Tomorrow we may be moved once again by a social achievement akin to the contemporary construction of enormous dams by the Chinese masses. Today, sensitized to the aesthetic values inherent in elementary geometric forms by an entire school of minimalist sculptors, we may look at the Great Pyramid as the greatest of minimal sculptures. The message changes with the evolution of our cultures, but the mysterious fascination of the Pyramids remains.

3 Loads

The collapse of the Meidum pyramid demonstrates that the problem of *loads,* of weight distribution, even in apparently simple geometric structures, is a complex, ever-present concern for builders. If the earth did not pull, the wind did not blow, the earth's surface did not shake or sink, and the air temperature did not change, loads would not exist and structure would be unnecessary. This would be, indeed, the Alice-in-Wonderland world of architecture where attention could be focused only on the definition and enclosing of interior spaces. But in the real world, the builder must concern himself with structure; structure supports all the loads that act, unavoidably, on buildings. The engineer's first job is to determine which loads will act on a structure and how strong they might be in extreme cases. This is anything but a simple task. Let us look into the world of loads.

Dead Loads

A structure consists of heavy elements like columns, beams, floors, arches, or domes which must, first of all, support their own weight, the so-called *dead load.* And here lies the paradox of structural design. To determine the weight of a structure, once the dimensions of its elements are established and the material chosen, one has only to compute the volume of the elements and multiply it by the weight of a unit volume of the material, its *specific weight.** Tables of specific weights are available to the engineer to facilitate this basic but boring task. The trouble is that, for example, in order to make sure that a beam will carry its own weight (*and* other loads on it), we must first know its dimensions, but these in turn, depend on the beam's weight. Structural design, the determination of the shape and dimensions of structural elements, can only be learned by experience.

The dead load is a load "permanently there." In some structures built of masonry or concrete it is often the heaviest load to be supported by the structure. By the way, any other load also permanently there is always included in the dead load—the weights of the flooring, ceiling, and insulation materials, for example. Similarly, the weight of the *partitions*—the walls dividing one room from another, which may be changed or shifted in rearranging the plan of an apartment but will always be there—must also be included in the dead load.

Live Loads

In addition to its dead load, a structure must support a variety of other weights—people, furniture, equipment, stored goods. These impermanent or *live loads* may be shifted around and they may change in value. One may be alone in one's room today and have ten visitors tomorrow. These may gather in one corner or spread themselves throughout the room. The next tenant may have massive furniture and distribute it differently. It is obvious that we can never know exactly what the live load is and how it is going to be distributed.

Concern for safety suggests that live loads must be established on the basis of the *worst* loading conditions one may expect during the entire life of the structure. These are determined by responsible and practiced engineers and contained in *building codes,* which are published by cities, counties, and states. In the United States a few codes have gained general acceptance and most local codes are based on their prescriptions. For example, the so-called Uniform Building Code is akin to the engineer's Bible and no designer ignores the live load values suggested in it.

The values of the code loads are conventional. They assume that the worst effect of the varying and shifting live loads may be represented

* For example, a reinforced concrete beam 30 feet long, 1 foot wide, and 3 feet deep has a volume of 30 × 1 × 3 = 90 cubic feet. Since one cubic foot of concrete weighs 150 pounds, the dead load of the beam is 150 × 90 = 1,350 pounds.

by a *uniform load,* that is, a load evenly spread over the surface of the floors. For example, the New York City Code suggests that the live-load allowance for a private apartment room should be forty pounds per each square foot of floor. (By the way, engineers abbreviate the words "pounds per square foot" as "psf.") This is a most conservative allowance, but engineers *must* be conservative when confronted with the uncertainties of live loads. It is better to run scared than to be responsible for a failure which may damage property and even kill people.

On the other hand, the chances are absolutely minimal that each square foot of each room at each floor of a building will be loaded *at the same time* by the full code allowance, and buildings designed for this absurd assumption would become unjustifiably expensive. Hence, the codes allow a *live load reduction,* which may reach sixty percent for a high-rise building.

Naturally, the value of the live load varies with the type of building, its location, and its importance. The floors of a warehouse must be expected to carry a much greater live load than those of an apartment house. The roof of a building in Colorado must support a much heavier load of snow than one in Alabama. The public areas of a building, its corridors and halls, which at times may be jammed with people, must be designed for larger live loads than a private room.

