-prone regions like Los Angeles.

Gusts of wind can be particularly dangerous when they come spaced in intervals that approach a building’s nat-

Disinheriting the Wind

Of the total cost of a high-rise, a substantial proportion—sometimes more than one third—goes to its structural skeleton. (Other big-ticket items include the building's architectural facade and mechanical systems, such as the elevators, automated window-washing equipment, and heating, ventilation and air-conditioning.) The beams, columns and other structural members must not only support the building and its contents, they must also withstand earthquakes and—more important for superskyscrapers—high winds, including those from hurricanes. To combat such severe forces, which could easily topple a high-rise, engineers have devised ingenious solutions [*see illustrations through page 72*].



CITICORP CENTER: The triangle is an inherently strong shape. In the Citicorp Center, giant steel diagonal bracing, hidden behind a glass-and-aluminum facade, stiffens the building to resist swaying and twisting from the wind. At the building's base, smaller triangular bracing within massive columns enables the corners of the high-rise to be truncated, resulting in a striking architectural effect. After the Citicorp was built, its bracing system was reinforced with additional welded steel to resist strong hurricanes.

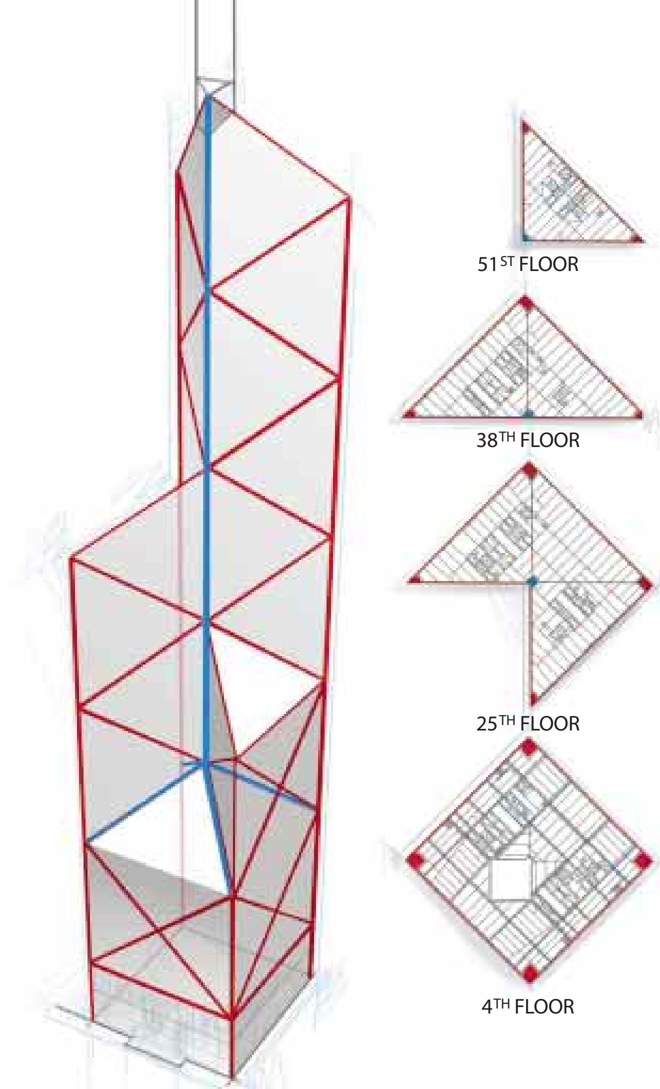
ural period: the amount of time the structure takes to complete one oscillation when it is swaying back and forth. In such situations, the wind can amplify the building's swaying—a physics phenomenon known as resonance. At the very least, such movement can cause motion sickness, along with aesthetic taboos such as swinging chandeliers and water sloshing in toilet bowls.

