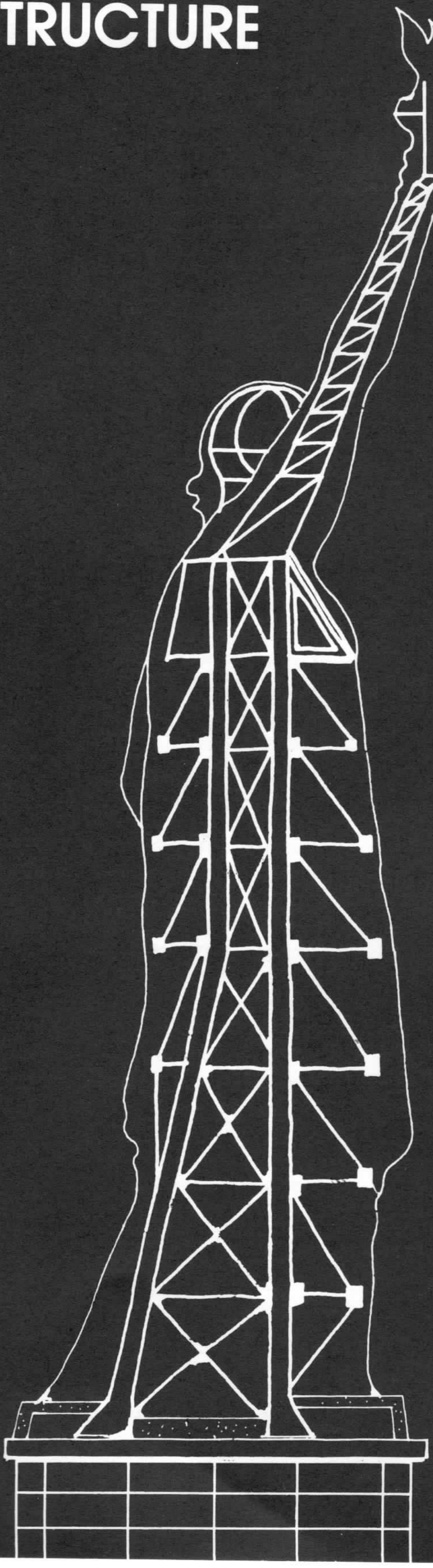
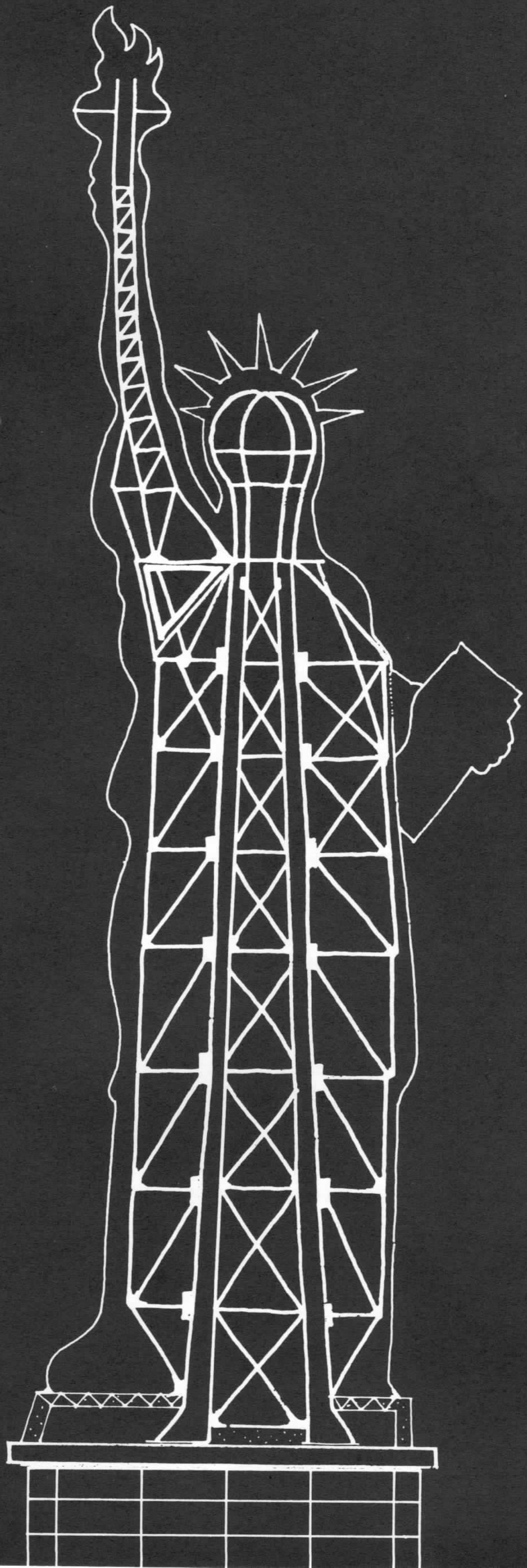
aaas SCIENCE RESOURCES FOR SCHOOLS

VOL. 2, NO. 2

IDEAS IN SCIENCE

STRUCTURE





Structure

The Statue of Liberty and a tall tree look very different. Yet they are very similar. Each is a structure, connected to the earth and able to withstand the forces of gravity and heavy winds. Weight and wind either push on the structure or pull it. The parts of the structure react by shrinking or stretching. The same actions and reactions occur in large structures like the Statue of Liberty, trees, suspension bridges, and skyscrapers as in small structures like cornstalks, street signs, and spider webs.

Students can learn about the science of structure by experimenting with physical models of structures. Working with materials is essential to developing an understanding of structure. Students can gain useful insights by building models with simple materials. Building life-size or model structures has long been a fascination of both adults and children. Exploration that starts out with wooden blocks and tinker toys, and progresses to specially prepared model-making kits, can eventually culminate in the building of one's own house.

The *Doing Science* activities in this packet show how a variety of structures can be made with plastic drinking straws joined together with pins. The activities have been carefully selected to help students learn about one kind of structural design —the truss.

The truss is used in structures ranging from the commonplace slanted roof on houses to the space frame that supports the expansive roof of an indoor shopping center. The truss is common in bridges and electric transmission towers.

The *Doing Science* activities focus on experiencing how structures react to forces, how the triangular design of a truss contributes to the rigidity and stability of a structure, and how the forces of tension and compression differ.

In the *Doing Science* activities the students build and study the frames of model houses and roofs, model bridges, and model towers. The importance of active involvement with materials will become apparent during these activities. Students often will design and build a roof or a bridge similar to ones they have seen, but questioning can discern whether they have merely imitated the structure without understanding why it works. When they test their model by hanging weights on it, they will begin to see how the structure functions—what parts of a structure are in tension, what parts are in compression. To discover how to make the structure stronger, they will first have to analyze how the weights act on a roof or a bridge and then visualize the best possible geometric arrangement of straws to counteract the weights. These two skills of analysis and visualization are fundamental to the sciences.