Live-load calculations are lengthy and important, although not very demanding on the imagination and intelligence of the engineer. Luckily, computer programs do most of the evaluations now, saving engineering time and increasing both speed of calculation and accuracy of results. The computer, when properly used, is a wonderfully useful slave.

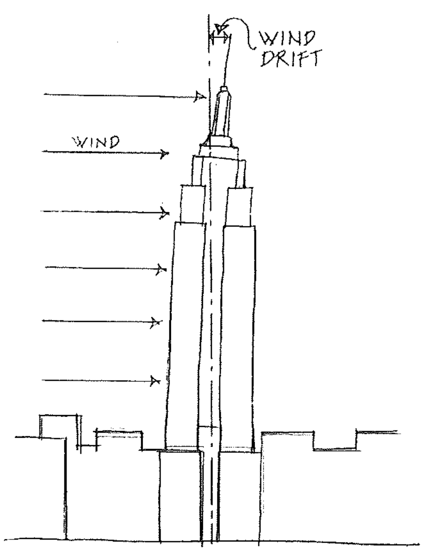
Dynamic Loads

The dead load is permanent and unchanging and the live loads have been tacitly assumed to change slowly, if at all. Together, these unchanging or slowly changing loads are called by engineers *static loads,* loads that stay.

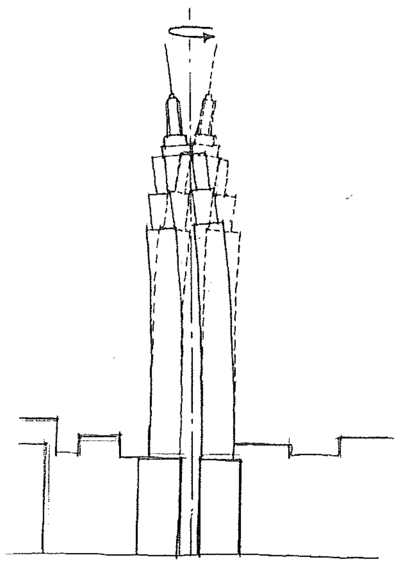
But other loads change value rapidly and even abruptly, like the pressure of a wind gust, or the action of an object dropped on the floor. Such loads are called *dynamic* and may be exceedingly dangerous because they often have a much greater effect than the same loads applied slowly. For example, a hammer laid slowly, gently, onto the head of a nail will make no impact. But dropping the same hammer suddenly on the nail will drive the nail into the wood. Such suddenly applied loads, actually called *impact loads*, can be shown to be fleetingly equivalent to many times their statically applied weights. The dynamic pressure of a slap, compared to the static pressure of a caress, may never have been measured, but one can certainly feel it.

The fleeting effects of a dynamic load depend on how fast the load varies. This raises a question: for example, should the pressure on a building created by a wind gust, first increasing and then decreasing, be considered a static or a dynamic load? The answer is that no varying load is ever static or dynamic *in itself*. As we shall see, its effects can be static or dynamic *depending on the structure to which it is applied*. To prove this let us consider a tall building acted upon by a wind gust.

Under the wind pressure the building bends slightly and its top moves (Fig. 3.1). Its movement may be small enough not to be seen by the naked eye, or even sensed, but since structural materials are never totally rigid, all buildings do sway in the wind. If one could push the top of a building, say, one foot to the right and then let it go, the building would start oscillating, going back and forth. Its top would first go back through its original vertical position, then move one foot to the left of it,



3.1 WIND SWAY IN A TALL BUILDING



3.2 PERIOD OF BUILDING OSCILLATIONS

and continue swinging back and forth until it eventually stops. It is easy to visualize these oscillations by considering the building as an up-side-down clock pendulum, which also swings back and forth when displaced from its lowest position. The time it takes a pendulum to complete a full swing, from extreme right to extreme left *and back*, is called the *period* of the pendulum. Similarly, the time it takes a building to swing through a complete oscillation (Fig. 3.2) is called its period. For example, the period of the oscillations of the steel Sears Tower in Chicago, which is 1,450 feet high, is eight seconds, while the period of a ten-story brick building may be as short as half a second.

