THE ODYSSEY OF INTUITION:

A Non-Reductive Interpretation of Technology through A Case Study of Bridges

by

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ABSTRACT

Between the idea and the reality lies the realm of the "creative act." The theme of this thesis deals with the realm inbetween abstraction and conception, knowing and doing, art and science, theory and practice. By using the particular realm between the architect and the engineer as the point of departure, the varying perceptions and definitions of the "bridge" are established.

Two levels of definition are proposed: first, the architects' and engineers' framework for defining "bridge," and secondly, the ontic-ontological dimensions of the "bridge." The case studies provide the facts to which these definitions can be applied.

Using the constraints of a historical time-frame, changes in bridgebuilding are documented and evaluated to provide the basis for the interpretation of technology.

Thesis Supervisor: Waclaw Zalewski

Title: Professor of Structures

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To Peter McCleary, in appreciation for advice and comments made in contribution to the development of this thesis, and to my advisor, Waclaw Zalewski, for his guidance.

To construct a bridge with a span greater than any attained previously not only requires great technical knowledge and ability, but also intuition and creative daring, since it represents a triumph over forces of nature and progress in the battle against human insufficiency.

F. Stussi

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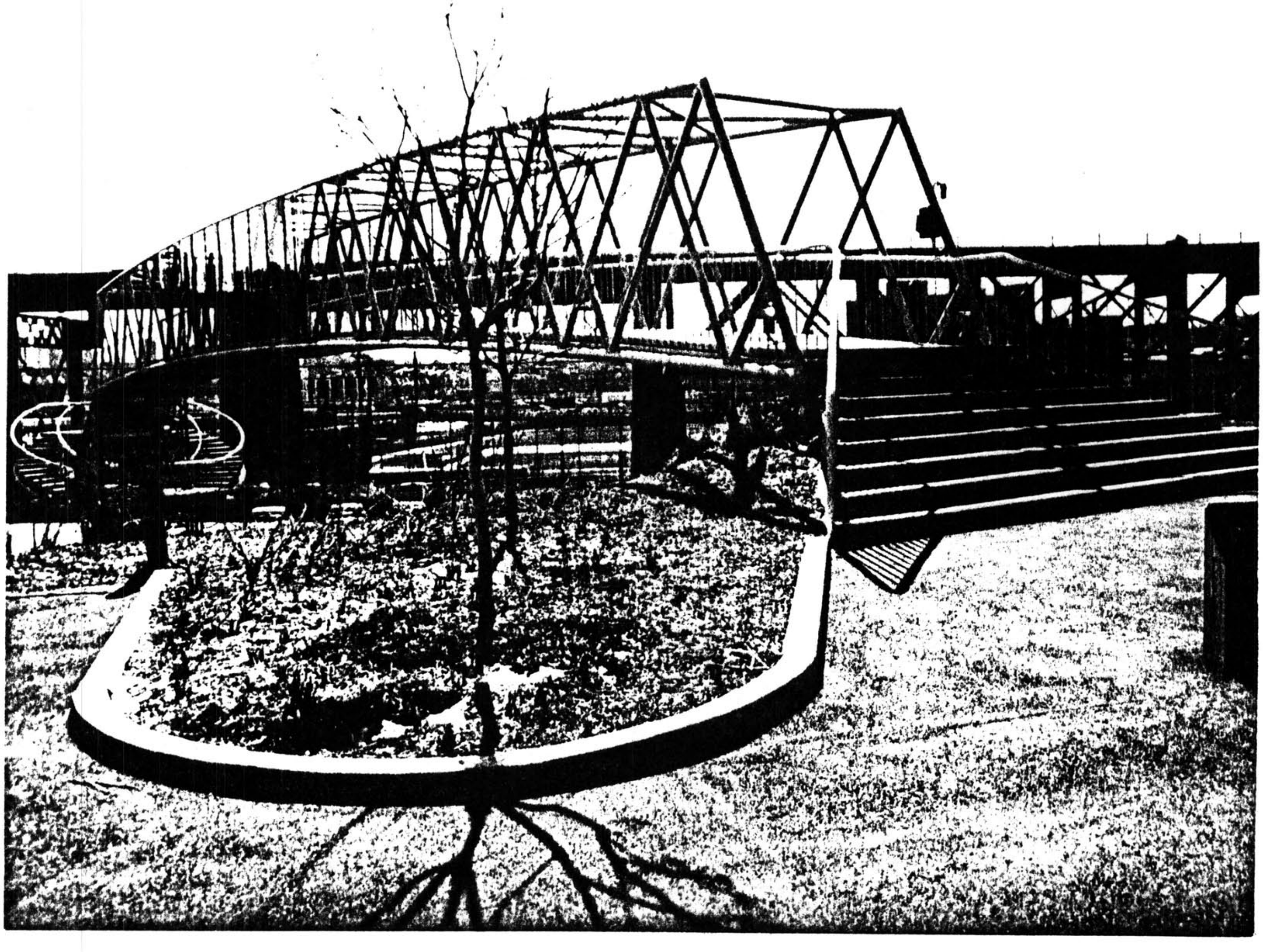


Chapter One: INTRODUCTION

Change, an obvious and admissable phenomenon, defies simple quantifiable measure. The causality of change, being interdependent upon man, his culture, and his technology, and as complex as man himself, similarly defies simple explication.

The clearest way to understand change is to investigate the circumstances that effectuate change. One source that assists in the understanding of the nature of change is found in the distinction between acts of "craft" and acts of "science" and in the transformation that occurred between the two "acts" in history. The significance of the shift from acts of "craft" to acts of "science" had irreversible effects upon man and his environment.

1.1 The distinction between acts of "craft" and acts of "science," rather than delimiting the possibilities of change, illustrates the different manner in which change is evoked.

Acts of "craft," (i.e., carpentry, pottery, building) reliant upon practical knowledge in the act of "making," are exclusively human, (by the nature of the idea, the material,

"McCleary Truss" Footbridge
University of Pennsylvania
Fig. 1

the energy, the tool, and the craftsman) and a fixed and limited activity.[1] Due to its empirical basis, the act of "craft" is either self-taught or apprenticed within the traditions of the past.

Improvements and modifications to the acts of "craft" are attributable to the personal style or skill of the craftsman, and as part of the continuous yet sometimes imperceptible process of "making" does not signify 'novelty.'[2] The modification, whether accidental or contemplated, survives only if perpetrated through accepted use and experience.

Therefore, the consequences of acts of "craft" can be varied, yet obviously evidence, if not technical advance, at least the capacity for change. In the acts of "craft," the creative artist (or artisan)

> ...makes suggestions rather than demonstrates conclusions with precision. Depending on the state of his environment his work may nucleate a prompt revolution in seeing, it may simply cooperate with other factors to create a gradual change, or it may fail to establish any external resonance whatever and be forgotten. 3

Acts of "science" (i.e., physics, mechanics, engineering) are defined by experiential knowledge which is based upon 'a priori' principles. As a collective discipline, acts of "science" rely upon the experimental basis for testing theory and therefore are learned through adaptation and replication. Acts of "science" are no longer limited to human activity as the technological advances (controlled by man's design and use) such as computers and other sophisticated machines evidence.