Building and analyzing models can be a real source of satisfaction for students. Much of schooling is oriented around "payoffs" that are years away. Construction of physical models, on the other hand, is an involvement of mind and hands with results that are immediate. Students achieve personal satisfaction and learning in trying out their own ideas. They receive a special sense of fulfillment in starting such a project and completing it. There is also "payoff" in the future, for experiential understanding of phenomena informs later, more formal study of the phenomena.

Figure 1 a. The structure of a tree.

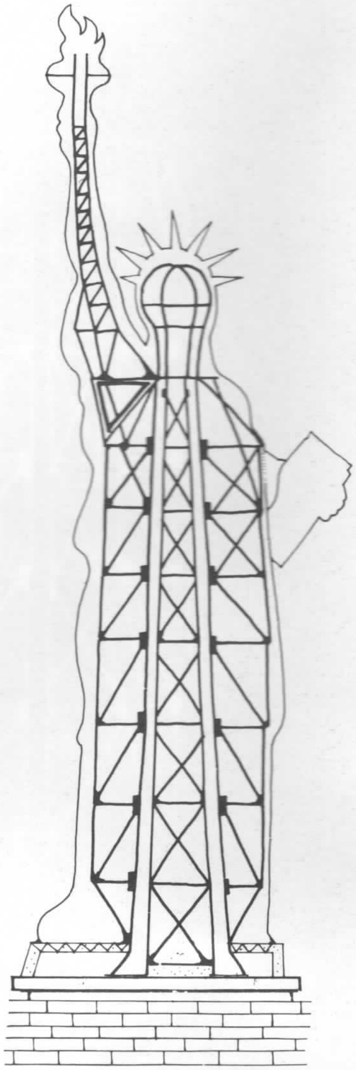


Figure 1 b. The Skeleton of the Statue of Liberty.

The Message of Structure

Figure 2 The Golden Gate Bridge, San Francisco.

Structure in nature and technology informs and satisfies our feelings and emotions. It evokes understandings of the world around us through experience with structural actions and forms.

Structure elicits in us a range of feelings. It satisifies our need for beauty and order. For example, we see majesty in a mountain such as Mt. Fuji (Japan) or a Gothic cathedral, gracefulness in a delicate spiderweb or the Golden Gate Bridge, strength in a big oak tree or a tall construction crane, elegance in a peacock's feather or the Eiffel Tower, and harmony in the workings of the human anatomy or a bicycle.

In turn, we give expression to our values and feelings in the structures we create—physical structures such as buildings, tools, machines, artifacts, clothing, and the nonphysical structures of our organizations, institutions, the arts, the sciences, literature, celebrations, and sports.

We encounter structure daily through our physical experience with structural actions and visual perception of structural forms.

Breaking a tree branch against your knee gives you an understanding of structural action from physical observation and muscular sensations. So does climbing up and down a hill.

When you walk, run, jump, bend, lift, and push you experience a variety of forces and sensations. Your muscles, bones, tendons, and ligaments work together as a system to effect the different movements and sensations. Your bones resist the pushing forces that your body encounters, while your muscles, tendons, and ligaments accommodate the pulling forces.

The branches of a tree, weighted by snow, wind, a squirrel, or fruit, visually suggest the action and behavior of cantilevers (beams supported at one end only). The large dimension of the branch is at the trunk or intersection; the slender dimension is at the tip. When you stand on the end of a diving board your body can sense the action of a cantilever.

The shape of a tree trunk introduces us to the requirements of designing for the cumulative gravity loads in tall buildings. Thus, we instinctively understand and accept the tapering of columns in buildings and monuments, and the tapering of towers and tall buildings.

In the Egyptian Pyramids, which have endured the forces of gravity and erosion over centuries, we can perceive a geometrically idealized shape equivalent to the shape of mountains. Indeed, we can see that stone is strong enough to support an entire mountain.

Domes such as in the U.S. Capitol, can also be understood in reference to experience with natural caves whose protective, curved interiors illustrate the compression strength of the arch's downward curvature.

The structural form of a sea shell is suited to protection. This form also has strong aesthetic content. Shells are ribbed in a variety of ways by which nature demonstrates methods of stiffening a curved three-dimensional surface.

A particularly striking example of the truss structure in nature is the form of the metacarpal bone in a vulture's wing. It is an example of a Warren truss. Compare Figure 3 with Figure 8 and the illustration of a Warren truss in *Doing Science* 3—"Building and Testing a Model Bridge."

Our experiences with structure evoke in us an intuitive knowledge of materials (wood, cement, bricks, steel, feathers, bones, muscles, tendons); knowledge of the effects of the forces of gravity and wind (tension, compression, shearing, buckling); and knowledge of geometry (triangles, rectangles, curved surfaces, symmetry). We acquire a sense of the distribution of forces on a structure, and a sense of action and reaction.

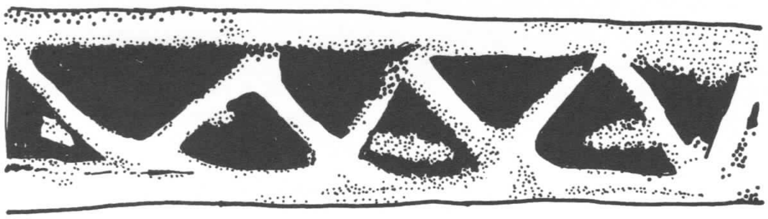


Figure 3 Metacarpal bone from a vulture's wing; stiffened after the manner of a Warren truss. From D'Arcy Thompson, On Growth and Form, *p. 236.*

Thinking About Structure

We are surrounded by man-made structures: houses, high-rise buildings, oil wells, bridges, radio towers, T.V. antennas, billboards, cranes, and furniture. Although these things differ in size and function, their designs share some basic similarities. Nature, too, surrounds us with structures. Leaves are so prominent on a tree that we tend to overlook the trunk and branching system that support them. Our bodies are intricate webs of tendons, muscles, and organs supported by a skeletal framework.

Buildings, bridges, and towers provide a useful introduction to the study of structure. To get yourself started, collect a box of plastic straws and some pins and try the following simple demonstrations with triangles.

Distinguishing Between Tension and Compression

To understand why the triangle is useful in structures it helps to visualize how parts of a triangle react to the forces exerted upon it. When a load is placed on a triangular structure, the horizontal member gets stretched. It is said to be under tension. The two side members react differently, because they are being pushed together, or being compressed.

You can demonstrate this for your class by building a straw triangle, each side made of two straws joined together as shown in Figure 4. When you gently push down on the top of the triangle the two sides will buckle out due to the compression, while the bottom side will come apart if the two straws have not been joined together too tightly.

