ROBERT MAILLART:

The Engineer's Synthesis of Art and Science.

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Maillart and the Unfractioned Idiom

In his recollections, Ernst Stettler, chief engineer of Robert Maillart's bridge design office in Bern, described his patron's weekly visits and concluded by observing that Maillart then went off to Zurich where he would meet with the avant-garde artists. Stealer's 1972 impression of Maillart in the 1930s becomes wildly inaccurate only with this final statement.[1] It reveals one feature of the modern world that helps create the academic illusions of our technological times.

Fig.1 Robert Maillart c1901

Because some of the avant-garde had lived in Zurich and had written about Maillart, Stettler thought that he must have become part of that modern movement in which ideas about art, aesthetics, and architecture abounded. He was completely wrong. Maillart spent his time in Zurich with engineers and mostly with his closest friend, the electrical engineer, Paul Nissen, whose connection with the avant-garde stopped with the light bulb. Rather Maillart stayed within the narrow confines of engineering; he did not desire or need the stimulus of intellectual discussions about new ideas in art; he was characteristic of engineers and his work is characteristic of engineering.[2] At the same time and because of that character, Maillart's ideas take us to the center of $_{20}$th century culture and that is how he dispels the academic illusions to which I shall return after describing the Maillart experience.

Robert Maillart (1872-1940) was born on February 6, 1872 in Bern to a Belgian father and a Swiss-German mother. He studied civil engineering at the Federal Polytechnic Institute in Zurich from 1890 to 1894 where he came under the influence of one of the greatest teachers of structural engineering, Wilhelm Ritter (1846-1906). Under Ritter, Maillart learned the scientific basis of structures, the practical context for the profession, and the visual power of form. It was an unusual education upon which he could draw throughout his 46-year career.[3]

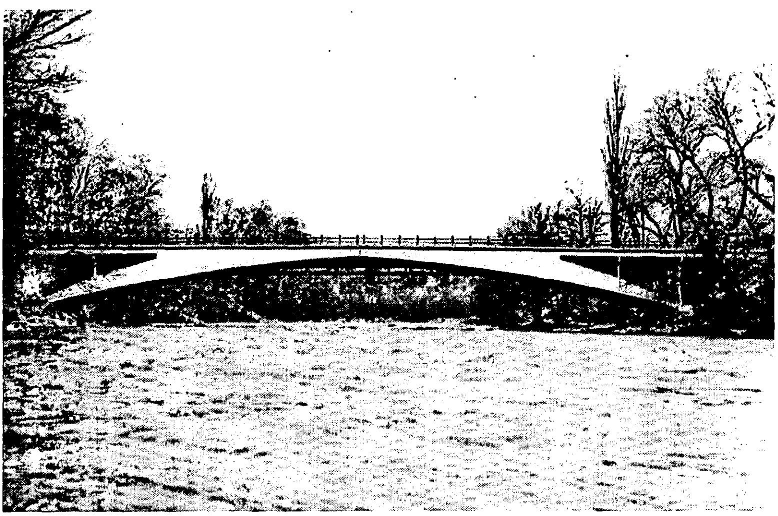

Fig.2 Vessy Bridge profile showing the broken arch and the narrow hinge sections at the abutments and at the crown

Maillart entered the profession at the same time as did a completely new material, the composite of concrete and steel, reinforced concrete. This was a fortunate period to begin designing structures because there were no rules, no codes, no standards, and no tradition. On the other hand, there were millennial years of tradition with stone and wood and a full century of experience with ferrous metal structures. Maillart, more than any other engineer, would find a way to abandon those older traditions and to establish one for this new and intriguing but ill understood material. Primarily with his modest alpine bridges and his few urban buildings, Maillart would astonish the avant-garde, infuriate the traditional art commissioners, and only barely penetrate the twentieth century academic engineering establishment.

One example with which I shall clarify the Maillart method is the Vessy Bridge of 1936 on the outskirts of Geneva. Here, after 40 years of practice, Maillart took the classical stone arch form and totally transformed it into shapes impossible to imagine before reinforced concrete. The arch is flat and broken at the crown where the thin vertical slit emphasizes the discontinuity created by a hinge. The buttresses at the abutments meet the arch at narrow points which expose hinges while the arch profile becomes deepest halfway between those hinges and the crown. The pattern of form boards tells the knowledgeable observer that the arch is hollow with a curved slab at the bottom and vertical walls that merge with the horizontal deck throughout the central half of the span. The arch, walls, and deck form an integral whole which we now call the hollow box in concrete. It was Maillart's first great innovation and it remains today a major structural form.

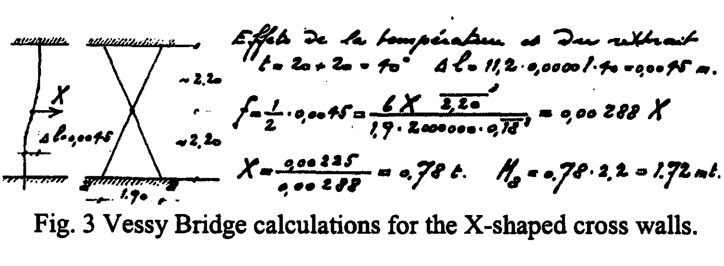

Fig. 3 Vessy Bridge calculations for the X-shaped cross walls.

But we find the most surprising aspect of the Vessy Bridge beneath its deck where the x-shaped cross walls give the structure a completely unique image which is, at once a fully rational design and the result of an aesthetic choice by the artist. Maillart's calculations demonstrate how the internal forces in those cross walls vary in magnitude exactly as the shape, which is, therefore, a prototypical example of engineering as a unity of art and science. But the bridges of Maillart could not even have been built had they not been politically acceptable. Indeed they never were in the traditional aesthetic world of the urban designers and politicians. It was only because the highly decentralized Swiss politics allowed local leaders to choose Maillart's designs, but even then only because they were never expensive and often less costly than standard designs. Moreover, his works could only have been built by a modern industrial society with careful workmanship and firm respect for plans and specifications.

