THE TOWER
AND
THE BRIDGE

THE NEW ART OF
STRUCTURAL ENGINEERING

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A NEW TRADITION: ART IN ENGINEERING

A New Art Form

While automation pros pers, our roads, bridges, and urban civil works rot. Children control computers while adults weave between potholes. The higher that high technology sails the worse seem our earthbound services for water, transportation, and shelter. Yet civilization is civil works and insofar as these deteriorate so does society, our high technology notwithstanding. We forget that technology is as much structures as it is machines, and that these structures symbolize our common life as much as machines stand for our private freedoms. Technology is frequently equated only with machines, those objects that save labor, multiply power, and increase mobility. In reality, machines are only one half of technology, the dynamic half, and structures are the other, static, half—objects that create a water supply, permit transportation, and provide shelter.
This book is devoted to the idea that structures, the forgotten half of modern technology, provide a key to the revival of public life. The noted historian Raymond Sontag titled his book on the period between the two world wars *A Broken World*, and his pivotal chapter called "The Artist in a Broken World" characterized the persistent hopes of the time by "the vision of mending the broken world through a union of art and technology." He had in mind groups like the ill-fated German Bauhaus, but he and all other historians missed the fact that such a union had for a long time already existed. It was a tradition without a name, confused sometimes with architecture and other times with applied science, even on occasion misnamed machine art. It is the art of the structural engineer and it appears most clearly in bridges, tall buildings, and long-span roofs.

This new tradition arose with the Industrial Revolution and its new material, industrialized iron, which in turn brought forth new utilities such as the railroad. These events led directly to the creation of a new class of people, the modern engineers trained in special schools which themselves came into being only after the Industrial Revolution had made them a necessity.

Such developments are well known and almost everyone agrees that they have radically changed Western civilization over the past two hundred years. What is not so well known is that these developments led to a new type of art—entirely the work of engineers and of the engineering imagination. My major objective in this book is to define the new art form and to show that since the late eighteenth century some engineers have consciously practiced this art, that it is parallel to and fully independent from architecture, and that numerous engineering artists are creating such works in the contemporary world of the late twentieth century. It is a movement awaiting a vocabulary.

The Ideals of Structural Art

Although structural art is emphatically modern, it cannot be labeled as just another movement in modern art. For one thing, its forms and its ideals have changed little since they were first expressed by Thomas Telford in 1812. It is not accidental that these ideals emerged in societies that were struggling with the consequences not only of industrial revolutions but also of democratic ones. The tradition of structural art is a democratic one.

In our own age when democratic ideals are continually being challenged by the claims of totalitarian societies, whether fascist or communist, the works of structural art provide evidence that the common life flourishes best when the goals of freedom and discipline are held in balance. The disciplines of structural art are efficiency and economy, and its freedom lies in the potential it offers the individual designer for the expression of a personal style motivated by the conscious aesthetic search for engineering elegance. These three leading ideals of structural art—efficiency, economy, and elegance—which I shall illustrate throughout this book, can be briefly described at the outset.

First, because of the great cost of the new industrialized iron, the engineers of the nineteenth century had to find ways to use it as efficiently as possible. For example, in their bridges, they had to find forms that would carry heavier loads—the locomotive—than ever before with a minimum amount of metal. Thus, from the beginning of the new iron age, the first discipline put on the engineer was to use as few natural resources as possible. At the same time, these engineers were called upon to build larger and larger structures—longer-span bridges, higher towers, and wider-spanning roofs—all with less material. They struggled to find the limits of structure, to make new forms that would be light and would show off their lightness. They began to stretch iron, then steel, then reinforced concrete, just as medieval designers had stretched stone into the skeletal Gothic cathedral.

After conservation of natural resources, there arose the ideal of conservation of public resources. In Britain, which was the center for early structural art, public works were under the scrutiny of Parliament, and private works were usually under the control of shareholders and industrialists. The engineer had, therefore, always to work under the discipline of economy consistent with usefulness. What the growing general public demanded was more utility for less money. Thus arose the ideal of conservation of public resources. The great structures we shall describe here came into being only because their designers learned how to build them for less money. Moreover, working with political and business leaders was a continuing and intrinsic part of the activity.
of these artists. They created not alone in a laboratory or a garret but under the harsh economic stimulus of the construction site.