We can now answer the question about the effect of wind pressure on a building. The action of the gust depends not only on how long it takes to reach its maximum value and decrease again, but on the period of the building on which it acts. If the wind load grows to its maximum value and vanishes in a time *much shorter* than the period of the building, its effects are *dynamic*. They are *static* if the load grows and vanishes in a time *much longer* than the period of the building. For example, a wind gust growing to its strongest pressure and decreasing in two seconds is a dynamic load for the World Trade Center towers with a period of ten seconds, but the same two-second gust is a static load for the ten-story brick building with a period of only half a second. In a sense, a force the building can slowly absorb is static; an unexpected one is dynamic. The weight of snow and people is always a static load because snow takes hours to accumulate and people enter buildings singly or in small groups. On the other hand, the explosion of an atomic device reaches its maximum effect and decreases so rapidly (less than a thousandth of a second) that it is a dynamic load on all structures, and has enormously destructive effects.

Interestingly enough, there are loads which, though not growing rapidly, do have dynamic effects increasing, not instantaneously, but progressively in time. This phenomenon, called *resonance*, is one of the most dangerous a structure may be subjected to. To understand resonance, let us consider how a heavy church bell, which swings like a pendulum, is made to ring by the relatively small yanks of a single man on its rope. If the bell weighs a few tons—often the case—the ringer might try in vain to move it with a single yank. But if the ringer starts yanking the rope with a small pull of, say, a few pounds and before yanking it again, waits for the bell to go through its first tiny swing, then keeps yanking in *rhythm* with the bell's oscillations, eventually the bell swings widely and rings. The trick here consists in yanking the rope at the beginning of each new oscillation, that is, at time intervals equal to the period of the bell, so the applied pulls will add up.

When a force is rhythmically applied to a structure with the same period as that of the structure, the force is said to be *in resonance* with it. Resonant forces do not produce large effects immediately, as impact forces do, but their effects increase steadily with time and may become catastrophic if they last long enough. If a long series of wind gusts, growing and waning in pressure with a relatively slow period of eight seconds, were to hit the Sears Tower, the swing of the tower would slowly increase until the structure of the building might sway so widely as to collapse. The story is often told of a German army infantry company goose-stepping across a small wooden bridge in rhythm with the period of the up-and-down oscillations of the bridge. The company ended up in the river when the bridge collapsed under the resonant load of the goose-step.

There are, finally, some perfectly steady forces which produce dynamic effects on certain types of structures. They derive from the interaction between the wind and the structure and are called *aerodynamic*. In 1940 the Tacoma Narrows Bridge in Washington, a particularly narrow and flexible suspension bridge 2,800 feet long, was destroyed by a steady wind blowing at forty-two miles per hour for about seventy minutes. Up-and-down oscillations of the bridge, travelling like a wave along the length of its roadway, had been noticed since its construction. Indeed, the bridge had been nicknamed "Galloping Gertie." These oscillations were caused by winds blowing at right angles to the bridge which, as the flexible roadway moved up and down, hit the bridge alternatively from below and from above, naturally in resonance with the period of the bridge oscillations. Their effects, while similar to those of a resonant load, had never been sufficiently strong to wreck the bridge. The collapse occurred when similar, but twisting, oscillations were added to the roadway by the wind blowing not horizontally, but at a slight downward angle. The downward wind pressure first pushed down slightly the *windward* edge of the roadway, twisting it; then the structure, reacting, twisted the roadway back up, thus allowing the wind to push the windward edge up from below. This cycle was repeated, again and again, gradually increasing the twisting oscillations of the roadway until the wind destroyed the bridge. Luckily nobody was killed, since authorities had cleared the bridge. The roadways of all modern suspension bridges are now stiffened against twisting to prevent this dangerous phenomenon.

It is interesting to notice that, although the recent technical literature had never considered the aerodynamic effects of winds on suspension

bridges, English newspapers at the beginning of the nineteenth century carried descriptions of the collapse of flexible suspension bridges caused by the identical aerodynamic phenomenon that destroyed the Tacoma Narrows Bridge. In the history of science and engineering, facts and laws have been forgotten which, if remembered, would have saved time, energy and, possibly, lives.