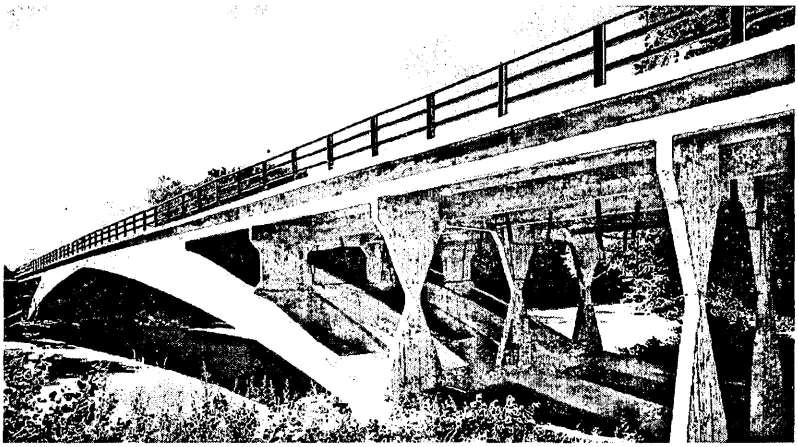
Fig. 4 Vessy Bridge showing the X-shaped crosswalls

We thus come to the central idea inherent in Maillart's bridges: that they cannot be understood without some insight into the physics of form, the context of politics, and the concept of structural art. In short, we find in a modest bridge a unity of knowledge that brings together in the terms of the three great liberal arts, natural science, social science, and the humanities. This is the meaning in Maillart, the iconographic study of our modern technological age, the character of engineering in public works.

But this unity does not come about from the disconnected study of the many so-called disciplines that adorn academic life at the turn of the millenium. This grand illusion reaches its fullest form in the so-called interdisciplinary studies that follow the disconnected ones. Maillart had no such courses just as he had no need to spend Zurich visits with the avant-garde. He had a teacher that brought the liberal arts into engineering in its most natural way, by showing that the cultural artifact, a bridge, required a consciousness of physics, politics, and art.

If you were to take a physics course on mechanics, a politics course on transportation policy, and an art course on modern painting, you would be totally unprepared to study a Maillart bridge. On the other hand, careful study of such a bridge could lead you into some understanding of mechanics, of how a democratic political

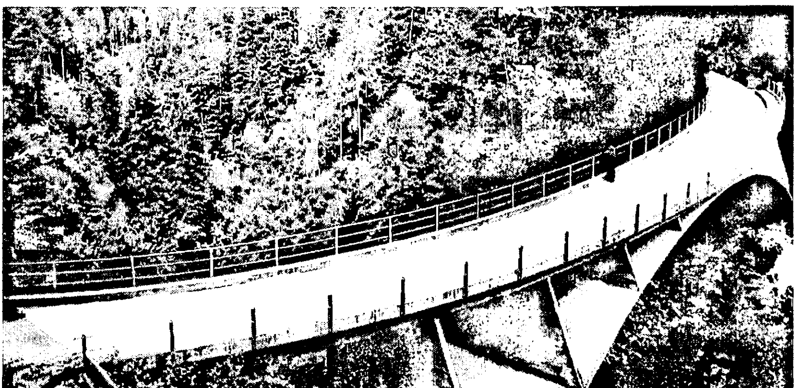

Fig. 5 Schwandbach Bridge with a thin arch integrated to the curved deck by trapazoidal cross walls.

system works, and of why a significant number of modern artists were so impressed with Maillart's art. A few objects in twentieth century culture allow this type of synthesis because they have a peculiar quality which might be called an unfractioned idiom, where every element seems reasonable in itself and fitting in its place within the whole. The Vessy Bridge is such a work and so is the 1933 Schwandbach Bridge, of a quite different form.

This Bernese structure exhibits Maillart's second major bridge innovation, the deck-stiffened arch. This new form in concrete consists of a thin arch and a relatively stiff deck. Maillart wanted the arch to be as thin as the bridge could be built, but still able to carry all traffic loads safely. A concrete arch can carry permanent loads when it is designed with the proper shape (for a load uniformly distributed over the horizontal bridge deck this shape would be a parabola). The difficulty comes when traffic loads only a part of the span length; then the arch will try to bend into a new shape. Such bending would normally break a very thin concrete arch so that engineers were compelled to design thick, heavy arches. Those designs were an anathema to Maillart; he reacted against massive concrete as a musician to tone deaf singers. How could he achieve extreme thinness with complete safety? This was the first of two basic challenges to innovation in structural art.

Maillart answered with the brilliant idea, quite obvious in retrospect, of using the bridge deck to stiffen the arch. Since his modest mountain structures had parapets, he thought, why not use them to prevent the evil bending from damaging his thin sliced arches. This deck-stiffened arch works because the arch and deck are connected firmly together by a series of cross walls. Then as the arch tends to bend when loaded say by traffic over one half of the span, the cross walls make the deck bend to the same new shape as the arch. The bending effect is now shared between arch and deck and, as Maillart further reasoned, that effect will load each part in proportion to its stiffness. (The load required to compress each of two springs the same distance will be proportioned to their stiffnesses.) Thus the arch, made far more flexible than the parapet, will now have very little bending and happily can be both strikingly thin and predictably safe.

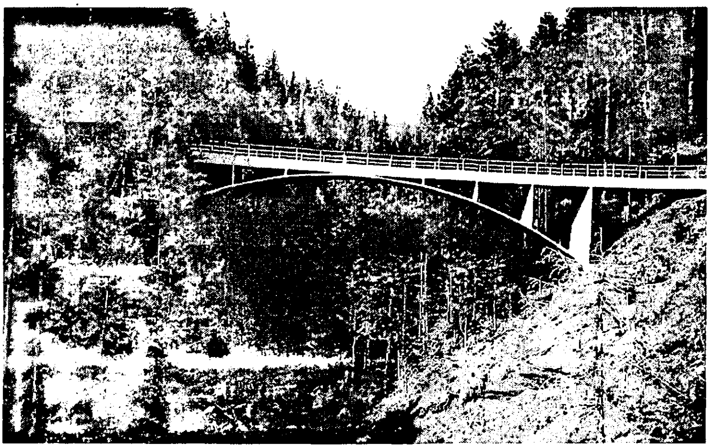

Fig.6 Schwandbach profile showing the thin arch and the stiff horizontal deck

Maillart met the first challenge by conceiving of a new form and correctly imagining how it would work; but the second challenge now was to find a reliable mathematical analysis to quantify the bending effect and thus to dimension his structure in detail. If Maillart's concept was radically new in an age where concrete arch beauty was related to Roman stone arch form, his mathematical analysis appeared to academic engineers to border on treacherous lunacy. First Maillart assumed that his thin arch actually had three hinges, one at each abutment and one in the crown. Of course it had no such mechanism. Second, and using that first assumption, he blatantly assumed that the arch had no bending whatsoever; all bending was to be in the deck. For the professors in Zurich this was *Tanzboden Statik* (dance floor calculations).