The distinction between the acts of "craft" and the acts of "science" cannot be fully defined without the recognition of technology as the mediator between art and science. Technology provided the impetus which transformed the empirically-bound acts of "craft" into the experimental scientific mode. This shift caused "methods of exact analysis and controlled observation to begin to penetrate every (department of) activity."[4]

Yet, change occurs on many levels with tributory effects. 1.2 The intellectual changes that result from shifts in meaning, or interpretation are acknowledged in the medieval argument, "ars sine scientia nihil est" (science without art is nothing.) This argument was originally presented in

1400 by Jean Mignot as support for his theory of Gothic Architecture at the Cathedral of Milan. James Ackerman[5] later proposed the argument in his discussion of the Gothic theory, but used it to illustrate the 'resolution of the contradiction in the built act.'[6]

Relative to the discussion of the nature of change, this medieval argument provides the necessary basis for understanding another level of meaning. Throughout history, the shifts in intelligibility and understanding of "ars" and "scientia" have been reflected in intellectual changes which subsequently affect the expressed built form.

Builders of Mignot's time, for example, may not have understood "ars" and "scientia" in abstraction, but were able to successfully achieve the unity of "ars" and "scientia" in practice, as the Cathedral of Milan evidences. "Ars" was perceived as craft (skill) with equal importance given to "scientia" as a "knowledge of consistent relationships." The rationale for medieval builders was based on appropriate 'fit' and did not necessitate the understanding of the science of mechanics.

By the early Renaissance, "ars" had a new interpretation as representational art (as opposed to applied art of craft) and "scientia" was seen as "theory based on arithmetic and geometrical formula." Differing from his medieval predecessors, the Renaissance builder became two distinct people: the technician-artist and the worker. By separating the "idea" from the practical application, "ars" and "scientia" were no longer seen in balance. "Scientia" dominated with the experimentally tested theory replacing the past empirical basis.

Today "ars" and "scientia" would be interpreted as practice and theory. One without the other is nothing. The balanced unity of practice and theory is the most sought after goal of designers today and remains a constant struggle.

These interpretive results of intellectual changes over time evidence another possible understanding of the nature of change.

To evaluate change, a context or time-frame is necessary 1.3
as a standard. Most historians utilize a chronological framework in order to illustrate the progressive evolution

of historical development. Giedion, for example, developed a "space-time concept"[7] which attempted to distinguish 'transitory' facts from 'constituent' facts as a method for discussion of the interrelationship of historical trends. Another organized format for historical development is apparent in Panofsky's[8] 'history of ideas' which acted as a 'continuum' over a certain time frame without chronological demarcations.

Some historians do not visualize historical developments as gradual change, but recognize discrete periods of flex and stability which mark change in history. The "periodicity" of technology proposed by Lewis Mumford's historical framework of the "eotechnic, paleotechnic, and neotechnic phases" provides an organized method for distinguishing between periods of change without time restrictions. Although these periods are successive, the possibility of "overlapping and interpenetrating phases" can be absorbed in the approach.[9]

The significance of Mumford's method is readily admissable as the interrelationships between ideas, concepts, inventions and techniques can be discovered within all phases.

The distinguishing factor that marks the shift from eo to paleo to neo is change in "technics." "Technics is a translation into appropriate, practical forms of the theoretic truths, implicit or formulated, anticipated or discovered, of science."[10]

In the eotechnic phase, the process of "making" is in the mind and hand of the worker. Location is also a predominant factor in the determination of choices made. Mumford notes that many inventions occurred in this phase, but the most important was the invention of the experimental method in science. "New order was supported by method."[11]

The paleotechnic phase shifted the control out of the hand of the worker. In the process of "making," now industry was the 'all-important end.' The significance was not in the quality of product but in the quantity. Mumford calls the paleotechnic phase a transitional period of change because its importance was what it led to:

> ...it helped by its very disorder to intensify the search for order, and by its special forms of brutality to clarify the goals of humane living. Action and reaction were equal--and in opposite directions. 12

The final period of change Mumford recognizes is the present-day neotechnic phase. The material developments of the neotechnic mark it as a period represented by "the shift from quantitative to qualitative standards."[13] Most important is the susceptibility Mumford recognizes in culture to slip into new phases without developing new goals and values independently of the past cultures.

Today's technological world has "paleotechnic purposes with neotechnic means." Mumford states further that the neotechnic is still in a transitional state ("meso-technic") "between two worlds, one dead, the other powerless to be born," thus implying that man is not capable of meeting the advances in technology yet.[14]

Mumford's "periodicity" of technology highlights the periods of change which affected bridge design throughout history. However, the periods of change in bridge design first parallel the development of aesthetic expression up until the 18th century. After that time, the developments brought about by technical change provide the basis for a historical framework.

The general perceptions of bridges throughout history reflect this shift from the importance of aesthetic expression to the importance of technical change, and alleviates the controversy of the architect vs. engineer argument.

Prior to the 18th century, early perceptions of bridges, were clearly influenced by the corresponding developments of art and culture. If 'style' can be equated with 'provenance' then the evolution of an art theory as a plausible history of "ideas" gives an adequately parallel source for assessing the 'aesthetic' perceptions of bridges. Realizing that the history of art concerns itself with the subject-matter (content) without dictating form; the purpose of this similitude is apparent. By understanding the ideological foundations of aesthetic thought as the pre-constituents of form, the distinction between idea and its expression can be recognized. The ineffectiveness of this comparison becomes apparent after the 18th century, as this transitional period was dramatically influenced by theoretical thought and therefore quickly isolates the comparative basis.

Historically as the perceptions of artists shifted with regard to his relation to nature, the form of expression changed (representational vs. fine arts). The changing perceptions of bridge designers as regard their relation to nature are evidenced in the expression of early bridge forms. The military bridges of the Romans compared with the later ornate stone bridges over the Tiber evidence not only a change based on utility but a change reflecting the historically accepted aesthetic style.

The Platonic "mimetic" interpretation of art taken by artists (and early bridgebuilders) delimited expression. By copying nature directly, the artist denied the object its true existence. Similarly, early architect-engineers answered to this method for form determinants. Aspiring to a higher meaning, the Aristotelian artist represented the "intellectual existence" of the object through its "Beauty," as the source for understanding man and his relation to nature.

Scholastics continued mimetically, yet sought a more advanced heretic level. By seeking order based on the "existence" of "Creation" than 'a priori' principles, the scholastics found a new truthful representation in their art.

Interestingly, the scholastics were probably the first to question this "unity beyond God and man: intuitus" and recognize its secondary form of "multiplicity: intuitus of the particular."[15] The scholastics sought to understand "how in the middle ages the artist worked...even if not from an idea in the real, metaphysical sense, at least from an inner notion of form that preceded the work."[16]

The Renaissance man (artist-architect-engineer) returned to a Neoplatonic ideal, which, limited by its own inception, never expressed reality. The heuretic level of 'artistic' genius is to be lauded; while the denial in explicit expression of this level of eclat cannot be condoned.