This effect can be demonstrated in another way by substituting a piece of string for the bottom side of the triangle. Before pressing down on the triangle, the string is loose; after pressing, it becomes taut.

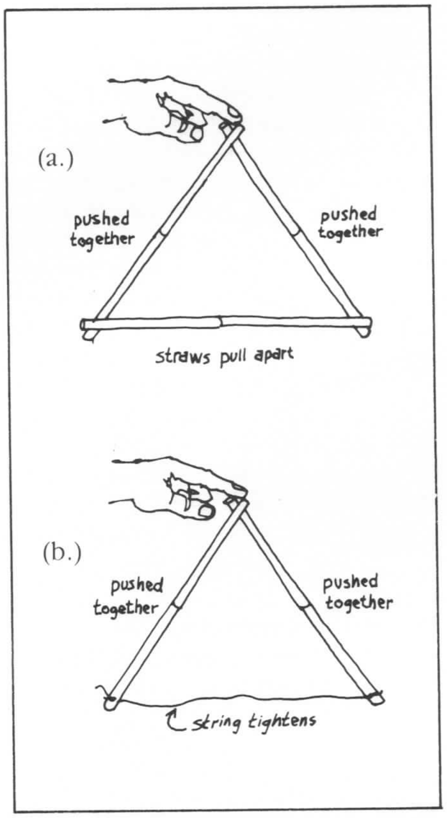


Figure 4 Sensing tension and compression in a triangular structure.

Students can identify directly with these forces by thinking about two kinds of actions in gymnastics. If you hang from a gym bar, your arms will be stretched and in tension. When you stand on your hands, your arms will feel as though they are being pushed down. They are in compression.

The triangular structure is very rigid. Unlike a square or pentagonal structure, it cannot change its shape without shortening or lengthening its sides. The geometric form of the triangle counteracts tension and compression from either vertical or horizontal forces. The use of triangular structures to achieve rigidity is common in houses, bridges, towers, and some skyscrapers.

House Structures

In a wood frame house diagonal braces and vertical studs help support the weight of the second and third floors and the roof. The triangles formed by the diagonals provide rigidity. Roofs of houses also exploit the structural properties of triangles. Consider the design of a slanted roof in Figure 6. In the simplest arrangement, a, the slanted portions of the roof rest atop the walls. This design is not very stable, since the weight of the roof can push outward and buckle the walls. Adding a horizontal beam, b, solves the problem of buckling and adds to the rigidity of the structure. If this beam is quite long, sagging can occur. In c, a vertical column is added to counteract sagging. The structure can be further reinforced by adding two other sections, as shown in d. The design of d is called a truss. The arrangement of triangles in a truss creates an especially strong and rigid form. The principles involved in its design can be applied, not only to houses, but to other structures, such as bridges and towers.

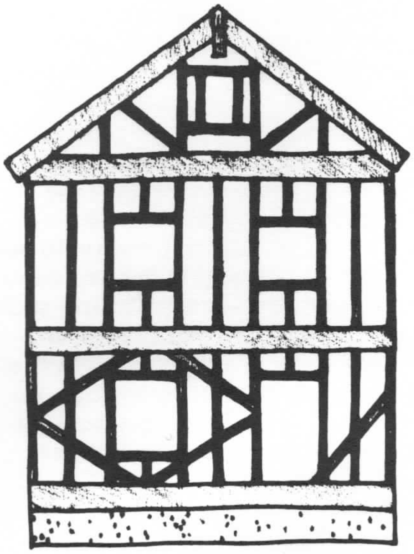


Figure 5 Triangles in a house frame.

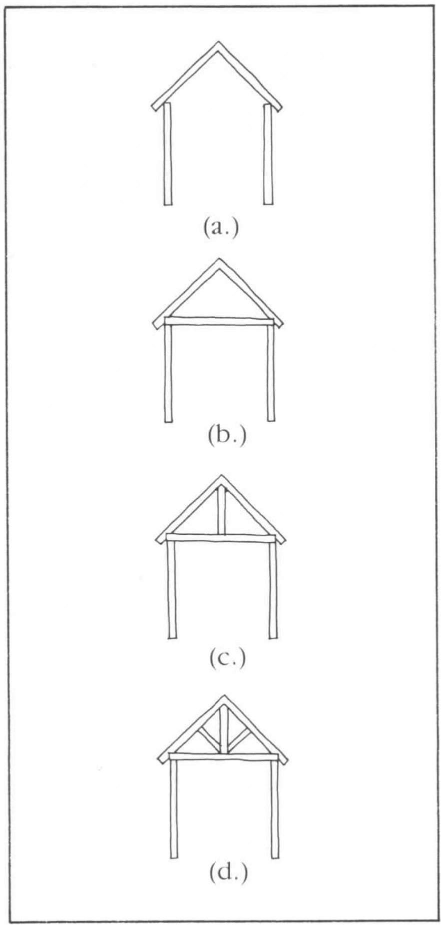


Figure 6 Triangles in roof design.

Bridges

In a certain sense a bridge functions in a manner similar to a slanted roof. Both sit on two end supports that channel all the loads carried by the structure. During colonial times in America a type of bridge resembling a simple roof truss was used to span small streams. Later, when the railroads moved westward, more elaborate truss bridges with multiple triangles were developed and built.

The concepts of tension and compression can be helpful in understanding how a simple bridge truss works. Build a bridge truss from drinking straws as shown in Figure 7. When you pull at the horizontal member, which parts of the structure start to buckle?

Substitute string for the middle members as shown and pull again. What happens to the string? The taut string indicates that these sections of the structure are in tension.

If you keep adding more triangles to lengthen the span of the bridge truss, you can demonstrate that the top members come under compression and the bottom members under tension, while the middle ones are in tension or compression depending on their location. In Figure 7c the shaded sections are in compression; the unshaded sections are in tension.

The entire frame acts together to support the load by a balancing of the tension and compression forces among the individual members of the truss. No individual triangle carries the whole load. The truss channels the load through its array of tensions and compressions.

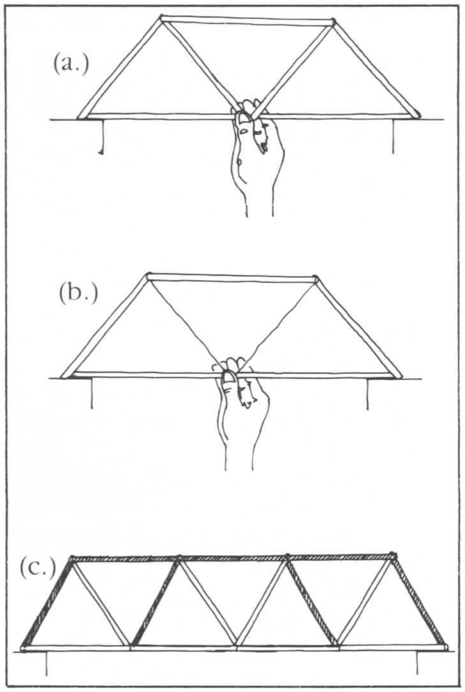


Figure 7 Sensing tension and compression in a bridge truss.