Curiously enough, whenever public officials or industrialists decided deliberately to build monuments where cost would be secondary to prestige this art form did not flourish. Economy has always been a prerequisite to creativity in structural art. Again and again we shall find that the best designers matured under the discipline of extreme economy. At times, when approaching the limits of structure late in their careers, they might encounter unforeseen difficulties which increased costs. But their ideas and their styles developed under competitive cost controls. Economy is a spur, not an obstacle, to creativity in structural art.

Minimal materials and costs may be necessary, but they are not, of course, sufficient. Too many ugly structures result from minimal design to support any simple formula connecting efficiency and economy to elegance. Rather, a third ideal must control the final design: the conscious aesthetic motivation of the engineer. A major goal of this book is to show the freedom that engineers actually have to express a personal style without compromising the disciplines of efficiency and economy. Beginning with Telford's 1812 essay on bridges, modern structural artists have been conscious of, and have written about, the aesthetic ideals that guided their works. Thus, this tradition of structural art took shape verbally as it did visually. The elements of the new art form were, then, efficiency (minimum materials), economy (minimum cost), and elegance (maximum aesthetic expression). These elements underlie modern civilized life.

Civilization requires civic or city life, and city life forms around civil works: for water, transportation, and shelter. The quality of the public city life depends, therefore, on the quality of such civil works as aqueducts, bridges, towers, terminals, and meeting halls: their efficiency of design, their economy of construction, and the visual appeal of their completed forms. At their best, these civil works function reliably, cost the public as little as possible, and, when sensitively designed, become works of art. But the modern world is filled with examples of works that are faulty, excessively costly, and often ponderously ugly.

Such need not be the case. If the general public and the engineers themselves see the extent and the potential of structural art, then public works in the late twentieth century can, more than ever, be efficient, economical, and elegant.

The History of Structural Art

I shall demonstrate the potential of structural art through its history, and have divided the book into two parts to reflect the two major historical periods. The first part of the book traces the history of structural art up to the completion of the Eiffel Tower, the last great work of iron, and the second describes the developments springing from the use of steel and concrete and concludes with a series of the late-twentieth-century works. The historical narrative begins in Britain toward the end of the eighteenth century. Here we can see how the rise of new forms is connected directly to the use of new materials in solving the transport problems posed by industrialization. The transportation networks—canals, roads, and railways—accelerated the pace of technological developments, leading to urbanization and further industrial change. As cities grew more crowded, office buildings became higher, and train terminals of longer span and bridges of truly immense proportions began to be economically feasible.

The second period of structural art begins in the 1880s, when steel prices dropped and reinforced concrete was developed. Engineers soon began to explore new forms with these materials, so that even before the cataclysm of 1914, a bewildering variety of structures arose at a dizzying pace. But the maturity of new forms in steel and concrete came only afterward, when Western civilization careened from one world war to another through boom, inflation, and depression. During this period, movements in art and architecture proclaimed solutions to city decay, focusing on the menace or promise of technology.

The best known of these movements was the German Bauhaus, whose aim was to "avoid mankind's enslavement by the machine" by integrating architecture and machine production, and by getting the artist away from art for art's sake and the businessman away from business as an end in itself. The new architect, in the words of the Bauhaus founder, Walter Gropius, would be "a coordinating organizer, whose business is to resolve all formal, technical, sociological, and commercial problems" and whose work leads from buildings to streets, to cities, and "eventually into the wider field of regional and national planning." The Bauhaus and other such movements barely recognized the tradition of structural art. For example, in a classic work defining the Bauhaus, Gropius included forty-five illustrations, not one of which
showed any work of structural art. Furthermore, in describing the comprehensive education given to the new architect, Gropius noted that there were no courses offered in steel or concrete construction. Although Gropius and others stimulated new thinking about technology and design, they did it from the perspective of architecture rather than structure. Indeed, the great influence of such architects on post-War II ideas about building has tended to obscure the tradition of structural art. In addition to the common confusion between structural art and architecture, there arose a misconception about the relationship of structure to science and to machine art. Therefore, I must say something about what this new engineering art is not, before showing historically what it is.