1.5 After the 18th century, the history of ideas does not correspond coherently with the development of art theory, nor do the "aesthetic" perceptions of bridges provide an absolute understanding of all the influences as form-determinants. The individuality in expression, which arose from the break of fine arts from craft, provides a multiplicity of interpretations and influences unique to each artist, time, culture, and place. So too, the movement from empirical craft of building to the theoretical science of construction, complicates rather than clarifies the basic perceptions of bridge. As "idea" began to originate in experience, it became obvious that the bridge could never succeed as an icon.

Beyond the humanist's view, the bridge demands a more emphatic perception. The causality implicit in the loss of traditional values and the knowledge of how "to do," does not substantiate the restraint that inhibits builders today. While the bridge provides an indicator of man's culture, "its technology is not simply an element of unlimited progress."[17] The slow evolution of materials development and its subsequent effects on bridge forms finds resolution in the same corollary that substantiates the similar lag in development of aesthetic thought.

Man cannot rely totally on outside factors but must realize an "inner" source which enables unrestrained freedom. This seemingly metaphysical theme of "inner" sources is empirically based and can be documented by briefly reviewing the historical attitudes of the architect/engineer specific to bridge design.

1.51 The Influences

As the writings of Vitruvius, Alberti, and Palladio indicate, from the ancients to the medievals, architects naturally assumed that bridges were theirs to build. "Before 1750, no one would have questioned the advisability of appointing architects to design bridges, or suggested that the design of bridges was the responsibility of any other type of person." In Changing Ideals in Modern Architecture, architect Peter Collins substantiates his succinct statement by perceiving the acknowledgement up until 1750 of bridge design "as simply an extension of the problem of masonry vaulting, or stereotomy" which the architect was most qualified and capable of solving. From this, Collins deduces the root of the "schism" between architect and engineer as attributable to the difference in scale. Bridgebuilding, in particular, would evidence this quite readily. Once the span was greater than 80 feet, the building of such a structure was beyond the realm of the masonry arch and therefore in a domain beyond the architect's previous experiences and expertise.[18]

Beyond these simple explicable facts, other confused influences provoked the deeper division between the architect and the engineer, which permanently isolated the one from the other. The "schism" was quickly written off by theorists and historians as a logical result of the distinct differences between "artistic" and "utilitarian" interests. This debate was not well-founded as the origins of both professions were similarly grounded in the arts and sciences with their parallel developments nurturing one another until the middle of the 18th century. Attributable to a shift in attitude, the architect brought about his own isolation. Historians, journalists, and theorists, perpetuated the belief that the differences were purely rooted in the aesthetic vs. utilitarian debate.[19]

The popular acclaim and successful bridgebuilding achievements of the engineer only diminished the architect's self-attitude, and added to his disdain for engineers. This 'insecure' attitude, as well as the denial be some architects that a "split" was actually occurring, inhibited (generally speaking) architects from realizing the benefits possible through the establishment of two separate schools of thought.

The engineer, too, regretted the "split" for similarly confused reasons, assuming that there would be a loss in aesthetics. This belief reconfirms the false perception of the "split" as a result of the existent gap between aesthetic and technical standards. Not all engineers and architects realized that the "quality of genius required to create beauty was equally meritorious in both instances (professions), and that the distinction of technique was influenced only by the requirements imposed by the need to design for very different spans."[20]

The development of bridge design clarifies the distinct difference between the 'changing ideals' and the obscurity caused by imputing the damage to the establishment of two schools of thought. The schools which were developed subsequent to the change in ideals actually relied heavily upon precedents. Bridges and bridgebuilders (not specified as either engineer or architect) reveal that the basic issue is not one of evolution of form specific to differences in aesthetic and technical standards but an issue rooted in man's complexity and his casuistry with regard to the application of his experiential knowledge.

When the Romans built their structurally solid bridges out of mortarless wedge-shaped stones, they confirmed the belief that the "image" or design was in the mind of the creator. The fact that the creator was also the laborer avoided the possibility of loss of "idea" through translation. The master builder embodied both the genius and the expertise. Roman bridges such as Hadrian's Pon Aelius or others such as the Pon Mulvius, Pons Milvio, or Ponte Celio, attest to the possibility of "idea" before knowledge of "idea."

The medieval masons, more than any other bridgebuilders, illustrate the indefinability of the "idea" which originates in experience. ("Abstract knowledge is easy to acquire and identify but concrete knowledge (experiential) is harder to acquire and to know and to express.")[21] The bridges of the Middle Ages pronounce an eclat of stability and aesthetic prowess, not readily surpassed today in any of the modern bridges. The bridges of medieval times are not known for their invention, yet for their innovative use of the Roman's structural possibilities. Particularly in 12th century France, the pointed arch bridges such as Trayere Bridge, (near Entraygues), the Tharne Bridge (at Montauboan), evidence a 'highly perfected structural system of vaulting that actually rivalled the Romans.'[22] The boldest medieval bridge, Bridge over the Adda, at Trezzo, Northern Italy, with its unprecedented 70' rise over its 236' length illustrates a daring that was only possible through the designer's understanding of materials, his correct application of experiential knowledge, and his inner desire or preconceived image.

The artist-architect-engineer of the Renaissance promulgating his expertise in all areas of knowledge, actually produced bridges from neither an experiential nor empirical basis but instead relied upon 'a priori' principles. Denouncing specialization, the Renaissance man lost grasp of reality by addressing broader perspectives. This approach did little if anything for the advancement of bridgebuilding as an engineering science. The intentional separation of designer from worker, compounded by the loss in continuity from inception of "idea" to its "execution" and fulfillment in the bridgebuilding process, caused a digressive period in technical development. The lack of innovative efforts can be illustrated further by the imitative and sculptural qualities portrayed in the bridges through the decorative ornamental medallions and statues.

Bridges of the later 17th century changed with the advent of techniques and material implementation based upon empirical knowledge. Bridgebuilders benefited (creatively) by the debate between the architect and engineer during the schism. Not needing to divorce themselves from or attach their loyalty to a system of ideas and experiences, heavily imbued by the traditions of the past, the bridgebuilders of the schism were exempted from the debate momentarily and yet merited from the architect-engineer's virtuous struggle. By the beginning of the 19th century, the transition from empirical to scientific (theoretical) basis of design, drastically affected the bridgebuilders' approach.

1.52 The Events

Why did the architect suddenly feel his inadequacies and his inability to meet the need of greater spans? The Ancient Egyptians never questioned their ability to construct large structures lacking empirical rules. Had not Louis XV, in 1747, specified that only architects be admitted to his newly founded School of Bridges and Roads (l'Ecole des Ponts et Chaussess) confirming the strengths of the architects' education and training? Why then the shift from architect to engineer as bridgebuilder?