Why were leading Swiss academics horrified by such a cavalier disregard for modern analysis? To answer this question we need to go back to the 1920s and to the emerging 20th century academic attitude to research. This was the time when research laboratories in the United States and research institutions in Europe were making great discoveries and turning them into practical applications. There was growing the belief that engineering design was really applied science, that scientists discovered after which engineers applied. Mathematically trained engineers began to see themselves as scientists with the practitioners as merely applying the insight and methodologies developed in research settings.[4]

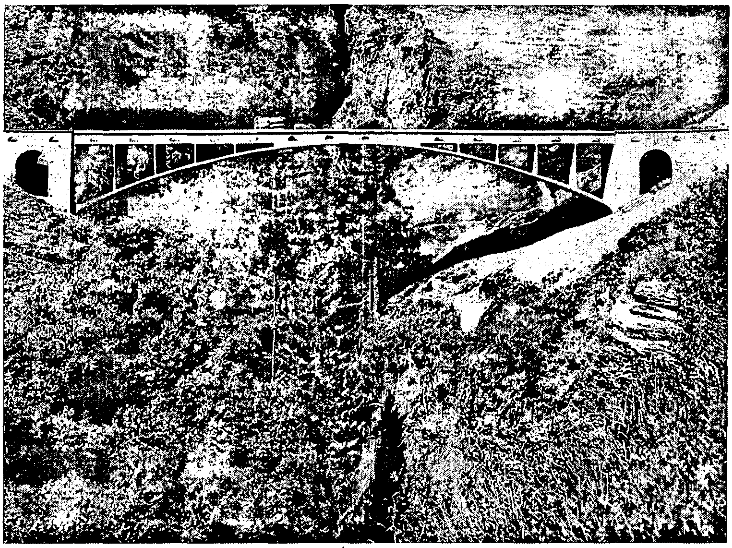

Fig. 7 Valtschielbach Bridge where the parapet stiffens the thin arch.

For structures, like the arch bridge, these academics had developed a complex methodology called statically-indeterminate analysis. For the Schwandbach Bridge, this analysis required the solution of nearly 30 simultaneous equations, a huge project in slide-rule days. Maillart solved the problem without any such equations. His analysis for the Valtschielbach Bridge of 1925 took one third of a page; later such analyses by his chief detractor at his alma mater took over 100 pages of calculations. Since that professor was spending his career developing such methods, it is no wonder that Maillart's approach would seem not only ridiculous but immensely threatening. Indeed in the 1940s one of his students proudly announced that the professor had succeeded in simplifying his general equations down to a brief approximate solution — just what Maillart had used two decades before.[5]

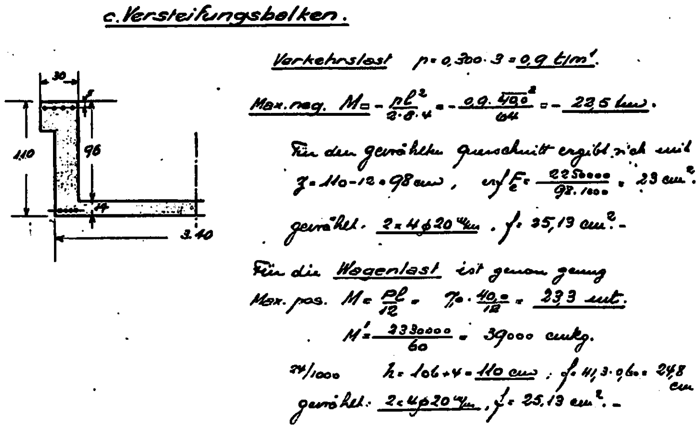

Fig.8 Calculations for the bending in the parapet of the Valtschielbach Bridge under half span live load.

The crucial breakthrough Maillart achieved was to develop an analysis ideally suited to the design that he had chosen for aesthetic reasons. His art dictated his science. His vision of form suggested its formula. But his method was suited only to his design; it would have been ridiculous if applied to a fixed heavy arch supporting a light deck. Maillart made function follow form. He decreed, by choosing his form, exactly how his structure would function. He then proceeded to develop an analysis suitable to that function. But that did not end Maillart's engagement with his structure; his new form had finally to pass its severest test, full-scale under heavy loading.

Each stage in this process is, at heart, a visualization. The designer learns to see, to imagine and to inspect. But to insure that his image will perform over its lifetime, the structural artist has to be convinced that the builder can construct it both correctly and economically. The art and the science must be integrated through a social process which requires the choice of a builder and the control of the costs. Structural artists must, therefore, not only imagine how the form will function but also how it will be brought into being. They must be builders as well; they need to develop novel construction procedures to make their new designs economical to build.

Maillart founded his own design-construction company when he was 30 and ran it successfully for 16 years. His innovations arose in an effort to achieve competitive structures and none was more useful to his business than the flat slab, what he called his mushroom slab (Pilzdeck). After large-scale testing in his construction yard, Maillart took out a patent in 1909 for a concrete floor system without any beams to support the slabs. Here was a flat concrete floor that rested only on a series of widely spaced columns. Maillart faced two major engineering problems with his new floor: how to connect the vertical columns to the horizontal slab and how to reinforce the stiff concrete slab with slender bars of steel.

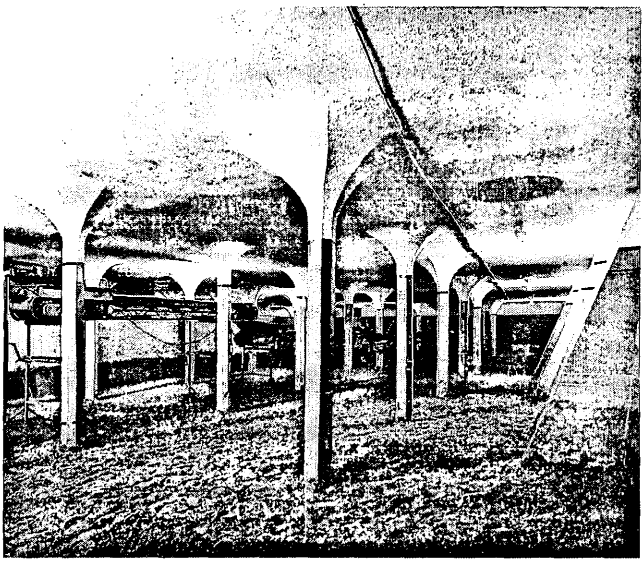

Fig.9 Hyperbolic flared capitals that connect columns to the roof slab of the filter building at Rorschach.