Wind Loads

The forces exerted by winds on buildings have dramatically increased in importance with the increase in building heights. Static wind effects rise as the square of a structure's height and the high-rise buildings of the 1970s, which are at times almost 1,500 feet tall, must be fifty times stronger against wind than the typical 200-foot buildings of the 1940s. Moreover, the speed of wind grows with height, and wind pressures increase as the square of the wind speed. Thus, the wind effects on a building are compounded as its height increases.

Wind pressures act horizontally and, in tall buildings, require a structure separate and different from that which resists the vertical gravity loads—the weights. In very tall buildings up to ten percent of the structural weight, and hence of the structural cost, goes into this *wind bracing*. In a twenty- or thirty-story building, on the other hand, the gravity structure is often sufficient to resist the wind. The chances are slim that the strongest possible wind will occur when the structure is also loaded by the heaviest possible gravity loads. Thus, the codes allow structural materials to be stressed thirty-three percent more when the loads due to gravity and those due to wind are taken into account simultaneously. This judicious allowance, based on probability, allows considerable structural savings without impairing structural safety.

One of the basic questions to be resolved before designing a building is often: "What is the strongest wind to be expected at its site?" To answer it, wind measurements are conducted daily in all parts of the world and maps are plotted, like that in Figure 3.3, which give at a glance the maximum wind speeds to be expected. But should one design for the strongest wind ever at the site of a building? If this maximum wind were always taken into account, the cost of the wind structure would become unjustifiably high. It is wiser to design buildings so that they will be undamaged by a wind with a chance of occurring once in, say, 50 years, but to allow *minor* damage under the forces of a *100 year wind* (as a wind is called that has a chance of occurring once in 100 years). The cost of fixing the minor damage would certainly be less than the long-term cost

3.3 WIND VELOCITY MAP OF THE UNITED STATES (MILES PER HOUR)

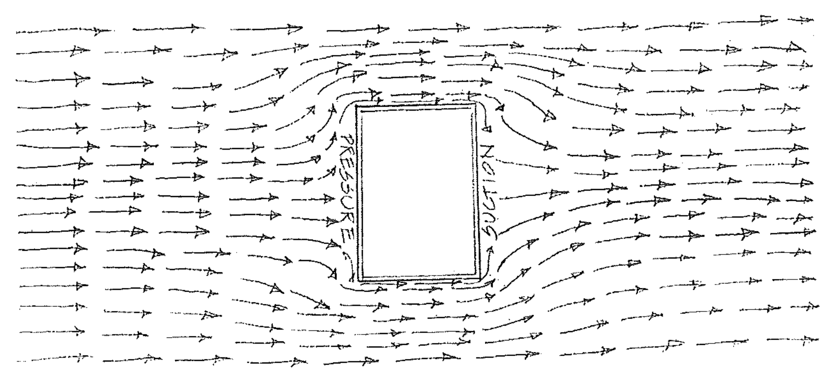
required to guarantee total integrity under the stronger wind. It is thus up to the engineer to choose the *design wind* and a 30 or a 50 year wind is often considered acceptable unless the strength of a 100 year wind is such as to endanger the entire building and the life of its occupants.

Besides depending on wind speed and building height, wind forces vary with the shape of the building. The wind exerts a pressure on the windward face of a rectangular building because the movement of the air particles is stopped by this face. The air particles, forced from their original direction, go around the building in order to continue their flow, and get together again behind the building as shown in Figure 3.4. In so doing, the air particles suck on the leeward face of the building and a negative pressure or *suction* is exerted on it. The total wind force is the sum of the windward pressure and the leeward suction, but each of these two forces has its own local effects. During hurricane Donna in New York City, in 1960, occupants of high-rise buildings were justifiably frightened when large glass panels of the curtain walls were blown *into* their offices by the wind pressure. They were probably even more frightened and amazed when the leeward wind action sucked the window panels *out* of

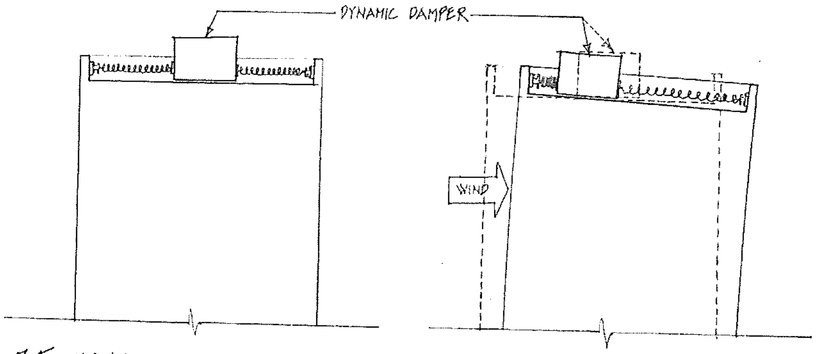
their offices. These leeward panels fell to the street, creating an additional hazard to passersby.