A variety of truss systems has evolved from the application of these basic principles of tension and compression. Several are illustrated in *Doing Science 3*.

If you look closely at bridges and towers that have their frameworks exposed, you can see that much of their bracing is in the form of trusses.

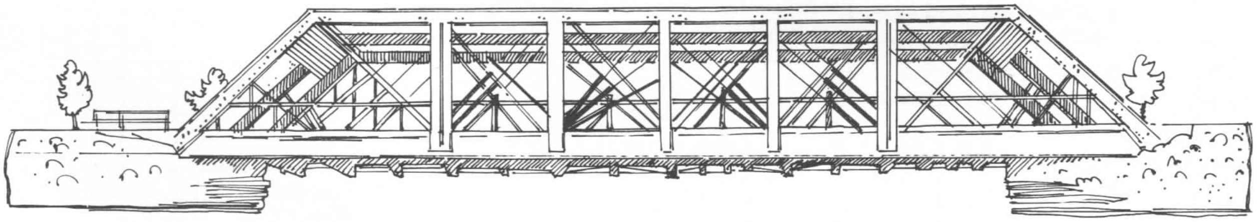


Figure 8 Railroad bridge.

Towers and Tall Buildings

The forces of tension and compression play a major role in the design of towers and tall buildings. The structure of a tower or tall building is typically made up of vertical columns, horizontal beams, and bracing to counteract bending and shearing. These components must channel the forces on the structure to the ground through the actions of tension and compression.

To get a sense of the design of towers and tall buildings, try the following exercises.

Form a straw tower by joining six or seven single straws together. What is needed to keep it from falling over? If you tape a penny to the top, the entire tower bends even more and swings slowly back and forth. The flexibility of the straws tends to make the tower unstable. You can sense the need for stiffness to make this straw tower stable.

To make a tower that is more rigid, form a tetrahedron with three single columns and a triangular base. The tower should be six or seven straws high. The triangular sides make your tower stiffer and more stable but there is still some bending and a tendency to buckle if you press down on its top.

To make it even more rigid try making each side a truss. Brace the sides with diagonal straws, and feel the increased stiffness and stability.

Tall buildings tend to be rectangular and not triangular. A notable exception is the Transamerica Building in San Francisco. You can get a sense of the need for rigidity in a tall building by making a rectangular framework out of straws. If you press down and sideways on the structure you find that it is subject to shearing, even with horizontal bracing along the sides. Form trusses on its sides, and feel the change in its rigidity.

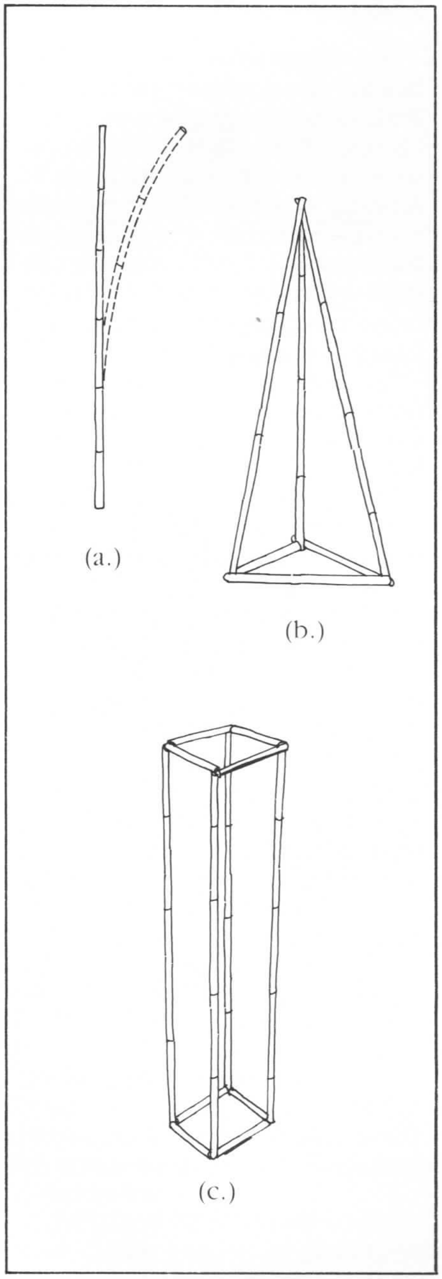


Figure 9 Sensing rigidity and stability in a tower structure.

Towers and tall buildings must accommodate two different forces —weight and wind. Their structures must be stable and stiff enough to withstand heavy winds. The action of tension and compression in a tall building under a lateral wind load is shown in Figure 10. On one side columns are being stretched and on the other side compressed. Through these actions the wind load is channeled to the ground.

However, the structures of towers and tall buildings are not completely rigid. In heavy winds they will bend and sway, although not enough to be seen from the ground with the naked eye. How much sway, depends on the building's structural design and dead weight. In a 100-mph wind the top of the Empire State Building was reported to have swayed 3 inches. The towers of the World Trade Center in New York City can sway up to 3 feet in a strong wind. You can get a sense of the wind's force by remembering what it is like to open an umbrella or carry a large piece of plywood on a windy day. A strong wind can push you to the ground.

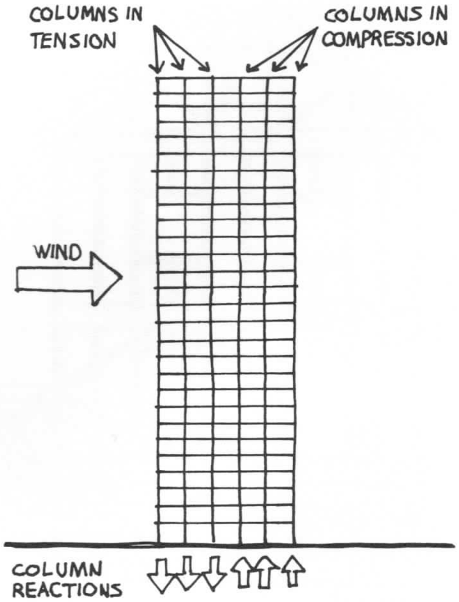


Figure 10 Tension and compression in a building structure.