Engineering and Science

The confusion of structural art with science assumes that engineering, being applied science, merely puts into practice the ideas and discoveries of the scientist. The honor of creative genius and the precedence in innovation belong to the scientist; the engineer is merely the technician, following orders from above. This idea is a common twentieth-century fallacy. It was articulated, for example, by Vannevar Bush, wartime director of the Office of Scientific Research and Development, in his influential report to President Truman which led to the establishment of the National Science Foundation. Bush summarized his ideas vigorously.

Basic research leads to new knowledge. It provides scientific capital. It creates the fund from which the practical applications of knowledge must be drawn. New products and new processes do not appear full-grown. They are founded on new principles and new conceptions, which in turn are painstakingly developed by research in the purest realms of science.

Today it is truer than ever that basic research is the pacemaker of technological progress. In the nineteenth century, Yankee mechanical ingenuity building largely upon the basic discoveries of European scientists, could greatly advance the technical arts. Not only is Bush's history of Yankee ingenuity inaccurate, but so is his general belief that "basic research is the pacemaker of technological progress." In a 1973 conference, leading historians of technology presented papers on the subject "The Interaction of Science and Technology in the Industrial Age." The conference summarized the wide variety of studies by then completed and "overwhelmingly, the group agreed in disagreeing with the conventional view (of Bush) that technology was applied science."

There is a fundamental difference between science and technology. Engineering or technology is the making of things that did not previously exist, whereas science is the discovering of things that have long existed. Technological results are forms that exist only because people want to make them, whereas scientific results are formulations of what exists independently of human intentions. Technology deals with the artificial, science with the natural.

Science and technology are best viewed as parallel activities, each one at times drawing on the resources of the other, but more often developing independently. An example of this independence is the fact that of the vast number of technological inventions made since World War II for the military, only about 0.3 percent can be traced to scientific discoveries; the remainder developed independently, from design stimuli within the technological community itself. A leading British scholar recently concluded that there is "very little indication of any clear or close links between basic scientific research and the great mass of technical developments." Having considered a wide variety of case studies, ranging from chemistry in Britain to structures in the United States, he observed that "science seems to accumulate mainly on the basis of past science, and technology primarily on the basis of past technology." In our present context, it is essential that we make the distinction between science and technology, so that we can focus on the true sources of engineering originality.

From the fundamental difference mentioned earlier flow a number of other crucial differences. Science works always to achieve general theories that unify knowledge. Every specific natural event, to be scientifically satisfying, must ultimately be related to a general formulation. Engineering, in contrast, works always to create specific objects within a category of type. Each design, to be technologically satisfying, must be unique and relate only to the special theory appropriate to its catego-
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It is this uniqueness that makes structural art possible. Were engineering works merely the reflections of general scientific discoveries, they would lose their meaning as expressions of the style of individual designers. The fact that these works need not—indeed, in some cases should not—be based on general theories is apparent from concrete studies in the history of technology. I give here two illustrations.

Robert Maillart, the Swiss bridge designer, developed in 1923 a limited theory for one of his arched bridge types which violated in principle the general mathematical theory of structures and thereby infuriated many Swiss academics between the wars. But Maillart’s limited theory worked well for that special type of form. Within that category type, Maillart’s theory was useful and had the virtue of great simplicity; he developed the theory to suit the form, not the form to suit the theory. In the United States, by contrast, some of our best engineers understood the general theory well, but not understanding Maillart’s specific ideas, they failed to see how new designs could arise. They were trapped in a view of an engineering analysis which was so complex that it obscured new design possibilities. Today the undue reliance on complex computer analyses can have the same limiting effect on design.