His solution to the connection, being a visible one, illustrates once again the intimate linkage between aesthetics and technique - between art and science. For this linkage, creating structural art, Maillart saw that he could widen the columns smoothly so that its capital merged without a break into both the vertical column and the horizontal floor. Maillart designed this hyperbolic form because it appealed to him visually and because it provided extra support for the slab. Moreover, the continuous curve directed the internal forces smoothly from the slab down into the column. Here the adverb smoothly provides an aesthetic and a technical meaning. The smooth capital was for Maillart more beautiful than one copied from Greek orders; and for the internal stresses, it is more rational by avoiding the dangers of cracking. But the linkage required Maillart to build his flat slab floors economically. For this he made the columns octagonal and the capitals thus splayout in eight surfaces, each one curved in elevation but composed of flat surfaces circumferentially. He could then form the capitals with straight wooden boards, achieving an inexpensive construction with the image of a flowering column reaching upward and outward to carry its floor.

Along with his visible solution went his answer to the placement question of reinforcing steel bars within the concrete floor. Maillart understood the behavior of slabs on column supports well before any theoretical approach had been published; he recognized that the bars could be placed in a rectangular grid that would be cheap to layout and build. Today Maillart's solution seems obvious and is the standard throughout the world, but in the first two decades of the 20th century few engineers recognized this simplicity. The American pioneer, C.A.P. Turner, propagated a complex reinforcing system based upon the contorted notion that all bars should converge over the columns, a costly complexity. Turner and nearly all others also followed imitative Greek capitals and designed awkward connections between column and floor.[6]

Maillart's three great innovations, the hollow box, the deck-stiffened arch, and the mushroom slab, each illustrate his design ideal of the fully integrated structure, examples of his unfractioned idiom. Seeing these works at the end of the century and over 75 years after their conception, one is struck by their modernity. They are not out of date or obsolete, yet they are prototypical works of modern engineering. The automobiles that first crossed his bridges have long since entered the antique market. The ethos of engineering seems to require continual change, acceleration of invention, and the discarding of even recently built innovations. How is it that Maillart's best structures have never lost their modernity?

The most obvious answer would be that they are works of art and almost by definition such things do not go out of date. Paintings by Klee and Mondrian are as fresh and vigorous today as they were when they first came to the attention of the art world, simultaneously with Maillart's designs. But merely claiming that Maillart's structures are art is not enough since they so clearly symbolize politics and physics. Clearly, that is, to those who know his story. That is why they represent the unfractioned idiom of our technological century; they bring together science, society, and symbol. The first two provided the disciplines for Maillart whereas the third helps explain his sense of play.

Natural Science and Engineering Innovation

The common belief that engineering is merely the application of scientific discoveries was put in its most notable form by Vannevar Bush in his 1945 report to President Harry S. Truman that led to the establishment of the National Science Foundation.

> 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.[7]

Politically this was a powerful and convincing argument for the establishment of a governmentally funded organization devoted to supporting scientific discovery. Intellectually it is an argument that in a 1973 symposium led the leading historians of technology to reject Bush's viewpoint and replace it with a more complex and historically accurate accounting. In short, the historians agreed that engineering was and is an activity separate and distinct from science. However, in the public mind, engineering is still viewed as a spin off from science so that clarity requires further analysis. And one observation essential to this further inquiry is that there is not one simple idea of engineering but rather four ideas and that each has a different history with a different relationship to science.[8] I shall briefly sketch these four ideas of engineering — structure, machine, network, and process — and then focus only on the first one which Maillart's career best illustrates.

Each idea has one major figure that characterizes its modern origins, i.e, during the early industrial revolution from about 1779 to 1879. Thomas Telford was the first major modern engineer of structure. He had no formal scientific or engineering education and indeed he came into structural engineering through architecture. He was not stimulated by any scientific discovery but rather by the 1779 Iron Bridge and he went on to create the first modern metal arch and suspension spans. His work stimulated the first scientific treatise on suspension bridges and in addition provided models for the next generation of bridge designers.

James Watt, often referred to as the father of mechanical engineering, like Telford had no formal education and came to machine design through work as an instrument maker. He conceived his major invention, the separate condenser, while studying a Newcomen engine and recognizing how it could be made far more efficient. There was no direct stimulus from any scientific discovery and indeed the science of thermodynamics came directly from the steam engine. Carnot's treatise began as an attempt to understand and explain the behavior of that type of engine, already in mature service for half a century.

When we come to networks the story has another direction because, unlike with structures and machines, the scientific discovery of electricity and magnetism preceded the design of the telegraph, the first great engineering network. How do we account for the prodigious genius of Thomas Edison? He clearly was centrally stimulated by the telegraph yet he, like Telford and Watt, was without any formal education in science and engineering. His remarkable engineering insight required no scientific foundation but as he moved into the large-scale network of power and light he definitely needed scientific collaboration, provided primarily by Francis Upton, a well-educated physicist-electrical engineer. So with networks there is a closer connection both to scientific discovery and to the continual benefit of new scientific ideas. This is why Vannevar Bush, an electrical engineer, would mistake his own field for all of engineering.

The fourth major idea, process, is like network, a system, rather than like structures and machines which are objects. A central figure in the first great process industry was Henry Bessemer whose invention led to economical steel making. Like the others, Bessemer had no formal education, but rather began as an inventor. Nevertheless his first Bessemer process did not work well and only after intensive collaboration with trained scientists was he able to convert his invention into an innovation and hence a major commercial success. Whereas networks tended to bring engineers close to physicists, processes seemed to require interaction between chemists and engineers.

The tapestry of engineering innovation is richer than this coarse weave suggests, but the principal picture is the same. Engineering is predominately an activity independent of natural science in the sense of its origins even though its refinements sometimes call for collaboration with scientists. Engineering is largely not applied science. Yet its works live in nature and must therefore follow nature's laws. Science is one of the disciplines of engineering even if not its primary stimulus.

When we turn to the twentieth century, the history is much the same with the structures of Maillart, the aircraft machines of the Wright Brothers, the radio networks of Howard Armstrong, and the chemical cracking process of William Burton. So now I shall return to Maillart and his relation to natural science, in this case the primary force of nature, gravity, and the material nature of concrete and steel.