Your kinesthetic sense of wind helps little in understanding how sharply the wind's effects on a tall structure change with height. Wind speed increases with height and wind pressures on a structure increase as the square of the wind speed. In addition, with greater height the force of the wind acts over a greater lever arm. For example, the wind atop the 1450-foot Sears Tower in Chicago is some fifty times stronger than atop a 200-foot redwood tree or a 200-foot high-rise apartment building.

To withstand high wind forces modern tall buildings incorporate two separate structural systems in their design—one to support building weight and the other to counteract the wind. Modern designs often employ a hinged frame to carry the vertical loads of weight rather than rigid connections between the beams and columns. A hinged frame, however, is not rigid enough to resist the wind. Under wind forces it will shear. So the design must have additional stiffening. In some buildings the hinged frame leans on a stiff inner core, inside of which run the elevators, pipes, and ducts. In other designs the outside walls of a tall building support the hinged frame. The inner or outer core resists the lateral forces of the wind and the hinged frame carries the vertical loads of weight.

The truss is one means of making the inner core rigid. The diagonals of the truss work in tension and compression to resist the force of the wind. An inner core of reinforced concrete is another way of accomplishing rigidity. The concrete counteracts forces of compression and reinforcing steel rods counteract tension.

The truss can also be used to make the outer core rigid, such as on the John Hancock Building in Chicago, shown in Figure 15. The World Trade Center towers in New York City achieve lateral rigidity with outside columns spaced only 3 feet apart and connected by deep outer beams. And the Sears Tower in Chicago achieves its rigidity by erecting nine square outer cores, one next to the other, in a pattern of three squares by three squares. It is like a bundle of tubes that reach up to different heights.

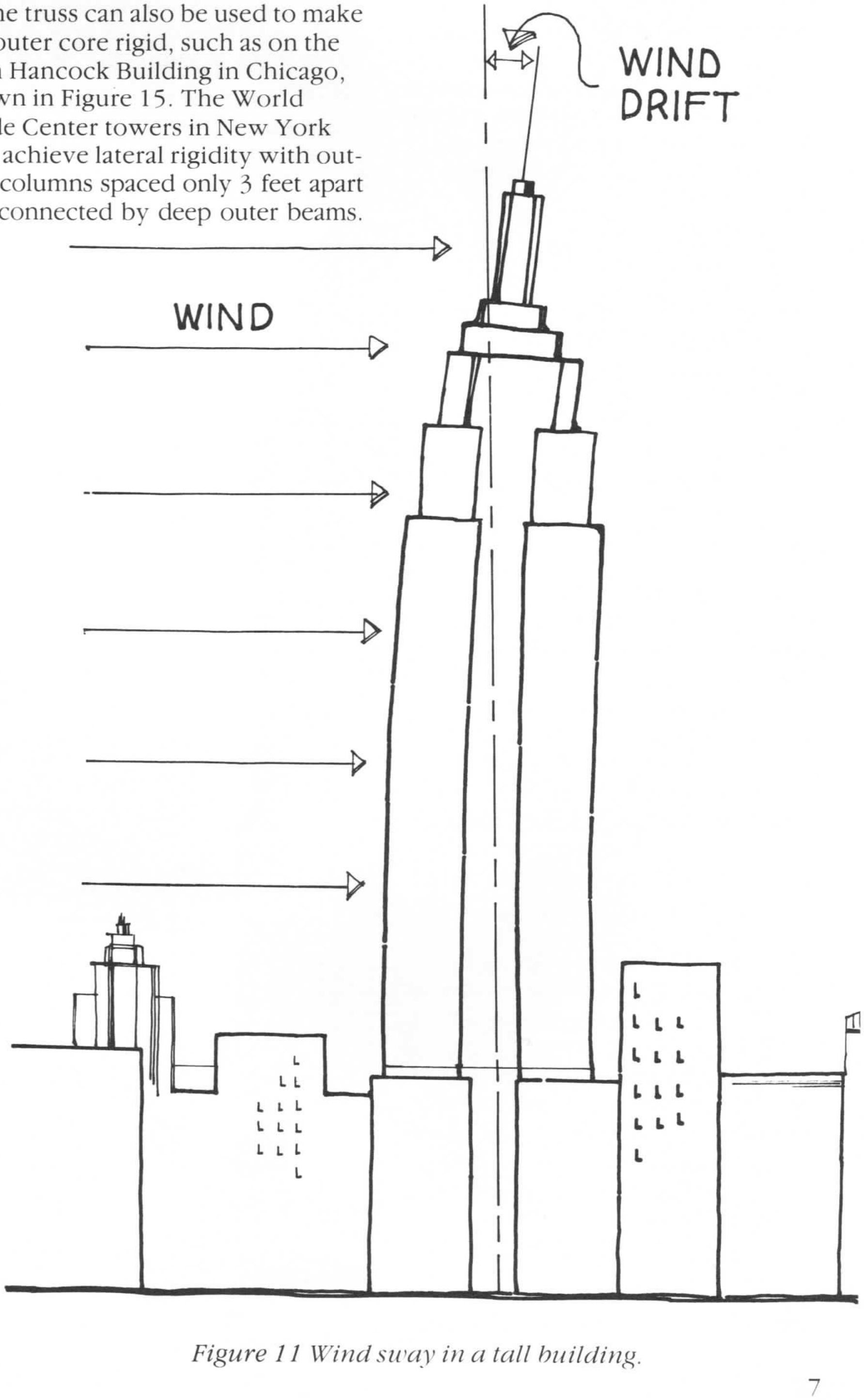


Figure 11 Wind sway in a tall building.

Skyscrapers

Skyscrapers symbolize many human values. For densely populated cities a skyscraper communicates efficiency. For business investors it represents financial return. For architects and builders the skyscraper is a conquest of natural forces and an achievement of beauty. The construction of a skyscraper is a civic drama of imposing magnitude, involving corporate presidents, city officials, real estate developers, banks, contractors, inspectors, architects, engineers, and hundreds of workers.

Today skyscrapers exhibit a diversity of structure with a variety of aesthetic messages. Most modern high-rise buildings are rectangular but there are round ones, as well as some with three to six sides. Some are grand mirrors reflecting the clouds, the sun, and other buildings. Some are massive fortresses of concrete or steel with smooth walls. A few show off textured sides, balconies, and sloping facades. Whatever their individual features, high-rise buildings have changed the appearance of cities, creating new skylines sometimes as impressive as mountain ranges.