A second, even more dramatic example occurred with suspension bridge design at the same time. A new and more general theory of analysis became fashionable in the 1920s. Imbued with the idea that more general theories would automatically give more complete insight into bridge performance, all leading designers of the period used that theory, which obscured rather than clarified understanding and helped cause the defective design for a series of major bridges in the 1930s and the Tacoma Narrows Bridge collapse of 1940.10

Such examples show how this new perspective on engineering design as an activity independent of basic science suggests a new type of research, basic to a design profession, where historical, humanistic study is as important as the development of scientific analyses.

Structures and Machines

Related to the fallacy that technology is applied science is the fallacy that technology involves only machines. This one-sided view dominated Jacques Ellul’s frequently cited Technological Society, allowing him to portray the modern world as both mechanistic and demonic, without personality, without art, and without hope.11 Crucial to Ellul’s argument was his insistence on defining technology (or, in French, la technique) as “the one best way,” the super-rational means by which one inevitably arrives at the single optimum solution to each problem. There is no possibility, in this view, for individuals to express their own personalities except, as Ellul puts it, by adding useless decoration to the machine. Only by compromising function or adding cost, two sides of the same thing, could the engineer inject any art. Ellul strongly ridiculed the idea of machine art, put forward by artists, architects, and critics between the wars. Like many other writers, Ellul argued that this art was merely symbolic of a machine age and did not at all reflect the efficiency of the “one best way.”

But technology is not just machines. There are two sides to technology: structures—the static, local, and permanent works—and machines—the dynamic, universal, and transitory ones. The Eiffel Tower (figure 1.1), Seattle’s covered stadium (the Kingdome), and the Brooklyn Bridge (see figure 1.2, p.18) are structures; they were designed to resist loads with minimum movement and to stand as long as their societies stand. By contrast, elevators, air conditioners, and cars are machines; they only work when they move and are continually replaced as they wear out or are made obsolete by newer models. Technology has always meant both structures and machines; they are its two sides.12

The civilized world requires both sides of technology. Structures stand for continuity, tradition, and protection of society; machines for change, mobility, and risk. There is a constant tension between these two types of objects—between the extremes of a frozen society where structure dominates and a frantic society dominated by machinery. Yet structures must be built by machines and must only can be built because of machines. Modern city buildings would be almost useless without elevators, and very few bridges would ever have been built without the pressure of railroads and automobiles. In the same way, machines
require structure to hold them together and would be useless without structures in which or on which to operate.

As intimately connected as they are, structures and machines must function differently, they come into being by different social means, and they symbolize two distinctly different types of designs. Structures must not move perceptibly, are custom-built for one specific locale, and are typically designed by one individual. Machines, on the other hand, only work when they move, are made to be used widely, and are in the late twentieth century typically designed by teams of engineers. General statements about technology are frequently meaningless unless this basic distinction is first made.

In addition to the two types of objects, technology can be thought of as including two types of systems: networks and processes, which are extensions of structures and machines respectively. Networks—such as canals, roadways, railways, electric lines, and airways—are immovable conduits distributing things. The network is a distributor not a converter. Processes, on the other hand, are systems that change the state of things—such as internal combustion, oil refining, water treatment, and electric power generation. These are dynamic systems, characterized by change and related intimately to machines such as engines, pumps, reactors, and turbines. Networks are static systems characterized by their permanence, and depend for their operation upon such structures as aqueducts, bridges, dams, airports, power plants, and transmission towers.¹³

I shall consider only structures, but it should be clear that they lose meaning if we forget their complementary relationship to machines. The Eiffel Tower is mainly lost to the general public without its elevators; the Kingdome would be useless without electric lights and air conditioning; and the Brooklyn Bridge was built by the use of all kinds of machinery and serves today as a major route for cars.