The interaction of gravity and structural form had led the Romans to design relatively long span arches long before the origins of any science of mechanics. The Romans also had well understood concrete made from a natural (pozzolan) cement. But reinforced concrete did not arrive until the late 19th century through the inventions primarily of two Frenchmen, neither of whom had any schooling in engineering or science: Joseph Monier (1823-1906) was a gardener and François Hennebique (1843-1921) was a builder. Quickly in the 1890s, trained engineers saw the wide possibilities for the new composite material and by the time Maillart graduated from engineering school, reinforced concrete was *the* new structural material.

Maillart's education was the best available and his principal teacher, Wilhelm Ritter grounded his students in the mathematics and science of structures but with one unique perspective, graphic statics. This visual approach to what was and is even today, an abstract mathematical analysis, forced students to think visually as well as algebraically. But even more critical was Ritter's teaching of both current practice and aesthetic appreciation. Missing entirely was any reference to reinforced concrete structures. Maillart would have to learn that on his own which he did from 1894 to 1901 as he worked for other people. That apprenticeship gave him the opportunity to study the new material under the pressure of having to make designs in a business setting. Especially from 1899 to the end of 1901 he worked for an affiliate of the vast Hennebique organization where he absorbed the state-of-the-art and quickly recognized how to improve on it.

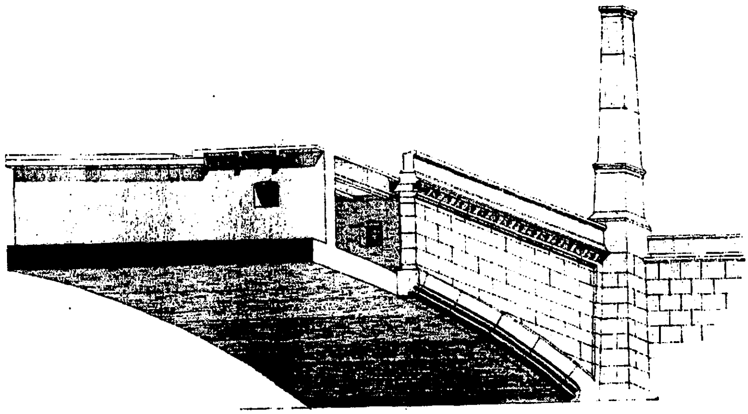

Fig.10 Stauffacher Bridge with a heavy arch that supports the crosswalls and deck as well as the masonry wall façade.

During these two years he created his first major innovation, the hollow box, by reflecting on his 1899 Stauffacher Bridge in Zurich. This structure consisted of a relatively heavy unreinforced concrete arch supporting cross walls which in turn carried the reinforced concrete roadway deck. The city insisted on fake masonry walls to give a stone masonry look. Such was the urban aesthetic that would block Maillart's later designs from Swiss cities. Maillart saw that the fake walls could integrate the arch and deck to create a new form thanks to the monolithic quality of field-cast reinforced concrete. The next year, in the wilderness of the Graubunden Canton, Maillart designed a bridge in this new integrated form for the little town of Zuoz. His stimulus was the image of the Stauffacher Bridge and the nature of the new material. There was no scientific discovery that preceded the idea. In fact it is just this lack of a stimulus from science that allows for the type of creativity Maillart possessed.

Natural Science and Structural Art

Classical physics and the chemistry of cement help to explain the performance of the Zuoz Bridge under loading but they do not explain Maillart's choice of form. That choice is the province of the designer; it is the hallmark of design and its origins lie in the imagination. The structural artist is someone who can imagine new forms that safely obey the laws of nature and, in addition, respect the rules of society. Disregard for nature risks collapse, disrespect for society wastes public funds. These

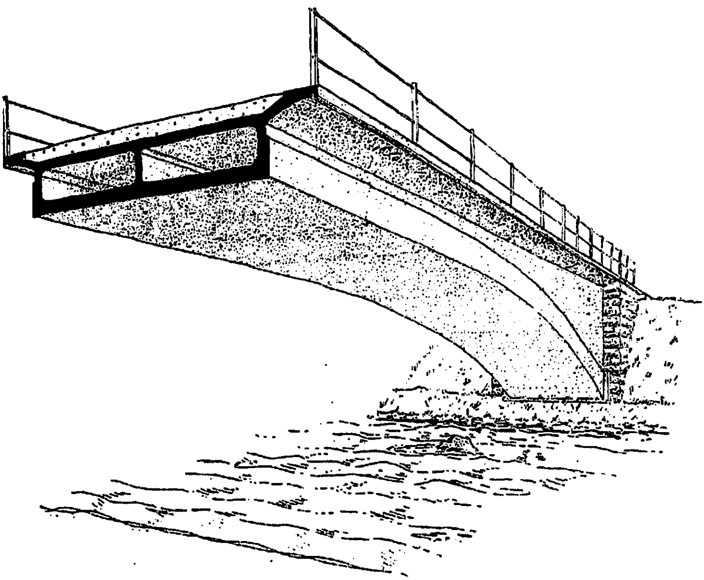

Fig.11 Hollow box, three-hinged arch bridge at Zuoz.

are the two disciplines of structural art: safe physical performance with minimum materials and reliable construction for competitive cost.

At Zuoz Maillart could reduce the arch thickness to one-third that of Stauffacher while greatly increasing the bridge's strength and hence safety. At the same time his design was competitive with a steel truss alternative. The truss would have been slightly less costly to build but more expensive to maintain. But following these disciplines never leads automatically to structural art. At the same time, continual contemplation of those disciplines provided Maillart with a stimulus to improve on his works. At Zuoz the Graubunden authorities forced Maillart's contemplation by asking him in 1903 to study and report on the cracks that appeared in the bridge walls near abutments. He realized a mistake in the design, not one that endangered the structure but one that made him rethink the form.

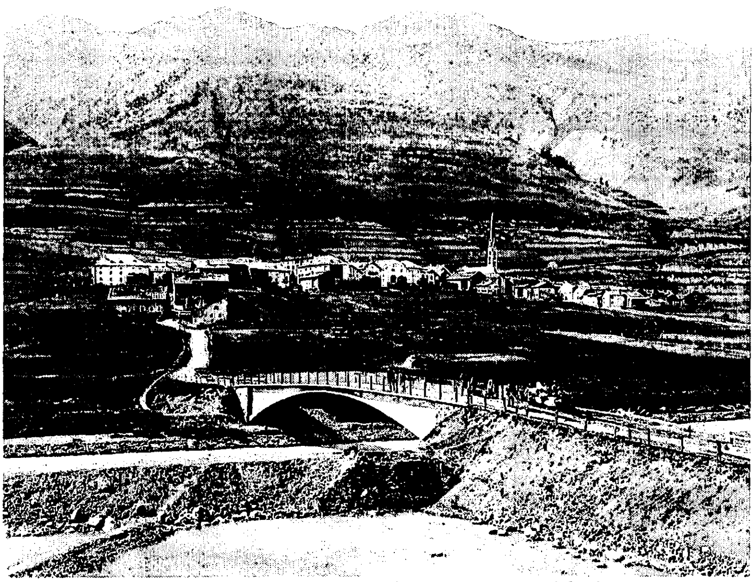

Fig.12 Bridge at Zuoz over the Inn River with the town in the background.