Interestingly, even a constant, uniform wind (essentially a "static" force) can lead to dangerous dynamic phenomena, including vortex shedding and flutter. With vortex shedding, a wind that blows around a high-rise creates alternating eddies, or vortices, that spin off the sides of the building, causing it to sway in a direction perpendicular to that of the wind. And when an object starts to oscillate, that motion can itself create its own airflow that can then make the building vibrate even more, a troublesome condition known as flutter. In addition to bending back and forth and swaying sideways, buildings can twist, and these various motions can reinforce one another. "Usually, with very tall buildings, the [wind] dynamics are just as important, if not more important, than the static aspect," avers Alan G. Davenport, director of the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario.

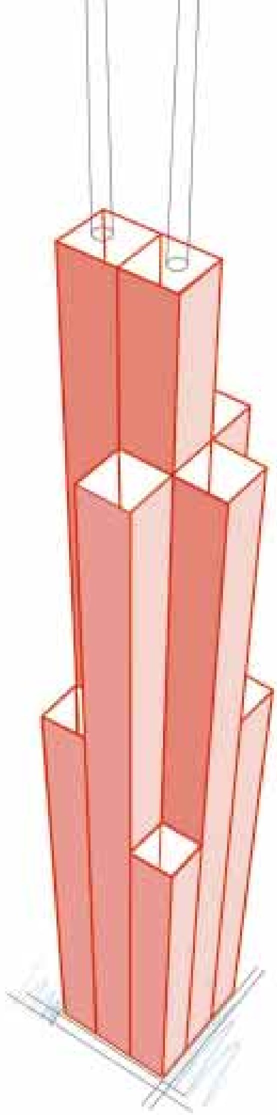
Therefore, architects and engineers have been paying greater attention to a building's aerodynamics. Generally speaking, uniform shapes—for example, a tall rectangular box—induce more vortex shedding than tapered buildings do. "Basically, you want to confuse the wind and inhibit its ability to build up significant forces," says Adrian Smith, a design partner with Skidmore, Owings & Merrill (SOM) in Chicago.

Smith's current project—the 112-story 7 South Dearborn, planned for Chicago—has an articulated shape reminiscent of an extended telescope [*see illustration on preceding page*]. And between its different cylindrical sections, the building has large notches (two to three stories high), where it recesses back to its center concrete core. "The notches are such that the wind never has a chance to set up a strong rhythm," Smith says. With the Shanghai World Financial Center, a dramatic opening—160 feet across (approximately the wingspan of a jumbo jet)—through the top of the 94-story tower helps to relieve wind forces.

Thanks to wind-tunnel tests and computer simulations, architects and engineers can fine-tune a build-



BANK OF CHINA TOWER: In a conventional braced-frame structure like the Citicorp Center, the frame exists in planes that are typically perpendicular or parallel to one another. With "space frames," a skyscraper like the Bank of China Tower can take full advantage of three-dimensional space. For example, note how the column that runs through the center of the building sits on the apex of a skeletal pyramid (*blue*) that is supported by the corner columns. The architect, I. M. Pei, modeled the building after a bamboo shoot, in which each new growth pushes the main stalk successively higher.