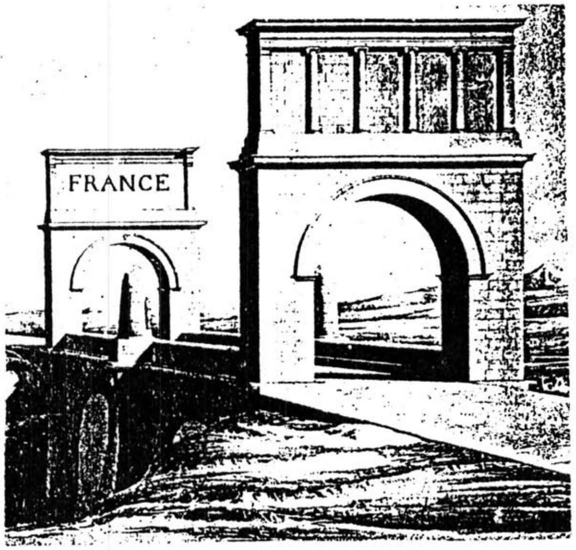
The causal interpretations of the 'schism' aside, the facts cannot be denied that in 1716, the famous "Corps des ingenieurs des ponts et chaussees" was created. A non-military school for bridgebuilders, it gave practical training to the artists and artisans who first attended. Another unusual development was the founding of "l'Ecole des Ponts et Chaussees" by Trudaine in 1747 and reorganized by Perronet in 1760.

The formation of the L'Ecole Polytechnique in 1764 and the establishment of the separate school for architects, L'Ecole des Beaux Arts, are thoroughly discussed by Richard Chaffee in his essay, "The Teaching of Architecture at the Ecole des Beaux Arts,"[23] and similarly in Peter Collins' chapter, "The Influence of Civil and Military Engineers."[24]

France became the first country to require a scientific education for its engineers. Gaspard Monge, (1746-1818) a scientist with an interest in descriptive geometry, developed the new teaching system at the Polytechnique. Mechanics, mathematics, physics and chemistry formed the basic curriculum. The importance of this new scientific trend in the development of bridge design, is evident in the subsequent theory of structures. The graduates of the Polytechnique and L'Ecole des Ponts et Chaussees combined the scientific with practical in their bridges (i.e., Perronet, Navier). Many published their theories: Belidor (1697-1761) <u>Science des Ingenieurs</u>, a manual which provided the mathematical basis for bending and theory of vaulting, De la Hire (1640-1718) equilibrium of vault as a mathematical problem of statics, Emiland Marie Gauthey (1732-1806) first book on bridges, Traite de la construction des ponts. Navier, Gauthey's nephew, published a paper on elastic theory, and a book on strength of materials.

Similarly scientifically-based Polytechnical schools were founded in Vienna and Zurich (by Dufour) at this same time, yet none in England until 1818 with the founding of the Institute of Civil Engineers. Russia's institute, founded by French engineers, was established as the Institute of Engineers of Road and Transportation in St. Petersburg, in 1809.

From the"brigades" of the Polytechnique to the "ateliers" at the newly formed L'Ecole des Beaux-Arts, the return to science could also be felt as the Beaux-Arts formal discipline, with its roots in historical precedents and Antiquity, was evolving not to teach 'generative ideas' but choices. Accordingly, Quatremere de Quincy's 'conception' vs. Gromet's 'parti,' which formed the origins of the 'battle of styles' within the Beaux-Arts substantiates the belief that "Beaux-Arts denotes not a style but rather a



Henri Labrouste. Ponte destine a reunite France a l'Italie Fifth year "envoi" 1829
Fig. 2

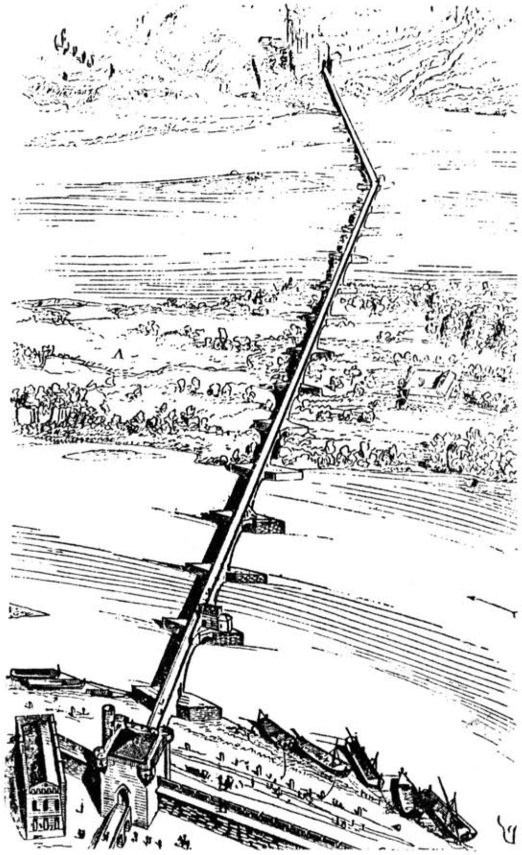
technique."[25] It was only in the last half of the 18th century that architecture, linking itself closely to science and society, came to maturity."[26]

The Ecole des Beaux-Arts' growth period was from 1792-1840, during which time six consecutive Grand Prix winners: Blouet, Gilbert, Duban, Henri Labrouste, Viollet-le-Duc, and Leon Vaudoyer, led a new radical movement.[27] The contradictions in logic of these rationalists from the conventional traditions of imitation provides a more valid explanation for the necessary "schism" between the architect and engineer than the complacent acceptance of justification (by Giedion and other historians) found in the fact of the two schools establishment. Labrouste provides the most obvious example of this revolution in thinking. Known for breaking Beaux-Arts traditions, Labrouste received sharp criticism for his "envoi" submission his third year at the Beaux-Arts, because instead of copying, he tried to find the 'skeleton' and structure of an ancient ruin and then decorated the structure. The significance of his endeavors signals the decisive recognition of the distinction between idea and its reality;

and of actualization made possible through "process," (i.e., development of basics of Beaux-Arts..."from the achievement of a glorious 'marché to the assembly of clearly separate parts").[28] This does not imply that form is learned through process but the structural form is an entity in itself. Labrouste helped shift the meaning from "the space enclosed to the structural organism enclosing it," thereby opening a new abstract way of looking at structural theory. "Architecture in itself was a structural entity not inhibited by any physical ideal and that had no eternal form, but evolved in form with the passage of time, and from place to place."[29]

The subsequent doctrines of Vaudoyer and his collaborators sharply confronted the previously accepted conventions of Laugier and Quatremere de Quincy, and the debate that ensued announced a new epoch of changing ideals unprecedented in the architecture of the students' projects at the Ecole.

Viollet-le-Duc went beyond Boullee's and Vaudoyer's critical view of architecture as imitation of nature, by "transforming the concepts of invention and imitation.



Drawing of Pont d'Avignon
from Viollet-le-Duc's
"Dictionnaire Raisonne de
l'Architecture"
Fig. 3

Invention had become reason, and imitation is seen in terms of process rather than form."[30]

The growth of the sciences and their application to the practical arts was heightened in the 1880's by the introduction of new materials: iron and steel. Important inventions and events made the introduction of these materials possible. In 1855, Bessemer's invention of blowing air through molten pig iron in a converter to produce steel surpassed the 'empirical art' of the puddling process of iron. This new process for steelmaking introduced not only a new manufacture of cast iron (i.e., structural supports, stove plates, etc.) but also a significant shift from the empirical to the scientific approach for bridge design.