The designer can control cracks in concrete by adding steel reinforcing or by changing the form. The former approach is easier and most engineers favor it because new forms are risky and demand contemplation. Maillart, however, took the risk and followed his passion for minimum material by eliminating those parts of the walls which showed cracks. Following this minimalist line, Maillart created a new form that represents, I believe, the first great work of structural art in concrete, the Tavanasa

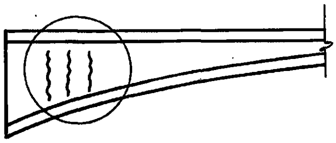

Fig.13 Cracks in the Zuoz Bridge.

Bridge of 1905, like Zuoz a Graubtinden work. By this time Maillart had his own design-construction company (founded in early 1902) so that he could build his own designs. Being financially responsible for the bridge forced Maillart to think carefully about costs and the quality of his designs. Later on owners would give Maillart contracts, even where he was not the lowest bidder, because of his reputation for high quality construction.

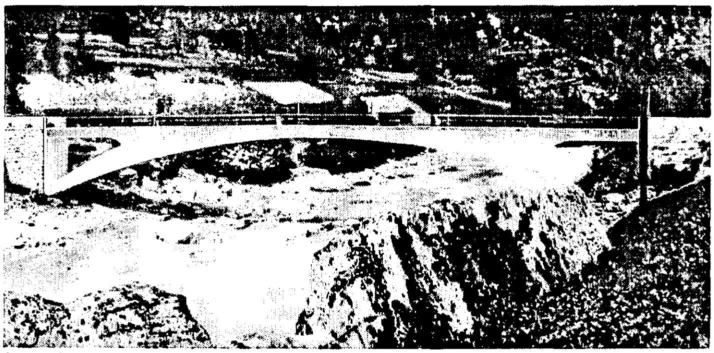

Fig. 14 Tavanasa Bridge showing the profile with the walls near the abutments cut out.

Zuoz and Tavanasa also represent a new construction idea. He designed the falsework (or scaffold) and formwork to support only the thin curved arch slab. Once hardened that slab could then support by itself the walls and deck of the hollow box. He thus economized on the costly temporary scaffold built in the river.

Proof of his construction on both bridges was the carefully instrumental full-scale load test carried out before the owners would accept the bridges. These were laboratory tests that often revealed small defects and always allowed Maillart to check his calculated predictions of performance. In that sense, he was discovering things about his structures as would a scientist, but always with the goal of improving the next design.

Fig. 15 Salginatobel Bridge

Tavanasa was, however, the last great bridge that Maillart would design and build. The high art world found it offensive and it blocked him for a quarter of a century. Then Tavanasa returned but sacrificially. Destroyed in a 1927 avalanche, the bridge resurfaced in an improved form a few kilometers away in the spectacular Salginatobel Bridge of 1930. Maillart was then only a designer, having lost his construction business because of an enforced stay in Russia during World War I. But he never lost his construction imagination — the visualization not just of the final form but also of its transient forms as it comes into being. As a result his 1928 Salgina design, submitted with a builder in a competition with 18 other designs, was the least expensive and thereby won the contract.

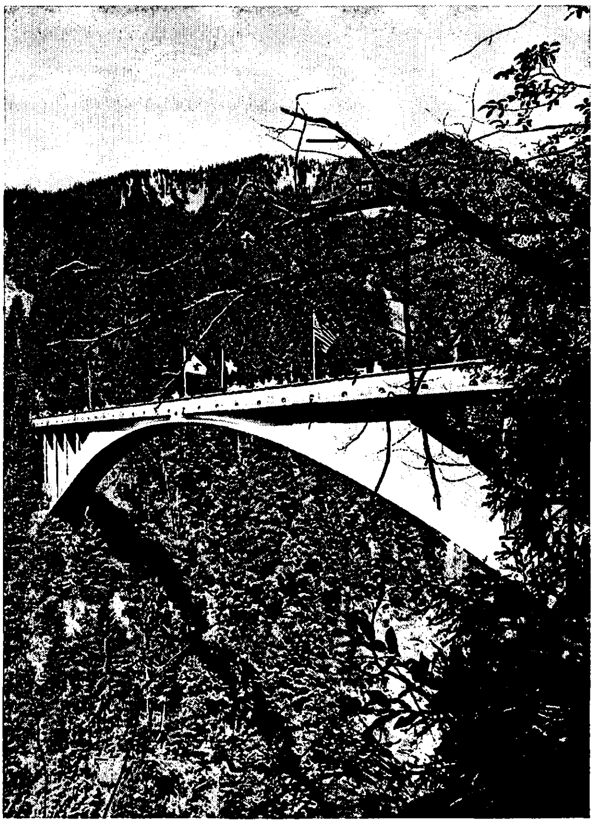

Fig.16 Dedication of the Salginatobel Bridge as an International Historic Civil Engineering Landmark

He had contemplated his lost Tavanasa, making redesigns in late 1927 and early 1928 in the vain hope of getting that contract.

So when the Salgina competition opened in the summer of 1928, he was ready with an improved form, one that abandoned all obvious references to the past (Tavanasa had stone abutments) and that extended the span to 90 meters over a deep ravine (Tobel). The bridge is now generally regarded as the greatest concrete bridge up to 1930 and in 1991 was named an international historic civil engineering landmark — the first concrete bridge so honored and only the 13th such landmark of any type. It was the culmination of Maillart's work in that sparsely settled Canton of the Graubtinden; after that he would spread the form throughout Switzerland until his death in 1940.

In 1932 he completed a similar bridge in the Canton of Bern, the Rossgraben, and in the next year one at Felsegg in the Canton of St. Gallen. In contemplating his Salginatobel Bridge Maillart recognized an error, not in the physical sense but in the visual expression. He had made the underside of the arch with a continuously smooth curve from abutment hinge to abutment hinge. This was wrong, he later wrote, because the hinge at the crown, representing a discontinuity physically, should be expressed visually. At Felsegg he broke the arch at the crown to make it more logical, as he said, but also to create a new form. It was this broken arch idea that he then used at Vessy several years later. The Vessy form is bolder, more dramatic, and still less expensive than earlier designs. All of his modifications had scientific justification but they arose in his mind from aesthetic motives.