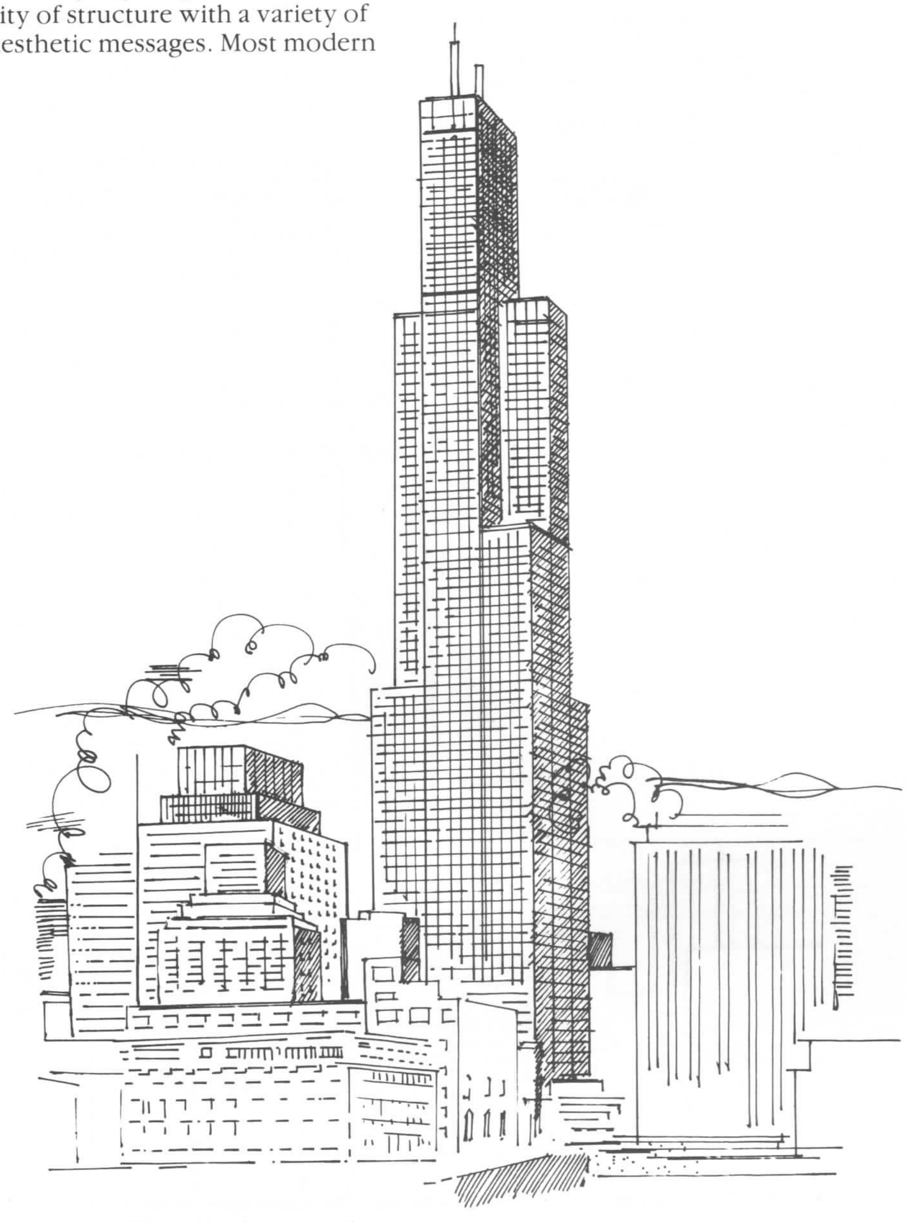


Figure 13 The Sears Tower, Chicago.

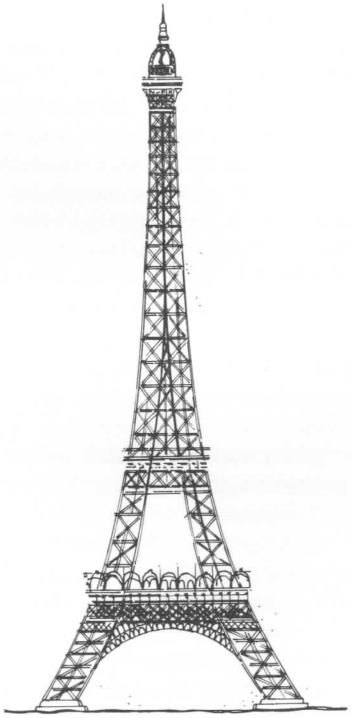


Figure 12 The Eiffel Tower.

The Eiffel Tower, nearly 100 years old, symbolizes the skyscraper's challenge to gravity and wind. It was completed in 1889 at a height of 985 feet, nearly twice as tall as the Washington Monument. This extraordinary steel structure was originally erected for an exhibition in Paris, providing a magnificent view of Paris. After the exhibition it was to be dismantled. But it did not take long for the Eiffel Tower to become not just one of the symbols of French culture, but a worldwide symbol. Its acceptance indicates not only a reversal of public opinion against its construction, but also the possibility of a pure aesthetic message communicated by a pure structure.

In 1913 the Woolworth Building in New York City was the first office building to reach 55 stories, soaring 791 feet to the sky. Only 18 years later, the Empire State Building reached 102 stories and 1250 feet in the sky. Today the Sears Tower in Chicago reigns as the tallest building in the world at 1450 feet. And Toronto claims the tallest self-supporting tower—the CN Tower—at 1815 feet.

Eiffel's triumph of design and construction engineering has strongly influenced modern skyscrapers. Like the Eiffel Tower and a Greek Doric column, a skyscraper is often narrower at the top and thicker at the bottom for stability. Its vertical columns carry the weight of all the floors above them. Consequently, the bottom columns carry the weight of all the floors of the building; the top columns carry only the load of the roof and their own weight.

In addition to the force of gravity, the force of wind determines the structural form of the skyscraper. In the early skyscrapers, closely spaced columns, deep beams, and heavy brick walls provided rigidity against the wind. When channeling gravity loads and resisting lateral wind forces came to be viewed as separable structural problems, a lighter and more flexible exterior hinged frame resulted with a strong inner core of wind-bracing columns.

A further modification of this design used outside frames as the wind resistant form, thus eliminating the need for an inner wind-bracing core. With this new structural form a skyscraper becomes an immense hollow cantilevered beam, stuck into the ground and anchored to a heavy foundation.