The new materials required architects and engineers to seek unprecedented ideas which could not be conceived either totally through experience or experiment. The new order of demands and possibilities advanced by technology necessitated the combination of theory, materials, and techniques.

1.53 The Impact: Aftermath of the "Schism"

Now that architects and engineers formally recognized their separation, what ideals did they each answer to? The facts presented, it is easy to summarize the simple implications of the "Schism."

Both the architect and engineer now realized and openly admitted to relying upon habit and history too heavily. The architect, as a consequence, was not as susceptible to conceive his job as "additive aesthetics" over 'engineered' structure.' The engineer similarly, strengthened in theory, sought the new experimental realm of science for discovery. Both the architect and engineer admitted that their reliance on 'memory' had limited their imagination and therefore invention. Freed from their past as a result of the changing ideals caused by the new teaching methods in France, and other countries (Vienna, Zurich), the architect and engineer at the turn of the century sought a new expression for form and for its meaning.

1.6 Particular perceptions of bridges in history arise from varied sources: literature, critics' viewpoints, poets' and artists' expressions, and through symbolism. A selective sampling of these references has been noted to aid in the understanding of the accepted interpretations of bridges and the resultant attitudes and interrelationships between the bridges' users and viewers.

1.61 Literature

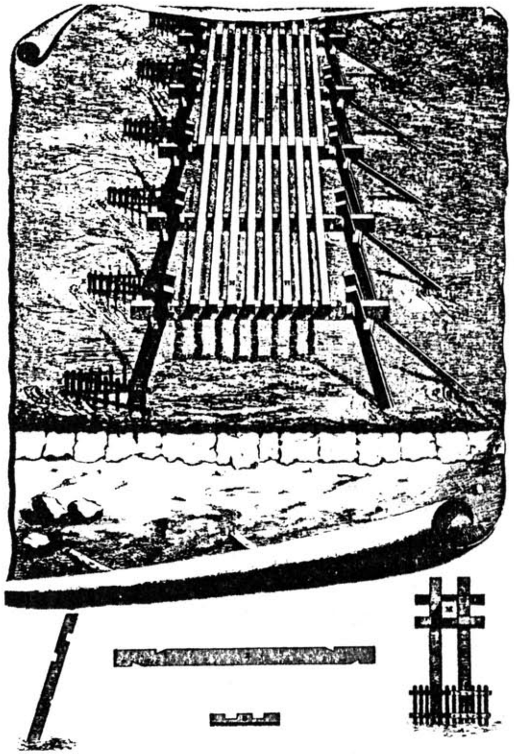
The writings of early architects and engineers, concerning bridge design, follow historically with the events leading to the "schism" and after 1750 parallel the shifts in ideology relative to 'professional' affiliation. Architects dominated the literary discussions of bridges until the split when the engineers came forward with theoretical treatises and construction manuals for bridgebuilding.

In the first century, A.D. Vitruvius' De architectura discussed the practical methods of the craftsman. The limitation in Vitruvian writings is the reliance upon classical orders without providing any sound principles. The fact that Vitruvius wrote about the technical details of cofferdams and aquaducts, although obsolete practices, acknowledges the understanding of the building of foundations and the importance of these practices to Vitruvius and his contemporaries in early Roman times.

Purporting the unity of theory and practice in the architect's role ("walking encyclopedia") as a man versed in all aspects of science and art, Vitruvius' writings fall short of realizing this 'praxis,' by emphasizing the practical side of the craftsman.

Alberti (1404-1472), an Italian architect, presents the early Renaissance humanist's view toward bridges in his book, <u>De re Aedificatoria</u>. Without dealing with the practical elements in the construction of bridges, Alberti is concerned instead with the location of the bridges as a "convenience" to the city, and the "proper" placement of piers in the river. Except for an unclear description, in which he reconstructs a bridge based on Caesar's bridge, Alberti's writings are not technical.

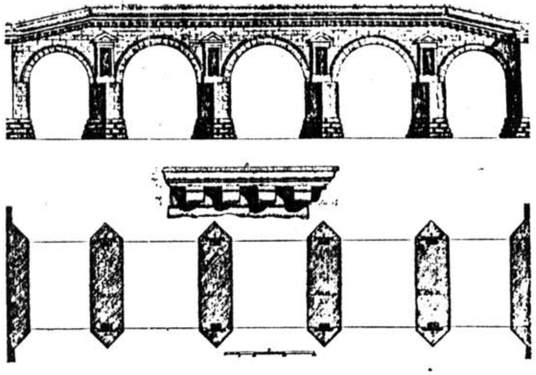
Alberti's intent is not on practice. Discussing



Palladio's Drawing of Wooden Bridge Described by Caesar
Fig. 4

the beauty and usefulness of bridges, Alberti evidences his view of architecture as "the supreme art, serviceable to mankind, dignified and enjoyable." His theory is based upon discovery of the "principles on which art is based, the parts of which it consists, and how they can be executed by the craftsman under the supervision of the humanist architect."[31]

As such, Alberti's writings reflect the attitude prevalent among architects at that time and represents the shift in meaning which accompanied the shifts from Vitruvian master builder to classical architect-engineer and subsequently to the artist-architect-engineer of the Renaissance.

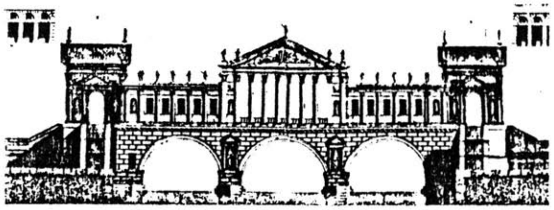


Palladio's Drawing of
Stone Bridge
Fig. 5

Palladio (1508-1580), the Italian architect who is responsible for the book, <u>Quattro libri dell' archettura</u>, (1570) provides a more specific and sophisticated perception of bridges. Writing both on timber and stone bridges, Palladio supports two distinct ideologies.

In his Third Book, Palladio first describes the simple framing and illustrates the details of Caesar's bridge. Then he proceeds by including illustrations and descriptions of three "inventions" which led to the development of the arched-truss timber form. The 'novelty' of the timber truss form represents a major theoretical development and a departure from the classical traditions of architectural practice. Until the 18th century whether due to reliance on stone for strength and permanence instead of the temporariness of wood, the timber truss form remained unrecognized by bridgebuilders.

Palladio's 'lasting' influence in bridge design, therefore, lies primarily with his stone 'inventions.' Interested in Roman masonry, Palladio effectively developed a style in compliance with the early Renaissance traditions of the Roman revival. The stone bridges were usually symmetrical arches and decorated facades with niches for statues above the pilasters. As "self-contained architectural exercises" the function of the bridge was "incidental."



Bridge Design by Palladio
Fig. 6

Elizabeth Mock blames Palladio's influence as a "picture-maker" rather than a builder" as the major cause for the split between the architect and the engineer. These "mimetic" forms of design represented "an attitude that gave the architect no encouragement to face squarely the new problems and possibilities of construction that came with the machine."[32]

Once the transformation from empirical craft to scientific construction had occurred in bridge design, the engineers' writings on construction and bridge design became prevalent. The separation of building construction into architecture and structural engineering became clearer.