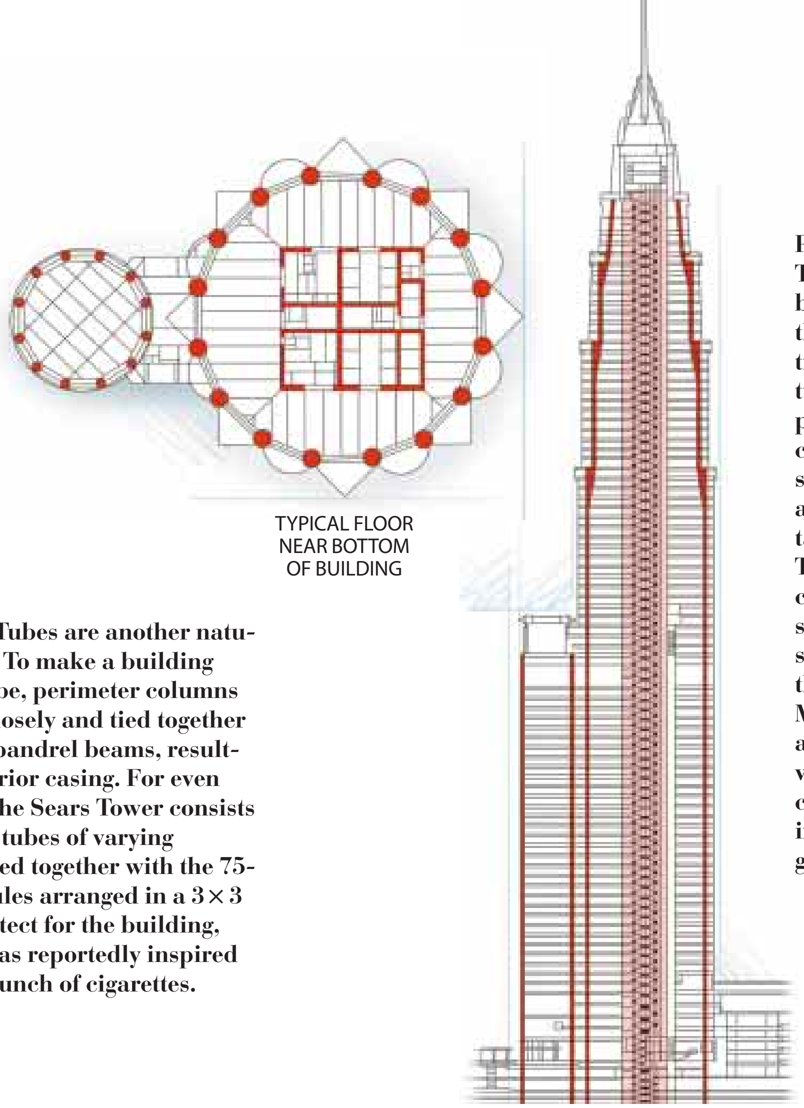
ing's shape, surface and structural characteristics (overall rigidity and mass, for example) to achieve optimum designs for withstanding high winds. Such modeling can also help determine if a new building will lead to dangerous gusts on the street below. "The shapes of superskyscrapers will start to be driven by their aerodynamics," predicts Charles Thornton, chairman of Thornton-Tomasetti Engineers/LZA Group in New York City.

Further assistance can come from mechanical systems that absorb, or dampen, a building's vibrations. The Citicorp Center in New York City has deployed a 400-ton concrete block connected by a spring and hydraulic piston (functioning as a shock absorber). On windy days, the so-called mass damper, located on a floor near the top of the high-rise, moves in opposition to the structure's swaying, sliding on oil to help dampen oscillations by as much as 50 percent. The World Trade Center in New York City relies on a sticky polymer coating sandwiched between steel plates. Thousands of these viscoelastic dampers have been inserted between columns and beams; when the building sways, friction between the plates dampens the motion.

For future skyscrapers, some experts foresee more aggressive systems with servomechanisms that use microelectronics and robotics to produce forces in counterdirections to the wind and earthquakes. "With the current technology, an aspect ratio of 10 is absolutely feasible," says Thornton, who was the structural engineer on the 1,483-foot Petronas Twin Towers. "And with more active damper systems, you can go to 15, maybe 20."

There are other ways to skin the proverbial cat. The Maharishi Mahesh Yogi, famous for teaching transcendental meditation to the Beatles in the 1960s, has plans for supertall buildings in India, Florida and São Paulo. The tallest of the trio, scheduled for India, will have an astounding height of 2,200 feet. The interesting thing about the pyramid-shaped skyscrapers is that they will have a hollow core.

An advantage of such structures is that windows can be located on the inside, perhaps overlooking a spacious atrium, making the interior space more attractive—and rentable. But such a maverick design poses huge technical challenges. For one, in a typical building the floors act as diaphragms to secure the walls, making the overall structure more rigid against the wind. Hollow buildings, on the other hand, do not have that kind of inherent lateral stability. "The walls will kind of billow in and out," says Robertson, who is working on the buildings with



SEARS TOWER: Tubes are another naturally strong form. To make a building function like a tube, perimeter columns must be spaced closely and tied together at each floor by spandrel beams, resulting in a rigid exterior casing. For even greater stability, the Sears Tower consists of nine such steel tubes of varying heights, all bundled together with the 75-foot-square modules arranged in a 3 × 3 matrix. The architect for the building, Bruce Graham, was reportedly inspired by the sight of a bunch of cigarettes.