In designing for wind, a building cannot be considered independent of its surroundings. The influence of nearby buildings and of the land configuration can be substantial. The buildings around a new hall at M.I.T. in Cambridge, Massachusetts, produced such an increase in wind velocity at ground level that it became, at times, impossible to open the entrance doors. Originally the two curved structures of Toronto's City Assembly Hall had only a narrow space separating them. This defile compelled the wind to increase its speed in order to pass through it. (Air is a fluid and increases its speed when constrained to go through a narrow space, just as water increases its speed when passing through a narrow gorge of a river.) This increase in speed created such high pressures on the two buildings that their wind bracing had to be redesigned on the basis of information gathered in wind tunnel tests.

The swaying of the top of a building due to wind may not be seen by the passerby, but it may feel substantial to those who occupy the top stories of a high building. Under a strong wind the top of the Sears Tower swings left and right of its vertical position by as much as one foot, and a 100 mile-per-hour wind can produce swings of up to three feet on each side of the vertical. These horizontal swings are not structurally dangerous, but they may be inconvenient for those who work at such great heights: occupants sometime become airsick. Recent research by engineers and doctors indicates that the airsickness induced by wind motion in high buildings is a resonance phenomenon. It occurs when the period of the building more or less coincides with the period of the up-



3.4 WIND FLOW PAST A BUILDING



3.5 TUNED DYNAMIC WIND DAMPER

and-down oscillations of our own insides. This explains why some, but not all, of the people in a building may feel queasy. To avoid excessive wind deflections (or *wind drift* as it is technically called) buildings should be stiffened so that their tops will never swing more than 1/500 of their height. Thus a three-foot wind drift is acceptable in a 1,500 foot building.

Lateral movement due to wind may be even more dramatic in long and flexible suspension bridges. After the collapse of the Tacoma Narrows Bridge, the actual lateral swings of all large suspension bridges in the United States were measured. It was found, for example, that the Golden Gate Bridge in San Francisco sways laterally as much as eleven feet under heavy winds. Sometimes the bridge must be closed to traffic since it is not safe to drive a speedy car on a roadway that moves right and left under it.*

How does one prevent the resonant oscillations in a building? The basic method consists in changing its period by reinforcing its structure to make it stiffer. The stiffer the structure, the shorter the period. This is

* Tall chimneys and high television towers, which have reached over 2,000 feet and are among the highest structures ever built, are subjected to a dangerous resonance phenomenon, in which they oscillate *at right angles* to the wind. As the wind hits these extremely slender structures, it tends to go around them and creates air eddies which separate from the sides of the structure, causing an alternating vacuum, first on one side and then on the other. When the air eddies separate with a rhythm that coincides with the period of the chimney or tower, the structure starts oscillating laterally with increasing swings, which may damage or eventually destroy it.

a costly remedy but recently a mechanical gadget used for years in cars and planes has been adapted to the reduction of wind oscillations. It is called a *tuned dynamic damper* and consists of a heavy mass of concrete attached to the top of the building by means of lateral springs (Fig. 3.5). This heavily springed mass has the same period as the building. When the building oscillates with its own period, the tuned damper after a short while also tends to oscillate with the same period, but in the *opposite* direction. One could say that the damper moves in antiresonance with the building. When this happens, the oscillations of the building are completely damped out by the counteraction of the damper. The damper's resonant oscillations do not grow because they are controlled by large shock-absorbers that brake its motion. A spring-connected, 400-ton mass of concrete at the top of the Citicorp Building in New York City reduces its top oscillations by 50% without a substantial increase in the cost of its windbracing. Similar dynamic dampers, consisting of heavy metal rings connected to the top of chimneys by radial springs, are used to avoid the lateral swings of these high structures due to air eddies.