Hubert Gauthier (1660-1737), the first "Genie Civil," wrote the first textbook, Traite des Pons, on bridgebuilding in 1714. French theoreticians continued to dominate the literary field from the mid-1700's through to the 19th century. Belidor (1697-1761), another French scientist, wrote Architecture hydraulique concerning military and fortress engineering. This contribution to scientific engineering literature marks a further separation of the architect's and engineer's role. Hydraulics and foundations had been assumed as architectural problems since the Romans. Belidor also wrote Science des ingenieurs, which expanded considerations to the practical aspects of public service and social concerns of contractor relations.

Jean Rudolphe Perronet (1708-1794) the first director of the reorganized "l'Ecole des Ponts et Chaussees," and builder of the Pont de Neuilly Bridge and the Pont de la Concorde Bridge over the Seine in Paris, differed from his contemporaries by attempting to combine science and experience. His writings on the technical details of foundation construction, centering procedures, and processes for utilizing water power to aid in construction went beyond the typical pragmatics by also supplying the principles upon which the building was based.

> Without actually submitting any difficult, statical calculations, Perronet sought to persuade his colleagues to adopt a scientific method of approach, and to utilize the results of research, especially those of strength tests, for engineering purposes. 33

In 1807, Thomas Young (1773-1829) an English scientist, known for his 'great knowledge of physical sciences' wrote a two volume series on <u>Natural Philosophy and the Mechanical Arts</u> which was a valuable contribution to the mechanics of materials. Young's theory on 'elastic bodies' provided an advance to the theory of strength of materials. England, however, did not properly acknowledge Young's work at this time.

Meanwhile in America, Thomas Pope, a shipbuilder, published his design for "The Rainbow Bridge," a cantilever bridge (sometimes called "flying bridge"), in his Treatise on Bridge Architecture. More significant than his own designs, Pope included knowledge of Finley's first suspension bridge across Jacob's Creek in Pennsylvania. This transfer of knowledge marked a definite advance in bridge design.[34]

The writings of these architects and engineers represent not only a historical documentation of the origins of bridge design but more importantly the promulgation of the "idea." As transfer of the "idea" was improved through improved means of communication, the lag in development from culture to culture could be alleviated, if recognized.

Historians' discrete perceptions of bridges voice the public's evaluations on several levels. Whitney calls the bridges the "triumph of science," expressing belief in the successful progressive development of the science of bridge engineering.[35] Mumford confronts the aesthetic as well as the social aspects of a bridge by noting it as a "visible sign of men's relation with the land."[36] The "nature" of the bridge becomes a predeterminate in the development of the form and therefore must rely upon man's understanding of the context and the environment. When specifically speaking about the Brooklyn Bridge, Mumford stated that it was "both a fulfillment and a prophecy" realizing that the bridge brought old materials and new materials together in a new way which would open up further possibilities.[37]

Schuyler rounds out the perspectives of the bridge by proposing the utilitarian view of the bridge as a "tool of traffic."[38] He supplements this functional aspect with a 'cosmic' view of the bridge as a legacy to future civilizations. Realizing that the durability and permanence of the bridge (which he likened to Roman structures) will allow the bridge to remain long after its builders are gone, Schuyler proposes that future generations will base their judgments on the merits and demerits of these large-scale accomplishments.[39]

1.62

Bridge, metaphorically, gives another perception of meaning. Whether a positive dictum for solving generation gaps, or patching irreconcilable quarrels, "to bridge" means to come together or join with happy result. Bridges have also been cited in expressions of decision-making, reinforcing the fact of their vitalness. 'Crossing bridges when one comes to them' or not 'burning any bridges' are two such sayings. The first implies the necessity to make a decision confronted and the second denotes the reversible effects of a decision by leaving a path of return.

The literal translation and origin of the word 'bridge' has a religious significance that dates to the Greeks and Romans. Derived from the Latin "pons," bridges were first built by Roman priests. The title of the chief Roman priest as Pontifex (pontis and factus) a bridgebuilder, was thus an appropriate honor. The first pontists were Christians who organized brotherhoods specifically to build bridges.

In France, by 1200, there were many such groups, such as the Hospitaliers des St. Jacques de Haut Pas, and the Freres du Pont organized by Benoit (also known as St. Benezet--patron saint of bridgebuilders). Chapels, built on these early bridges, not only met spiritual needs but also financial. The early builders turned the chapels into toll stations and collected charges from users.

1.63 The Critic's View

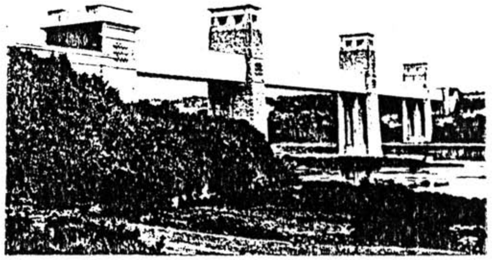
Montgomery Schuyler, an architectural historian who influenced modern thought from the 1870's to World War I, frequently demonstrated his literary effects on bridges; a fact significant in itself. Bridgebuilding was accepted as having influence upon the changing ideals in modern architectural thought. Schuyler's criticisms, however, provide not a foresighted explication of new ideology, but substantiate the belief that critics aided in hazing the basic issues by inciting the standard argument of separation of aesthetics from science. In various articles published by Architectural Record, Harper's Weekly, or or Scribner's[40] Schuyler falls victim to this erroneous interpretation by, for example, commending the Brooklyn Bridge as a 'noble work of engineering' while condemning it for not being a 'work of architecture.' The premise may be valid opinion, but his suppositions are incorrect. Schuyler contends that a mimetic view prevents the development of creative ideas (referring to the stylized 'Gothic Revival' masonry support towers) yet he bases his argument on the division of aesthetic and scientific construction caused by the rise of 'monumental' engineering. He elaborates the contrasts between 'monumental' and mechanical conceptions in his article on the "New York Bridges," yet condemns the acceptance by some "to draw a hard and fast line between scientific construction and artistic construction." Not accepting that the "split" occurred Schuyler bemoans the lack of aesthetics being taught to engineers (and similarly the lack of science being taught to architects).

The Brooklyn Bridge
New York City 1883
John and Washington Roebling
Fig. 7

In a very descriptive essay on the Alexander III Bridge Schuyler correctly identifies the problem of "additive" aesthetics (stylistic decoration and ornament) yet does not penetrate beyond the "inorganicness" of this approach. His lack of understanding the root of the problem acknowledges the continual debate of what makes structural form and architectural expression mutually exclusive and/or mutually inclusive.