FIGURE 1.1
The Eiffel Tower, Paris, 1889, by Gustave Eiffel. When built for the Paris exhibition of 1889, this 300-meter-high iron tower was the highest man-made structure in the world. Its shape expresses visually the engineer’s ideal for resisting the forces of wind.
Structures and Architecture

The modern world tends to classify towers, stadiums, and even bridges as architecture. This represents yet another, albeit more subtle, fallacy similar to the confusion of technology with applied science and with machines. Here even the word is a problem because “architect” does come from the Greek word meaning chief technician. But, beginning with the Industrial Revolution, structure has become an art form separate from architecture. The visible forms of the Eiffel Tower, the Kingdom, and the Brooklyn Bridge result directly from technological ideas and from the experience and imagination of individual structural engineers. Sometimes the engineers have worked with architects just as with mechanical or electrical engineers, but the forms have come from structural engineering ideas.

Structural designers give the form to objects that are of relatively large scale and of single use, and these designers see forms as the means of controlling the forces of nature to be resisted. Architectural designers, on the other hand, give form to objects that are of relatively small scale and of complex human use, and these designers see forms as the means of controlling the spaces to be used by people. The prototypical engineering form—the public bridge—requires no architect. The prototypical architectural form—the private house—requires no engineer. We have seen that scientists and engineers develop their ideas in parallel and sometimes with much mutual discussion; and that engineers of structure must rely on engineers of machinery just to get their work built. Similarly, structural engineers and architects learn from each other and sometimes collaborate fruitfully, especially when, as with tall buildings, large scale goes together with complex use. But the two types of designers act predominantly in different spheres.

The works of structural art have sprung from the imagination of engineers who have, for the most part, come from a new type of school—the polytechnical school, unheard of prior to the late eighteenth century. Engineers organized new professional societies, worked with new materials, and stimulated political thinkers to devise new images of future society. Their schools developed curricula that decidedly cut whatever bond had previously existed between those who made architectural forms and those who began to make—out of industrialized metal and later from reinforced concrete—the new engineering forms by which we everywhere recognize the modern world. For these forms the ideas inherited from the masonry world of antiquity no longer applied; new ideas were essential in order to build with the new materials. But as these new ideas broke so radically with conventional taste, they were rejected by the cultural establishment. This is, of course, a classic problem in the history of art: new forms often offend the academicians. In this case, it was beaux-arts against structural arts. The skeletal metal of the nineteenth century offended most architects and cultural leaders. New buildings and city bridges suffered from valiant attempts to cover up or contort their structure into some reflection of stone form. In the twentieth century, the use of reinforced concrete led to similar attempts. Although some people were able to see the potential for lightness and new forms, most architects tried gamely to make concrete look like stone or, later on, like the emerging abstractions of modern art. There was a deep sense that engineering alone was insufficient.

The conservative, plodding, hip-booted technicians might be, as the architect Le Corbusier said, “healthy and virile, active and useful, balanced and happy in their work, but only the architect, by his arrangement of forms, realizes an order which is a pure creation of his spirit... it is then that we experience the sense of beauty.” The belief that the happy engineer, like the noble savage, gives us useful things but only the architect can make them into art is one that ignores the centrality of aesthetics to the structural artist. True, the engineering structure is only one part of the design of such architectural works as a private house, a school, or a hospital; but in towers, bridges, free-spanning roofs, and many types of industrial buildings, aesthetic considerations provide important criteria for the engineer’s design. The best of such engineering works are examples of structural art, and they have appeared with enough frequency to justify the identification of structural art as a mature tradition with a unique character. That character has three dimensions.
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The Three Dimensions of Structure

Its first dimension is a scientific one. Each working structure or machine must perform in accordance with the laws of nature. In this sense, then, technology becomes part of the natural world. Methods of analysis useful to scientists for explaining natural phenomena are often useful to engineers for describing the behavior of their artificial creations. It is this similarity of method that helps to feed the fallacy that engineering is applied science. But scientists seek to discover pre-existing form and explain its behavior by inventing formulas, whereas engineers want to invent forms, using pre-existing formulas to check their designs. Because the forms studied by scientists are so different from those of engineers, the methods of analysis will differ; yet, because both sets of forms exist in the natural world, both must obey the same natural laws. This scientific dimension is measured by efficiency.