We have acquired a great amount of knowledge about wind in the last twenty or thirty years and it is comforting to know that very few modern well-designed structures suffer today from wind damage.

Earthquake Loads

Earthquakes have wreaked destruction since oldest antiquity and it is only in the last thirty or forty years that our knowledge of earthquakes and of their impact on buildings has resulted in the design of earthquake-resistant structures. These are built with particularly strong "wind bracing" type structures, which tests and computer calculations prove capable of resisting the jerking forces of an earthquake. Even so, the number of quake victims is still high all over the world. When 27,000 people died in the Guatemala earthquake of 1967 we thought we had seen the worst, but 242,000 people died in an earthquake later in the same year in the region north of Peking.

The earth's crust floats over a core of molten rock and some of its parts have a tendency to move with respect to one another. This movement creates stresses in the crust, which may break out along fractures called *faults*. The break occurs through a sudden sliding motion in the direction of the fault and jerks the buildings in the area. Since the dynamic impact forces due to this jerky motion are mostly horizontal, they can be resisted by the same kind of bracing used against wind.

Earthquake strengths are evaluated on scales like the Richter scale, which measures the magnitude of the energy in the earthquake. For example, an earthquake measuring 4 or 5 on the Richter scale does little damage to well-built buildings, while one measuring 8 or above collapses buildings and may cause many deaths. Not all parts of the earth are subjected to earthquakes, but there are two wide zones on the earth's surface where the worst earthquakes take place. One follows a line through the Mediterranean, Asia Minor, the Himalayas, and the East Indies, the other the western, northern, and eastern shores of the Pacific.

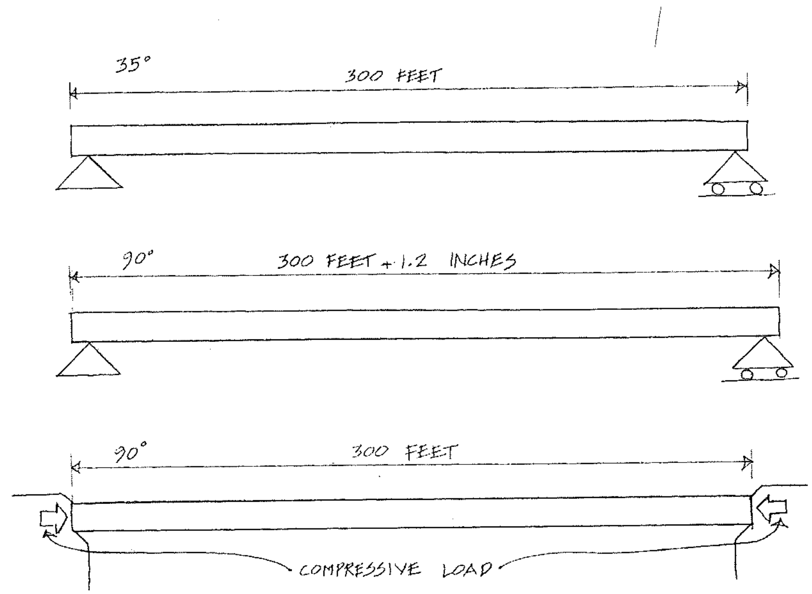
It is comforting to know that we are on the threshold of accurate earthquake forecasting and that some earthquakes have already been fairly well predicted in the United States and abroad. (In this we lag behind horses and cows which give obvious signs of fear at the approach of an earthquake.) Our new capabilities are due to the fact that when an explosion is detonated at a point in the earth's crust, waves move out concentrically through it, as they do when we drop a stone in the calm waters of a lake. It has been proved that the wave-speed through the crust increases when the stresses in it increase. Thus, when a geologist notices that the velocity of the waves created by a small explosion increases, he knows that the stresses in the crust are increasing and concludes that an earthquake may be imminent. The first successful prediction in the United States was made by a Columbia University student in the Adirondacks only a few years ago.*

Thermal and Settlement Loads

The last category of loads the engineer must worry about consists of those caused by daily or seasonal change in air temperature or by uneven settlement of the soil under a building. These are sometimes called hidden or *locked-in loads.*

Let us assume that a steel bridge 300 feet long was erected in winter at an average temperature of 35°F. On a summer day, when the air temperature reaches 90°F., the bridge lengthens, since all bodies expand

* While earthquake prediction will certainly be a great boon to humanity, it will present extremely complex social problems. What will the mayor of Los Angeles do if he is told by scientists that a strong earthquake will hit the city a few days or even hours hence? Is it possible to evacuate at short notice a city of 7 million people in an orderly manner? What if at first the geologists are not accurate and predict an earthquake that does not take place? Will people believe them if they cry wolf once too often? Scientific progress can only be a blessing to humanity if man learns to use its results wisely.