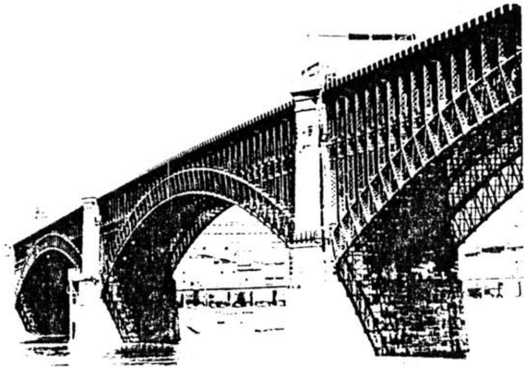
Interestingly enough, however, in the same article, a passing comment exposes the obverse side of Schuyler. He denounces the Britannia Bridge, stating that it is the "ugliest of great Bridges" because "it tells nothing of itself."[41]

Ada Louise Huxtable, a contemporary architectural critic, unfortunately has not broken from the past's proliferation of the meaning in building by confusing structure and its form. In a delightful commentary on the Eads Bridge, in St. Louis, Huxtable correctly states that "innovations abound in its construction: use of hollow tubular steel, the introduction of the pneumatic caisson method of founding piers, and the new analyses and solutions to stress/strain to predict efficiency."[42] Yet Huxtable, ineptly, overlooks the underlying reasons for the appearance of these new techniques. Presenting the 'unprecedented'



The Britannia Bridge
Menai Straits, Wales 1846
Robert Stephenson
Fig. 8

issues of the Eads Bridge provides ample import to the discussion that visible structure and expressed form do not necessarily denote the full meaning. The final bridge design of the Eads Bridge represents a synthesis of experience, materials, techniques, theories, never actualized before. Seen in this perspective, the Eads Bridge expresses a new volition of technology, which distinguishes the contrasts between invention and design, while simultaneously separating them from the contrasts between innovation and science.



The Eads Bridge
St. Louis 1874
Captain James Buchanan
Fig. 9

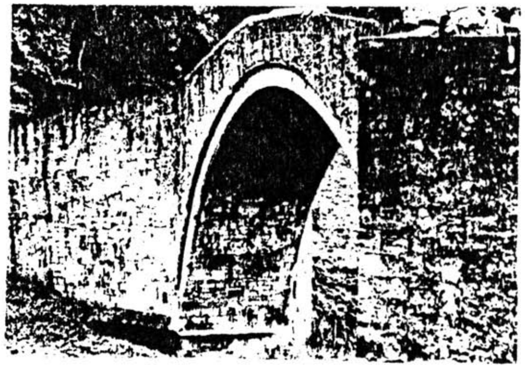
Unable to distinguish the processes from the product, Huxtable labels the visible structural expression as the matter of importance and the only contribution that the new Eads Bridge makes to architecture. By this indictment, Huxtable's myopic view denies the potential impact of the bridge upon design ideology.

1.64 The Artists and the Poets

Novelists' and poets' work not only pronounce the popularity of the bridge as a resourceful idiom of their endeavors, but also acclaim the critical change and overpowering effects of the industrial society.

William Wordsworth used the bridge as the stage for his poem, "Composed Upon Westminster Bridge," wherein he describes the new vantage point for an awesome view of the city that "Dull would be of soul who could pass by A sight so touching in its majesty...."[43]

Robert Burns' "Tam O'Shanter," the tale of Brig-O-Doon, exemplifies the belief in superstitions associated with bridges. The climax of this story about a young girl and her mare comes in her redemptive crossing of the bridge, when she reaches the middle of the bridge. The superstition holds that the devil cannot pursue one beyond the center of the bridge.



Brig 'a Doon
medieval bridge
Alloway, Scotland
Fig. 10

Bridges in their personification have been the basis for many legends throughout history. Bridges seen "as an act of defiance over the spirit of water" have developed legends such as the one about Xerxes bridge, and the sacrifice thereafter of bridgebuilders to the "angried god." Wilbur Watson's book, Bridges in History and Legend, as well as "the Endless Bridge" chapter in Gies' book, Bridges and Men, give a comprehensive exploration of bridges in literature.

Walt Whitman's poem, "Crossing the Brooklyn Ferry," personifies the Brooklyn Bridge. By depicting the daily occurrences, the routine of traveling to and from work under the watchful eye of the bridge, Whitman exposes the inner feelings of the bridge.

The most revealing of any poet's writings on bridges is the epic poem about the Brooklyn Bridge, entitled "The Bridge," by Hart Crane. This poem epitomizes the inherent qualities of the bridge beyond the organic representation of its parts. Crane's poem reaches beyond imagery by actually basing its story on the Brooklyn Bridge as a "terrific threshold" in which all phases of human and cosmic experiences are embodied: love and death; time with its flow of day and night; season and year; eternity with its star and sun.

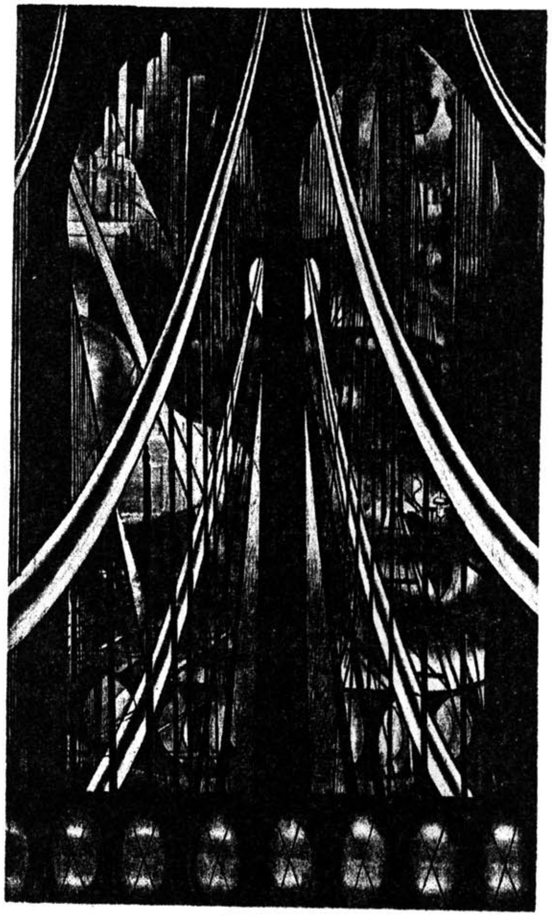
Appropriately, Max Weber's critique of "The Bridge" notes that

> The first seven stanzas contain one of Crane's favorite themes: that of man's blindness to inherent essence, and this is developed to indicate that the Bridge has not been understood. 44

Contrary to the architectural critic's myopic view of bridges, Crane not necessitating the loose usage of the term 'essence' has discovered the deeper meaning and implications of the Bridge through his epic poem.

Willa Cather, a 20th century novelist, provides another perception by using a bridge, its builder and the story of the bridge's construction, as the material framework to develop two themes: the romantic love story and the story of inner conflict between conscience and will. Thus Alexander's Bridge presents a simply told tale dramatized by the forceful parallel of bridgebuilding.

Artists frequently use bridges as background to their portraits (i.e., Mona Lisa has a bridge behind her), or as objects in their landscapes (Impressionist French painters). Yet it is not until the early modernists such as John Marin, Max Weber, Joseph Stella, and Charles Sheeler, that bridges provided the inspiration for a new revolutionary approach



Panel from
"New York Interpreted"
"The Bridge"
Joseph Stella
Fig. 11

in artistic expression. The artists' intentions remained revisionary. The technical prowess and magnificence of these engineering feats were not the aims of their depiction. Instead, the importance of the expression of bridge was seen as an "invitation to vertigo, by experiencing viscerally the complexity, grandeur, and scale of the city's new urban projects."[45]

The social purport of these artists' work cannot be underestimated, however, since the 'content' implies the emphatic force bridges had upon the thoughts and lives of society, particularly at the turn of the century in New York City.