Maillart was showing the way for all structural artists and a brief look at his successor in Switzerland, Christian Menn (b. 1927) will show the same motivation and improvements as he contemplates new designs. Three bridges will characterize Menn's search for new forms during the last half of the 20th century in the same way that Maillart did during the first half.

Like Maillart, Menn's early works (during the 1960s) were largely in the Graubtinden, his home Canton. But they gained him a national reputation which became fully confirmed with his competition winning design for the 1974 Felsenau Bridge just outside of the Swiss capital of Bern. Here Menn took the by-then standard prestressed concrete cantilever construction and modified it into the finest of these bridges anywhere and the longest spanning work in Switzerland up to that time.

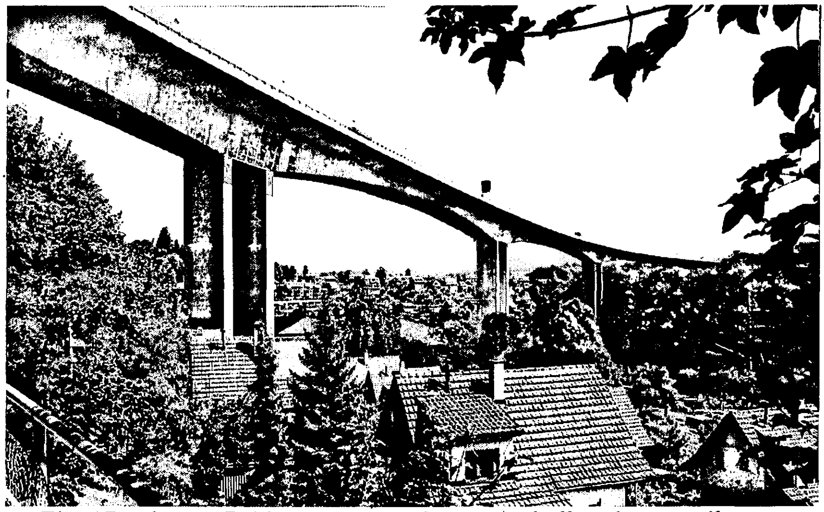

Fig. 17 Felsenau Bridge, prestressed concrete hollow-box cantilever.

Several years later the Federal Highway department asked him to explore a design for the Simplon Road which he turned into the low cable-stayed Ganter Bridge of 1980. Here he could have easily designed a Felsenau-type form but that did not satisfy him because the bridge height is so much greater at Ganter.[9] Because of the visual weakness Menn observed in similar high viaducts (especially the Kocherthal Bridge in Germany), he decided to carry the columns above the deck and support the span by cables radiating from the top. Because the spans are relatively short, he could support them by cables that did not require a high tower. Because of the roadway curve, he encased the cables in concrete thus creating a powerful profile completely unique but well within the disciplines of structural art.[10]

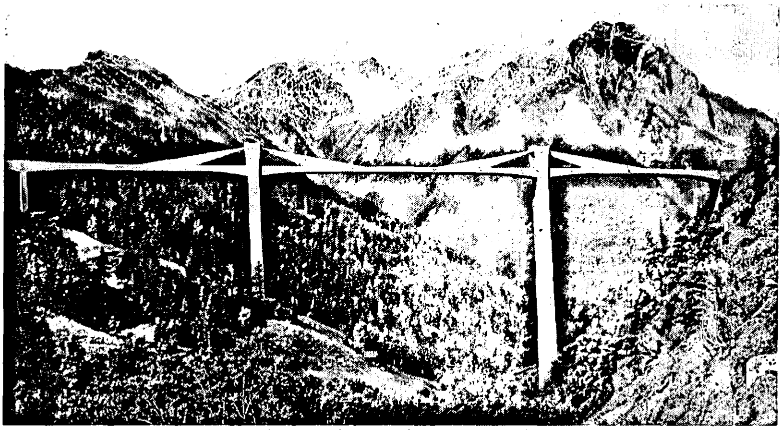

Fig. 18 Ganter Bridge. A low cable-stayed bridge with cables encased in concrete.

Yet on this famous bridge, which found its way onto the covers of numerous technical journals, Menn realized a serious visual defect. He had been so intent on the overall s-shaped plan and the striking profile view, that he overlooked the image of the towers as seen by a driver crossing the bridge. The towers are connected by a rectangular crosspiece devoid of elegance. Like Maillart's stone abutments at Tavanasa and smooth curve at Salginatobel, Menn's cross pieces presented no scientific difficulties. It was on his latest bridge that he found a way to avoid this difficulty and to make further improvements on his low cable-stayed bridge ideas.

The 1998 Sunniberg Bridge, built on a curve and high above one of the most beautiful Swiss valleys, Menn achieved the same type of perfection that Maillart did at Vessy. It seems to be a splendid coincidence that this end of century bridge stands only a few kilometers from the Salginatobel Bridge. Sunniberg is destined to become such a landmark. Here Menn paid special attention to the tall columns which he has shaped as two thin corrugated sheets, one on either side of the roadway. They flair out at the top parallel to the roadway and they are smoothly inclined outward from the deck so as to allow the cables to meet the curved roadway without the need for an encasement of concrete. Above the roadway there is no connection between these columns. They are complete by themselves and their extreme thinness opens up the luxuriant valley view from below.[11]

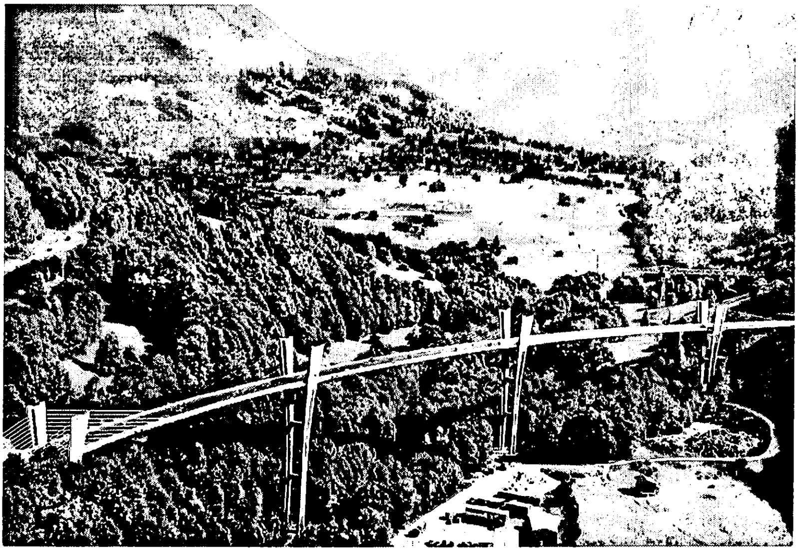
Fig.19 Sunniberg Bridge. A low cable-stayed bridge on slender columns.