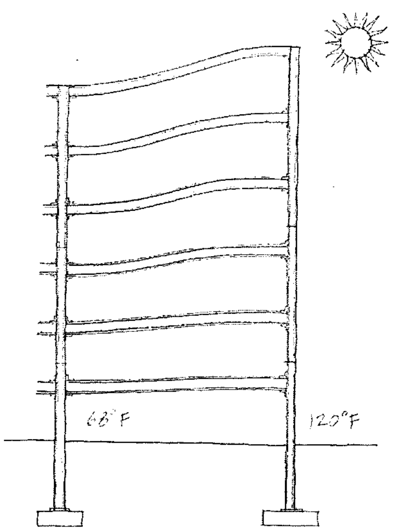


3.6 THERMAL EXPANSION OF BRIDGE

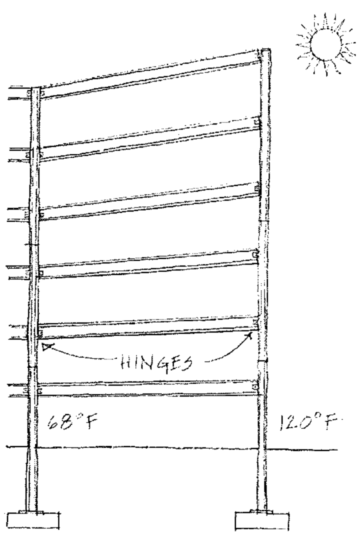
when heated. The increase in length of the bridge can be computed to be only 1.2 inches (Fig. 3.6). It is indeed small, one three-thousandths of the bridge length, but, if the bridge is anchored to abutments that do not allow this thermal expansion, the abutments will push on the bridge to reduce its length by 1.2 inches. Unfortunately, steel is so stiff that the compressive load exerted by the abutments uses up half the strength of the steel. There is only one way of avoiding this dangerous overstress: one of the bridge ends must be allowed to move to permit the thermal expansion to occur. While gravity loads must be fought by increasing the strength and stiffness of a structure, thermal loads must be avoided by making the structure less rigid.

Similar thermal loads appear at the bottom of large domes, which tend to expand when the temperature of the ambient air increases. Due to thermal expansion, the lower edge of a large dome tends to move outward and, since it is impractical to allow this edge to move in and out depending on temperature changes, one must build around it a strong ring to prevent this motion. Most of the large domes built in the past have shown a tendency to crack at their supported boundary (due to both thermal and gravity loads) and have since been circled with hoops of steel. Hagia Sophia in Constantinople and Saint Peter's in Rome have been so reinforced after cracks appeared at their edges.

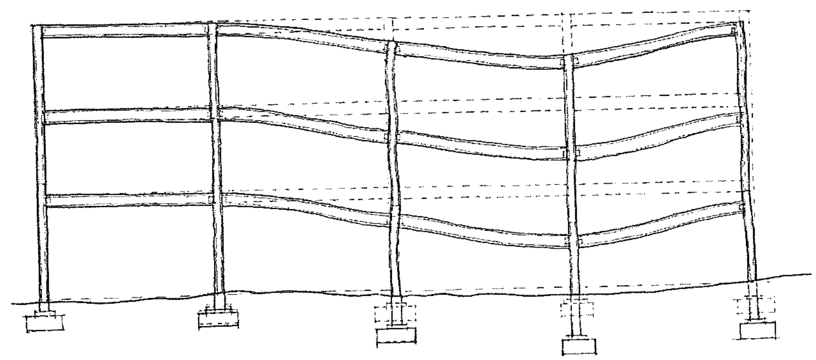
In many modern high-rise buildings the structural frame is set outside the curtain wall, rather than hidden inside it. An emphasis on the importance of structure and a feeling for its aesthetic value is at the basis of this architectural innovation. Good examples are the 100-story John Hancock Insurance Company steel building in Chicago (see Fig. 7.9) and the Columbia Broadcasting System concrete building in New York (see Fig. 7.12). While there is no denying the aesthetic value of some of these exposed structures, it must be noticed that they create problems for the engineer. The interior of these buildings is air conditioned and maintained at a constant temperature of 65° to 72°F., while the exposed structure is subjected to air temperature changes. In summer the exterior columns may reach a temperature of up to 120°F., and become two or three inches longer than the interior columns, while in winter they may become that much shorter when their temperature goes down to 20°F. These variations in length do not damage the columns, but, as shown in Figure 3.7, they bend the beams connecting the outer to the inner columns, particularly at the higher floors. These would be badly damaged if they were not properly designed, either by reinforcing them or by