Technological forms live also in the social world. Their forms are shaped by the patterns of politics and economics as well as by the laws of nature. The second dimension of technology is a social one. In the past or in primitive places of the present, completed structures and machines might, in their most elementary forms, be merely the products of a single person; in the civilized modern world, however, these technological forms are the products of a society. The public must support them, either through public taxation or through private commerce. Economy measures the social dimension of structure.

Technological objects visually dominate our industrial, urban landscape. They are among the most powerful symbols of the modern age. Structures and machines define our environment. The locomotive of the nineteenth century has given way to the automobile and airplane of the twentieth. Large-scale complexes that include structures and machines become major public issues. Power plants, weapons systems, refineries, river works—all have come to symbolize the promises and problems of industrial civilization.

The Golden Gate, the George Washington, and the Verrazano bridges carry on the traditions set by the Brooklyn Bridge. The Chicago Hancock and Sears towers, and the New York Woolworth, Empire State, and World Trade Center towers—all bring the promise of the Eiffel Tower into the utility of city office and apartment buildings. The Astrodome, the Kingdome, and the Superdome carry into the late twentieth century the vision of huge permanently covered meeting spaces first dramatized by the 1851 Crystal Palace in London and the 1889 Gallery of Machines in Paris.

Nearly every American knows something about these immense twentieth-century structures, and modern cities repeatedly publicize themselves by visual reference to these works. As Montgomery Schuyler, the first American critic of structure, wrote in the nineteenth century for the opening of the Brooklyn Bridge (figure 1.2), “It so happens that the work which is likely to be our most durable monument, and to convey some knowledge of us to the most remote posterity, is a work of bare utility; not a shrine, not a fortress, not a palace but a bridge. This is in itself characteristic of our time.”16 So it is that the third dimension of technology is symbolic, and it is, of course, this dimension that opens up the possibility for the new engineering to be structural art. Although there can be no measure for a symbolic dimension, we recognize a symbol by its elegance and its expressive power.

There are three types of designers who work with forms in space: the engineer, the architect, and the sculptor. In making a form, each designer must consider the three dimensions or criteria we have discussed. The first, or scientific criterion, essentially comes down to making structures with a minimum of materials and yet with enough resistance to loads and environment so that they will last. This efficiency–endurance analysis is arbitrated by the concern for safety. The second, or social criterion, comprises mainly analyses of costs as compared to the usefulness of the forms by society. Such cost–benefit analyses are set in the context of politics. Finally, the third criterion, the symbolic, consists of studies in appearance, along with a consideration of how elegance can be achieved within the constraints set by the scientific and social criteria. This is the aesthetic–ethical basis upon which the individual designer builds his work.

For the structural designer the scientific criterion is primary (as is the social criterion for the architect and the symbolic criterion for the sculptor). Yet the structural designer must balance the primary criterion with the other two.17 It is true that all structural art springs from the central ideal of artificial forms controlling natural forces. Structural
FIGURE 1.2
The Brooklyn Bridge over the East River, New York, 1883, by John A. Roebling. When completed, this steel-cable suspension bridge was the longest-spanning structure in the world. Its diagonal stays express Roebling's idea of how a flexible bridge must be stiffened to prevent failure due to oscillations from wind.
forms will, however, never get built if they do not gain some social acceptance. The will of the designer is never enough. Finally, the designer must think aesthetically for structural form to become structural art. All of the leading artists of structure thought about the appearance of their designs. These engineers consciously made aesthetic choices to arrive at their final designs. Their writings about aesthetics show that they did not base design only on the scientific and social criteria of efficiency and economy. Within those two constraints, they found the freedom to invent form. It was precisely the austere discipline of minimizing materials and costs that gave them the license to create new images that could be built and endure.