PETRONAS TWIN TOWERS: Tubes do not necessarily have to be uniform, square and steel, as in the Sears Tower. Each of the Petronas towers is a tapered circular tube with concrete columns on the perimeter. The interior concrete core that surrounds the elevator shafts also provides stability against the wind, as does the attached, smaller circular "bustle." These tall skyscrapers require concrete with a compressive strength of 12,000 pounds per square inch (psi), more than twice the 5,000 psi commonly used in Malaysia. The improvement was accomplished by the addition of very fine particulates that increased the surface-contact bonding between the cement and the gravel in the concrete.

Minoru Yamasaki Associates in Rochester Hills, Mich., the architectural firm that designed the World Trade Center. The preliminary drawings call for a giant "space frame," an efficient type of structure that Robertson used successfully in the 1,209-foot Bank of China Tower in Hong Kong [*see illustration at above left*].

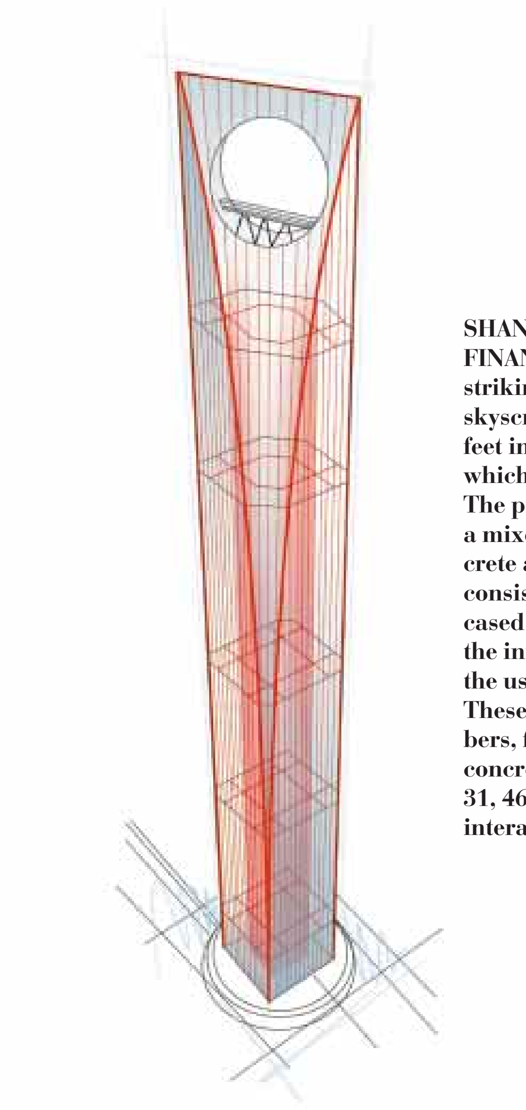
Many structural engineers predict that future superskyscrapers will be an extensively symbiotic mixture of concrete and steel. Concrete, an ancient material, provides excellent compressive strength, considerable mass to limit accelerations from wind, and good damping qualities because it will undergo harmless microcracking to absorb and dissipate energy. But concrete is weak in tension: when a strong wind pushes a building, the concrete columns on the windward side may stretch and begin to crumble. That's where steel comes in. "The trick is to use each of the materials for what it does best," notes John Zils, a structural engineer with SOM. As a striking sign of this trend, the 1,380-foot Jin Mao Building, which was recently completed in Shanghai, has a number of horizontal steel trusses that tie the building's concrete core to its exterior concrete and steel megacolumns.

Structural materials will not be the only composite thing about superskyscrapers. For economic reasons, many of them will have a mixed occupancy. For instance, 7 South Dearborn will include parking, offices and residences, with the top stories reserved for communications equipment for the building's 500-foot HDTV antenna. "Mixed use helps to make a building economically viable; the real-estate market cannot often bear several million square feet of office space being put onto the market at one time," says Smith, the lead architect on the project.