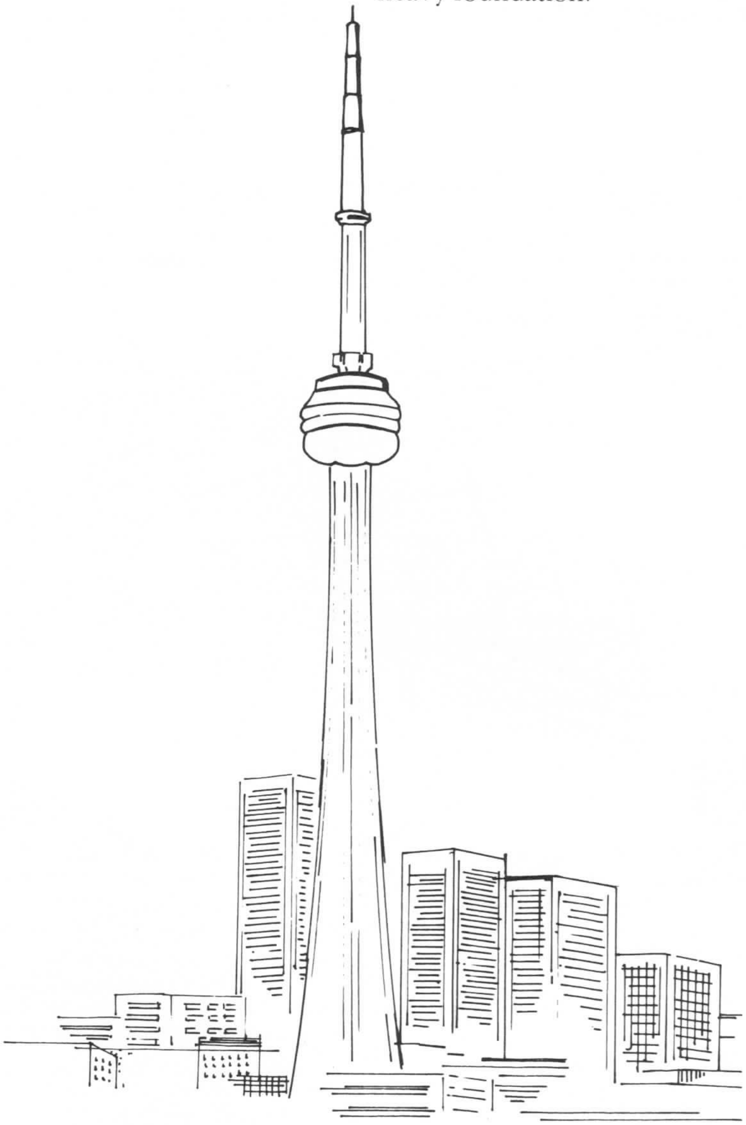


Figure 14 The CN Tower, Toronto.

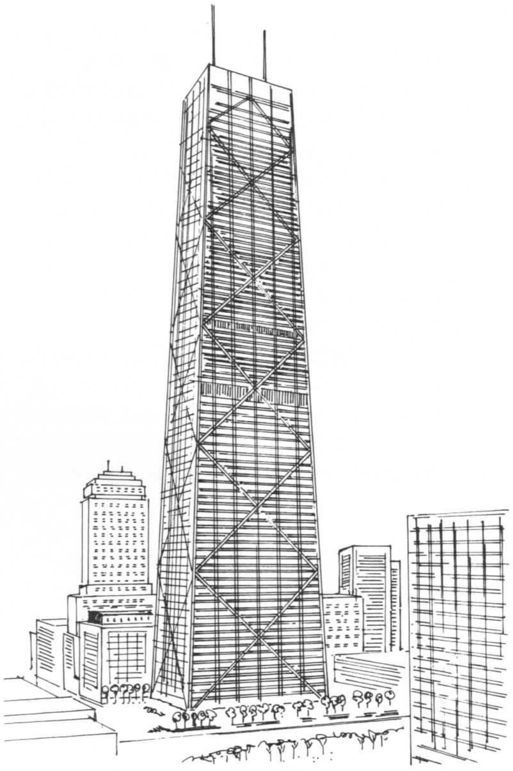


Figure 15 The John Hancock Building, Chicago.

In a cantilever the actions of tension and compression exist at the same time. A person standing on the end of a diving board bends it down. The top portion of the board is in tension (being pulled) while the bottom portion is in compression (being pushed in). The wind has the same effect on a skyscraper as shown in Figure 10. The skyscraper acts like a vertical cantilever.

The John Hancock Building, the World Trade Center towers, the Sears Tower, and the CN Tower are all impressive examples of vertical cantilevers. The John Hancock Building withstands the wind with a 100-story vertical truss, much like a massive bridge truss turned upright. Each X in the truss is 18 stories high. In contrast, the CN Tower is a vertical cantilever made out of reinforced concrete, and the Sears Tower is a 3x3 square of "hollow tubes" bundled together.

Other Structural Designs

The truss is only one way of designing for resistance to weight and wind. It is one way of spanning space and channeling loads through tension and compression.

During ancient and medieval times the arch was a frequent way of spanning rivers or supporting the large roofs of churches. Stone was particularly suitable because of its high resistance to compression. Through the centuries structures have evolved from the massive heavy ones in which stone is the dominant material to modern stadiums with roofs made of thin membranes.

The most graphic example of a thin membrane acting as a roof or as a structure itself is the "inflatable." Like giant balloons very strong, thin plastic sheets are supported just by air, sometimes covering acres in area. As structures they have been used to house tennis courts, swimming pools, and sports fields. In the Pontiac Silverdome stadium in Pontiac, Michigan, the entire roof is a fiberglass fabric reinforced with steel cables and inflated by electric fans six feet in diameter, which produce an air pressure slightly greater than the outside air.

The roadway on a suspension bridge hangs from long steel cables, which are pulling at the two towers. The cables are under tension while the towers are under compression. The Brooklyn Bridge is an example of a suspension bridge in which the cables hang from towers made of stone. In contrast, the towers of the George Washington Bridge, also in New York City, are made of steel trusses.

Domes are another structural form that extends back to ancient times. They are elegant examples of spatial geometry, from the Pantheon built by the Romans in 123 A.D. to St. Peter's Cathedral in Rome to the modern Houston Astrodome. Domes have been built of stone, brick, concrete, and steel.