Structural Art and Society

Most people would agree that the ideals of structural art coincide with those of an urban society: conservation of natural resources, minimization of public expenditures, and the creation of a more visually appealing environment. As the history of structural art shows, some engineers have already turned these ideals into realities. But these are isolated cases; how might they become the rule instead of the exception? We can address this question historically, by identifying the central ideas that have been associated with great structural art. These ideas reflect each of the three dimensions: the scientific, social, and symbolic.

The leading scientific idea might be stated as that of reducing analysis. In structural art, this idea has coexisted with the opposite tendency to overemphasize analysis, which today is typified by the heavy use of the computer for structural calculations. One striking example comes from the design of thin concrete vaults—thin shell roofs. Here, the major advances between 1955 and 1980—a time of intense analytic developments—were achieved, not by performing complex analyses using computers, but rather by reducing analysis to very simple ideas based on observed physical behavior. Roof vaults characterize this advance and they carry forward the central scientific idea in structural art: the analyst of the form, being also the creator of the form, is free to change shapes so that analytic complexity disappears.

The form controls the forces; and the more clearly the designer can visualize those forces the surer he is of his form. The great early and mid-twentieth-century structural artists such as Robert Maillart and Pier Luigi Nervi have all written forcefully against the urge to complicate analysis. We shall see the same arguments put forth by the best designers in the late twentieth century. When the form is well chosen, its analysis becomes astoundingly simple. The computer, of course, has become more and more useful as a time saver for routine calculations that come after the design is set. It is also increasingly valuable in aiding the designer through computer graphics. But like any machine, while it can reduce human labor, it cannot substitute for human creativity.

Turning to the social dimension, a leading idea that has come out of structural art involves what might be called the economy of public design competitions. Design quality arises from the stimulus of competing designs for the same project rather than from complex regulations imposed upon a single designer. Thus, governments could insure better designs by relinquishing some of their control on who designs and on what forms are chosen, and by giving this control to an informed public. It is not enough for the public merely to protest the building of ugly, expensive designs. A positive activity is essential, and that can only come about when the public sees the alternative designs that are possible for a project. The idea and meaning of alternative designs can best be illustrated by the history of modern bridges, but it applies as well to all other works of structure.

Although there is little tradition in the United States for design competitions in structure, such a tradition is firmly rooted elsewhere, with results that are both politically and aesthetically spectacular. Switzerland has the longest and most intensive tradition of bridge design competitions, and it is no coincidence that, by nearly common consent, the two greatest bridge designers of the twentieth century were Swiss: Robert Maillart (1872–1940), who designed in concrete, and Othmar Ammann (1879–1965), designer of the George Washington and Verrazano bridges, who designed in steel. That Switzerland, one-sixth the size of Colorado, and with fewer people than New York City, could achieve such world prominence is due to the centrality of economics and aesthetics for both their engineering teachers and their practicing designers, a centrality which is encouraged by the design competitions. Maillart's thin concrete arches in Switzerland were the least expensive
proposals in design competitions, and they were later to provide the main focus for the first art museum exhibition ever devoted exclusively to the work of one engineer: The New York City Museum of Modern Art's 1947 exhibition on Maillart's structures. Othmar Ammann has been similarly honored; his centennial was celebrated by symposia both in Boston and in New York and by an exhibition held in Switzerland. Both Maillart and Ammann wrote articulately on the appearance as well as on the economy of bridges. They are prime examples of structural artists.

This Swiss bridge tradition continues today with a large number of striking new bridges in concrete that follow Maillart in principle if not in imitative detail. The most impressive post–World War II works are those of Christian Menn, whose long-span arches and cantilevers extend the new technique of prestressing to its limits, as Maillart's three-hinged and deck-stiffened arches did earlier with reinforced concrete. Design competitions stimulated these engineers and also educated the general public. Such competitions must be accepted by political authorities, must be judged by engineers whose opinions will be debated in the public press, and must be controlled by carefully drawn rules.