Menn, like Maillart, received a sound scientific education at the Zurich engineering school and like Maillart he had an inspiring teacher, Pierre Lardy (1903-1958). Lardy, like Ritter, was an artist of piano and taught his students both mathematical rigor and visual sensitivity. In an almost mystical way, Lardy can be sensed in the region of the Salgina and Sunniberg.

There in 1929, as a teacher of mathematics in Schiers (he had a doctor's degree in mathematics), Lardy saw the Salgina arise and the next year returned to Zurich, changed careers and got a second doctor's degree, this one in structural engineering. Ritter and Lardy were not designers but they are crucial figures in the history of structural art. They taught their students about this tradition and their students never forgot their lessons. What they taught and what their students learned was the unfractioned idiom of structure as a natural consequence of the needs of the modern world.

The Unfractioned Idiom of the Twentieth Century

> Again the traffic lights that skim thy swift
> Unfractioned idiom, immaculate sign of stars,
> Beading thy path—condense eternity:
> And we have seen night lifted in thine arms.[12]

America's most famous lyric poet of the first third of the twentieth century published these lines in praise of a bridge at just the time the Salgina was crossing its Tobel. It was part of Hart Crane's mission to make sense of America in the early $_{20}$th century by creating an object of unity, a unifying symbol of the new technological culture. The poet's search was for a spiritual interpretation of a material culture and Brooklyn Bridge caught his imagination. Many writers and painters of the 1920s saw in that bridge the same meaning for the still young republic. It was an heroic work, designed by the powerful genius of John Roebling and built by the courageous tenacity of his son Washington Roebling. Its form reflected the $_{19}$th century fascination with ancient styles (the Gothic towers) and the 20^{th} century's discovery of new possibilities (the cabled spans). Moreover, it embodied the politics of urban America complete with scandals, high ethical actions, and the amalgamation of America's first and third largest cities (Manhattan and Brooklyn).[13] Physics, politics, and painting combined to tell the story of a bridge. That is its idiom but to the general public that idiom lies hidden behind the form; its history is a secret that only education can reveal.

This hidden idiom is like the "secret history" George Sarton identified in essays that appeared in his journal *Isis* (1921 and 1924) at the same time as artists were discovering the Brooklyn Bridge. As he put it: "The history of mankind is double: political history which is to a large extent a history of the masses, and intellectual history which is largely the history of a few individuals."[14]

He contrasts the emperors, Caesar and Napoleon, who could accomplish nothing without the collaboration of millions, with Spinoza, Newton, and Pasteur who worked on their own in seclusion. These latter made up "the essential history of mankind [which] is largely secret." And Sarton took it as his life mission to reveal that secret history through the history of science, in which he found the unity of mankind, a unity that "is hidden but deep-seated". In other words the unfractioned idiom.

Art historians have found this idiom in the best paintings and Crane sought it in his book-length poem *Brooklyn Bridge.* So it is that we may find that idiom in the works and ideas of a few extraordinary engineers such as Maillart and Menn. They have linked the science of structure to the images of structural art and created bridges that illustrate the potential in our material culture for new structures both in public works and in higher education.

References

[1] ERNST STETTLER, "Reflections on Maillart", *Maillart Papers,* Dept. Civil Engineering, Princeton University, 1973, pp. 129-136.

[2] DAVID B. BILLINGTON, *Robert Maillart: Builder; Designer and Artist,* Cambridge University Press, New York, 1997. All discussion of Maillart's works and ideas come from this biography.

[3] DAVID P. BILLINGTON, "Wilhelm Ritter, Teacher of Maillart and Ammann", *Journal of Structural Division, ASCE,* Vol. 106 *(5T5),* May, 1980, pp. 1103-1116.

[4] DAVID P. BILLINGTON, *Robert Maillart's Bridges: The Art of Engineering,* Princeton University Press, Princeton, N.J., 1979, Chapter 9. For the "Tanzboden Statik" see Stettler, *op. cit.*

[5] R. MAILLART, *Brücke ilber den Valtschielbach: Statische Berechnung,* No. 4094/4, Geneva, April 20, 1925, p. 4. For Ritter's calculations see letter from Ritter to the City, February 12, 1934. For Ritter's simplified solution, see Billington (1979), *op. cit.,* p. 103.

[6] R. MAILLART, "Zur Entwicklung der unterzulosen Decke in der Schweiz und in Amerika", *Schweizerische Bauzeitung,* Vol. 81 (No. 21), May 22, 1926, pp. 263-267.

[7] VANNEVAR BUSH, *Science, The Endless Frontier: A Report to the President,* Washington, D.C., 1945; cited and discussed in Edwin Layton, "American Ideologies of Science and Engineering", *Technology and Culture,* Vol. 17, 1976, p. 689.

[8] These ideas are described in some detail in David P. Billington, *The Innovators: The Engineering Pioneers Who Made American Modern,* John Wiley & Sons, Inc., N.Y., 1996, chapter one.

[9] DAVID P. BILLINGTON, "Swiss Bridge Design Spans Time and Distance", *Civil Engineering,* Vol. *51,* Nov. 1981, pp. 42-46.

[10] CHRISTIAN MENN and HANS RIGENDINGER, "Ganterbrücke", *Schweizer Ingenieur undArchitekt,* Vol. 97, 1979, p. 736.

[11] "Sunnibergbrücke", *Schweizer Ingenieur und Architekt SC+A,* No.44, 1998, Special offprint 25 pages.

[12] *The Complete Poems and Selected Letters and Prose of Hart Crane,* Ed., Brom Weber, Doubleday & Co., Inc. Garden City, N.Y., 1966, p. 46.

[13] ALAN TRACHTENBERG, *Brooklyn Bridge; Fact and Symbol,* Oxford University Press, New York, 1967.

[14] GEORGE SARTON, "Secret History", *The Life of Science: Essays in the History of Civilization,* Indiana University Press, 1960, pp. 61-64.