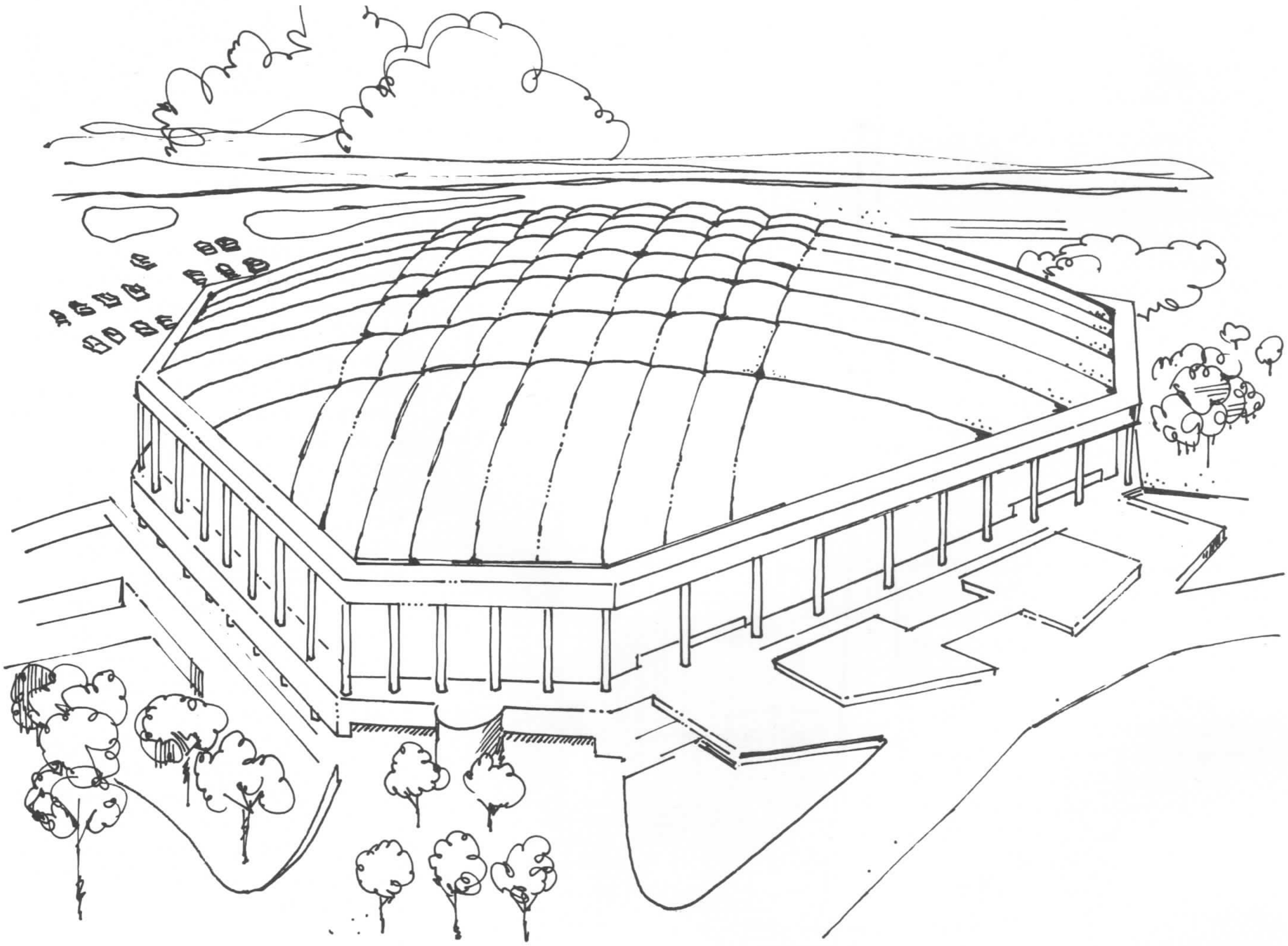


Figure 16 The Pontiac Silverdome in Pontiac, Michigan.

Resources

Periodicals

- Cohalan, Michael. "Tension in the Cathedral," *Science 81* (December 1981): 32-41. The use of plastic models and optical stress analysis to study the designs of medieval Gothic cathedrals. A new look into the tension and compression forces within these structures.
- Condit, Carl W. "The Wind Bracing of Buildings," *Scientific American* (February 1974): 92-105. About how the evolution of the skyscraper inspired elaborate methods of providing resistance to the wind. In the largest buildings a technique invented more than 100 years ago—the truss—has been revived.
- Hansen, James. "The Delicate Architecture of Cement," *Science 82* (November 1982): 48-55. A look at the ingredients, the processes of combining with water, and the properties of cement and its product—concrete. Complements this packet on Structure.
- Mark, Robert, and William W. Clark. "Gothic Structural Experimentation," *Scientific American* (November 1984): 176-185. About how Gothic builders used the cathedrals themselves as models, modifying designs as structural problems emerged. Information spread rapidly among building sites.
- Tucker, Jonathan B. "Superskyscrapers: Aiming for 200 Stories," *High Technology* (January 1985): 50-63. A well-illustrated review of various structural designs for notable skyscrapers over the past 100 years and several proposed future superskyscrapers from 140 stories to 210 stories high. A glimpse of the structural material of the future—high-strength concrete. Brief discussion of the superskyscraper as a socio-technological system with enormous technical challenges.

Paperback Books

- Salvadori, Mario, and Michael Tempel. *Architecture and Engineering: An Illustrated Teacher's Manual on Why Buildings Stand Up.* New York: New York Academy of Sciences, 1983. A wide-ranging teacher's manual with 10 units and 70 lessons. Includes suggestions on how to use the manual for upper elementary, junior high, and high school levels. Units include: the forces that act on structures, tension and compression, the effect of wind on buildings, and trusses.
- Salvadori, Mario (drawings by S. Hooker and C. Ragus). *Why Buildings Stand Up: The Strength of Architecture.* New York: McGraw-Hill Book Co., 1982. Well illustrated review of why buildings stand up. Includes explanations of loads, houses, skyscrapers, the Eiffel Tower, bridges, domes, and more.
- Thompson, D'Arcy. *On Growth and Form.* Abridged edition. Edited by J.T. Bonner. New York: Cambridge University Press, 1961. A book about the way things grow and the shapes they take—including horns, teeth, tusks, jumping fleas, bees' cells, raindrops, soap film, oil bubbles. Analyzes biological processes from their mathematical and physical aspects. A classic.
- Wilson, Forrest. *Structure: The Essence of Architecture.* New York: Van Nostrand Reinhold Co., 1971. The principles of structure in terms of our perceptual responses. Extensively illustrated.
- Zubrowski, Bernie (illustrated by Stephanie Fleischer). *Messing Around with Drinking Straw Construction.* A Children's Museum Activity Book. Boston: Little, Brown and Co., 1981. A companion reference for the *Doing Science* activities. Written for children.

Books

- Gordon, J.E. *Structures: Or Why Things Don't Fall Down.* New York: Plenum Press, 1978. Readable explanations of the principles of structure. Includes specific sections on why structures carry loads, tension structures, and compression and bending structures. Well illustrated.
- Salvadori, Mario (illustrations by S. Hooker and C. Ragus). *Building: The Fight Against Gravity.* New York: Atheneum Publishers, 1979. Basic structural principles presented simply and with engaging illustrations. A good first source of information for teachers.
- Wilson, Forrest. *Architecture: A Book of Projects for Young Adults.* New York: Reinhold Book Corp., 1968. Thirty-three do-it-yourself projects with simple materials. Enables the reader to experience a variety of structures and structural elements: the arch, tension and compression in a beam, paper columns, trusses, space frames, etc. Includes open-ended activities for the inventive mind. Good glossary of architectural terms.

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