Once again, it is false images of engineering that keep us from insisting on following our normal instinct for open competitions. The American politics of public works falsely compares the engineering designer either to a medical doctor or to a building contractor. Supporters of the first comparison argue that you would never hold a competition to decide on who will remove your appendix; rather, you would choose professionals on the basis of reputation and then let them alone to do the skilled work for which they are trained. Similarly, if an already built bridge develops cracks, the solution is to hire a consultant who has a sound reputation for diagnosing and rehabilitating such defective works. But design is not the same kind of activity as diagnosis and rehabilitation. It needs more chances to exercise than there are chances to build, and it is stimulated by competition. However frustrating it may be to lose a competition, the activity is healthy and maturing, especially when even the losers are compensated financially, as they often are in Switzerland.

For proponents of the second false comparison, design competitions are to be run just as building competitions in which the lowest bid for design cost gets the design contract. In American public structures, design and construction are legally distinct activities. The cost of design is normally well below 10 percent of the cost of construction. Therefore, a brilliant engineer might spend more on a design which, as can often happen, will cost the owners substantially less overall. By the same token, an engineer who cuts his design fee to get the job may have to make a more conservative design which could easily cost the owner more in overall costs. Hence, large amounts of potential savings to the public are lost by a foolish policy of saving a little during the first stage of a project.

In one type of Swiss design competition, a small number of designers are invited to compete, some of whose costs are covered, and they get additional prize funds in the order recommended by the jury. The winner usually gets the commission for the detailed design. Only several such competitions a year are needed to stimulate the entire profession and to show the general public the numerous possibilities available as good solutions to any one problem. This method of design award opens up the political process to local people far more than does the cumbersome and largely negative one of protest, legal action, and negation of building that so dominates public action in the late-twentieth-century America.

Properly defined design competitions reveal truths about society that are otherwise difficult to define. The resulting designs, therefore, became unique symbols of their time and place. This brings us to the third leading idea that has been associated with great structural art—the idea that its materials and forms possess a particular symbolic significance. Perceptive painters, poets, and writers have recognized in structural art a new type of symbol—first in metal and then in concrete—which fits mysteriously closely both to the engineering possibilities and to the possibilities inherent in democracy. The thinness and openness of the Eiffel Tower, Brooklyn Bridge, and Maillart's arches, as well as the stark contrast between their forms and their surroundings, have a deep affinity to both the political traditions and era in which they arose. They symbolize the artificial rather than the natural, the democratic rather than the autocratic and the transparent rather than the impenetrable.

The primary reason that the Eiffel Tower and the Brooklyn Bridge became dominant symbols was that their forms were new, transparent, and accessible to the general public. Contrast these to the 1884 Wash-
ingston Monument and the 1831 London Bridge, two solid masonry structures that in their costly and monumental quality remind us of pre-industrial imperial eras rather than the democratic times in which they actually were built. Stone is a natural material; since the industrial revolution its use for structure has implied great cost and hence restriction to the wealthy. Moreover, its solidity, its inability easily to carry shifting loads, and its consequent massiveness imply heavy fortress-like forms. Metal and concrete, properly designed, in every way contrast with stone. They are artificially made materials. Their forms reflect directly the inner springs of creativity emerging from contemporary industrial societies.

These forms imply a democratic rather than an autocratic life. When structure and form are one, the result is a lightness, even a fragility, which closely parallels the essence of a free and open society. The workings of a democratic government are transparent, conducted in full public view, and although a democracy may be far from perfect, its form and its actual workings (its structure) are inseparable. Furthermore, the public must continually inspect its handiwork; constant maintenance and periodic renewal are essential to its exposed structure. Politicians do not have life tenure; they must be inspected, chastised and purified from time to time, and replaced when found corrupt or inept. So it is with the works of structural art. They, too, are subject to the weathering and fatigue of open use. They remind us that our institutions belong to us and not to some elite. If we let them deteriorate, as we flagrantly have in our older cities and transportation networks, then that outward sign betokens an inner corruption of the common life in a free democratic society.

These ideas about politics, about science, and about art both animate and integrate the historical account of engineering art to which we now turn for the substance of this book.