3.7 THERMAL BENDING OF FIXED-END BEAMS



3.8 THERMAL ROTATION OF HINGED BEAMS



3.9 UNEVEN SETTLEMENT OF BUILDING FOUNDATIONS

allowing their ends to rotate, that is, by *hinging* them to the columns (Fig. 3.8).

It is easy to conceive of a mechanical way of avoiding these beam stresses: have the hot and cold water systems circulate inside the outer columns of the building and regulate the water flow so that the temperature of the outer columns be always more or less equal to that of the inner columns. This system has not been applied yet because of its cost, but the United States Steel Building in Pittsburgh does have a cold-water circulation system in its outer columns. Its purpose is to prevent any heat generated at a point on the outer structure, say, by a fire, from dangerously heating and possibly melting these columns.

Bending of the beams connecting outer to inner columns may also occur if the soil under a building settles unevenly (Fig. 3.9). Such uneven settlements caused the leaning of the Tower of Pisa, which started while the tower was being built. The Pisans thought they had straightened the tower up by building its upper part vertically, but the 191-foot tower is still going over at the rate of about one inch every eight years and its top is now out of plumb by sixteen feet. Various measures are being studied to arrest this dangerous rotation, but the Pisans are resolved to stabilize the tower in a leaning position, since no tourist would travel far to look at a straightened-up tower.

It must be emphasized that most damage to buildings is caused by foundation problems. Soil mechanics, the study of soil behavior, has moved to a science from an art only during the last fifty years. The island of Manhattan is blessed by a rocky soil, which permitted in 1913 the erection of the first high-rise (the Woolworth Building). Mexico City, on the other hand, is built on a mixture of sand and water. Such soils settle when heavy buildings are erected, squeezing the water out of the sand. The National Theatre in the center of Mexico City, originally built at grade level with a heavy cladding of stone, in a few years sank as much as ten feet. Downward stairs had to be built to its entrance. People were amazed when later on the theatre began to rise again, requiring the construction of an upward staircase. This strange phenomenon can be explained by the large number of high-rise buildings which had been erected nearby. The water squeezed out from under them by their weight pushed the theatre up.

Loads may be a necessary evil to both the architect and the engineer, but their basic importance cannot be minimized. Wise is the engineer who gives them his care and attention before starting the design of a building.

4 Materials

Tension and Compression

The purpose of structure is to channel the loads on the building to the ground. This action is similar to that of water flowing down a network of pipes; columns, beams, cables, arches, and other structural elements act as pipes for the flow of the loads. Obviously, this becomes a complex function when the structure is large and the loads numerous.

The remarkable, inherent simplicity of nature (Einstein called it elegance) allows the structure to perform its task through two elementary actions only: pulling and pushing. Many and varied as the loads may be and geometrically complicated as the structure may be, its elements never develop any other kind of action. They are either pulled by the loads, and then they stretch, or are pushed, and then they shorten. In structural language, the loads are said to *stress* the structure, which *strains* under stress. The imagery of this terminology is significantly human. When a structure is "overstressed," it "breaks down" and sometimes "buckles." (As will be seen later, this is said of thin elements subjected to compressive loads too high for their capacity.)

Another basic law of nature governs the structure's response to the loads. With a judicious sense of economy, or intelligent laziness, a structure will always choose to channel its loads to the ground by the *easiest* of the many paths available. This is the path requiring the minimum amount of work on the part of the structural materials and is a consequence of what is termed in physics "the law of least work." Structure behaves humanly in this respect too.