But mixed use can complicate a building's design. If a high-rise contains just offices, for example, the engineer can assume that workers won't be there during a typhoon. But if the office tower has a hotel tacked onto its top—as is the case with the Jin Mao and the planned Shanghai World Financial Center—engineers must minimize the acceleration of the building during a storm or risk motion sickness among the hotel guests.

Such technical challenges are nothing new to the architects and engineers of high-rises. Indeed, the century-old history of skyscrapers is replete with advancements in ancillary technologies, such as fluorescent lights, which enabled the relatively cool illumination of interior offices. It is ironic that elevators, which made it possible for high-rises to be built in the first place, have now become a major stumbling block.

For any building of noteworthy height, the elevator system consumes an immoderate amount of floor space: each of the



SHANGHAI WORLD FINANCIAL CENTER: The most striking feature of this elegant skyscraper is the large hole (160 feet in diameter) through its top, which helps to relieve wind forces. The preliminary drawings call for a mixed design using both concrete and steel. The exterior tube, consisting of steel columns encased in concrete, will be tied to the interior concrete core through the use of large "outrigger beams." These story-high structural members, fabricated from steel and concrete, will occur on floors 16, 31, 46, 66 and 80, resulting in an interactive composite system.

twin towers of the World Trade Center contains 99 elevators, for instance. "With supertall buildings you need to do very clever things or else you'll end up with a ground floor of just elevators," cautions Lynn S. Beedle, director emeritus of the Council on Tall Buildings and Urban Habitat at Lehigh University.

Part of the problem with elevators is speed. The human ear is slow to adapt to changing pressure, which restricts the acceptable speed of descent to a maximum of 2,000 feet per minute and ascent to 3,000 feet per minute. (Decreasing pressures are more tolerable than increasing ones.) Interestingly, the maximum acceleration—the "jerk"—is also limited by passenger comfort and by the bladder control of pregnant women.

Because of such factors, engineers have worked on increasing the efficiency of elevators, resorting to double-decker cars, such as those used in the Sears Tower to service even and odd floors simultaneously, and to transfer systems that deploy express and local elevators. A future advance might include cableless operation: the cars would be powered by their own motors and run on tracks, possibly with more than one car in the same hoistway. Other innovations include the use of fuzzy logic and neural networks in the dispatching system to decrease waiting times, particularly in peak traffic periods.

Recently, Schindler Elevator Corporation developed a clever system in which passengers enter their destinations on a keypad near the elevator bank, and the system responds by displaying which car they should take. Behind the scenes, a control computer efficiently groups people with the same destinations together in the same car, thus minimizing the number of stops people will have to endure before reaching their destinations. Schindler claims that the system could help reduce the number of elevators in a typical office building by as much as 25 percent.

Such technological advances are desperately needed to make superskyscrapers more economical. "None of these structures are cheaper as a single building than they would be as two buildings at half the height," admits SOM's Smith. As a cautionary note, the $800-million Petronas towers, which were completed in 1997, have stood just half full, mainly with government and Petronas employees. "One may ask whether it's rational to build much taller. Doesn't the tallness race become nothing but an egomaniacal gesture at some point—a form of high-profile indecent exposure?" wrote Paul Gapp, architecture critic for the *Chicago Tribune.*

To be sure, the issues are numerous. What kind of shadow will the new building cast? How will it affect the local real-estate market? Will traffic in the area become too congested? Will the skyscraper be a potential danger to airplanes? (Because of such concerns, the Taipei Financial Center, which at 1,667 feet was supposed to have become the world's tallest building, is currently being downsized.)

That said, there is a certain undeniable prestige that comes with height. In Malaysia, national pride helped push through the construction of the Petronas towers, a pet project of Prime Minister Mahathir Mohamad. Another intangible yet powerful factor is the egos of developers.

Nevertheless, a high-rise that doesn't make sense financially is a high-rise that will have trouble leaving the drawing board. Thornton, a veteran of the industry, has these words of wisdom: "Most of the world's tallest buildings that are proposed never happen."

About the Author

ALDEN M. HAYASHI is the coeditor of this issue of *Scientific American Presents.* At age four he constructed his first "skyscraper," a two-foot-tall tower of Legos.