Joseph Stella recognized the Brooklyn Bridge as an inseparable part of his life. The fact that he painted this bridge over and over again in many studies, and in one of the panels in his highly regarded piece, "New York Interpreted" as well as the subject in two studies, "Brooklyn Bridge," attests to the penetration of this splendid structure to his inner desires and expression.

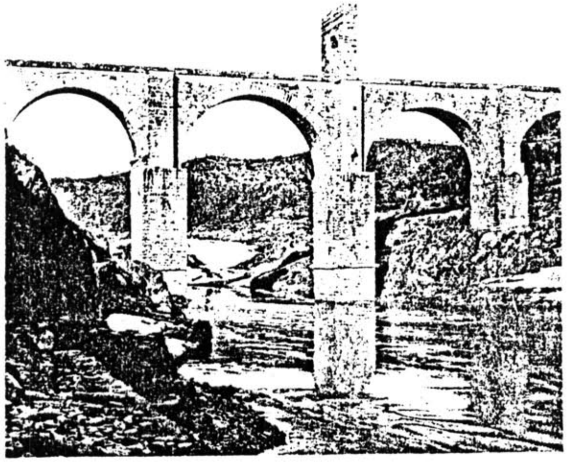
"Steel - Croton"
Oil on canvas, 1953
Charles Sheeler
Fig. 12

1.7 What is Bridge?

A user sees a bridge as providing passage between two places which nature by either gorge, river or ravine, or man by his highways or railroad tracks, has prevented. Unlike a tunnel, or a monorail, a bridge creates this link by physically beginning and ending on the edges of man's environment, or by supporting itself periodically in the intervening landscape. This dependence on place creates a unique and inseparable relationship with the environment. Not a natural occurrence, the bridge takes on site-specific qualities which affect its subsequent identity with the landscape. By its permanence and presence, the bridge furthers the identity of a place.

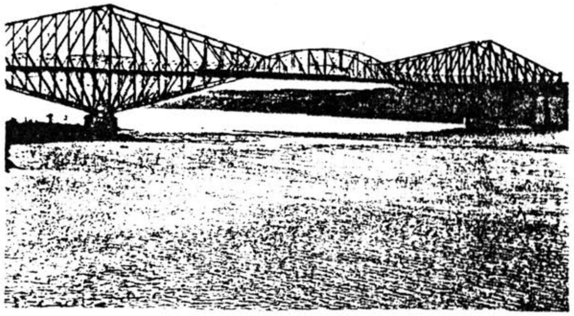
A bridge is a better time capsule of information about civilization and in particular man's ability to build, than any history text. Living evidence of past achievements in technique, experiment, and knowledge, the bridges that have endured today present a concise documentation. Obversely, bridges that have not been preserved only add to the testimony of bridges' vitalness as in the cases of wartime, where bridges were frequently the targets of air raids and enemy destruction.

To the designer, bridges are of three different types: arch, beam, and suspension. Understanding these types as three separate structural systems based on material capacity and load carrying functions, distinct from the superficial form, alleviates confusion between the function and expressed form. Eduardo Torroja's comprehensive chapter on "The Arch" in his text, Philosophy of Structures, defines the differences between the false arch and the real arch. The simple explanation of false vs. real arch gives us the best understanding of the definition of bridge. It is only by understanding the forces which act within the bridge that one can define bridge. Arches, being strong in compression, lend themselves naturally to masonry and brick, and, whether built-up or spandrel, were prevalent in bridge design since the arch was developed. The connection of the arch with "the idea of powerful stress, and of a leap to dominate distance"[49] confirms its appropriate use in the first bridges, and underscores the bridge's definition.



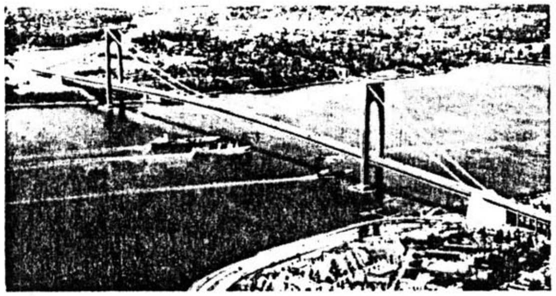
The Puente Trajan
Roman Bridge 98 A.D.
Julius Caius Lacer
Fig. 13

The beam type of bridge provides another dimension to the definition, by expressing the forces as simply supported upon the ends, or in greater spans upon intermediate piers, or foundations. Whether a continuous beam or not, the beam bridge needs to be constructed of materials that are strong in both tension and compression, such as timber, reinforced concrete, and iron. The cantilever, and the rigid or portal frame variations of beam, act as beams yet due to their similarities in appearance to arches, are frequently confused with arched structures. The beam type of structure reinforces the identity of bridge as far back as the primitive logs over river streams. A new term for bridge becomes possible with the utilization of beam structure in iron trussed bridges, or reinforced concrete cantilever (monolithic) bridges.



Quebec Cantilever Bridge
Quebec 1917
Ralph Modjeski
Fig. 14

The third type of structure, the suspension, culminates the designer's definition of bridge. Looked upon as a reversed arch, the suspension type of structure is in tension at the abutments, instead of compression as in the arch, and therefore needs materials which are flexible, yet strong

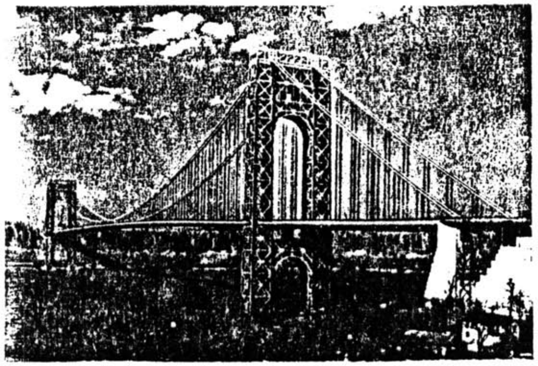


Verrazano-Narrows Bridge
New York City 1964
O.H. Ammann
Fig. 15

in tension (i.e., wire-cable, rope, metal chains). The 'aerodynamic' qualities of the suspension bridge are achieved by the incorporation of light weight material such as steel or lightweight reinforced concrete in its (stiffening) deck girder. The new meaning of bridge is conclusively defined by its structural competence and solution to the challenge of longer spans.

As part of the historical accumulation of knowledge, perceptions serve to enhance the intelligibility and significance of bridges without actually defining "bridge." In order to adequately define "bridge," two levels of definition are proposed. The first deals with the visual, social, and cultural aspects which contribute, along with the construction and the mechanics of the bridgebuilding process, to the realization of the bridge. The second order of definitions is derived from the ontiological dimensions of the bridge and is described within a phenomenological framework of 'essential-essence-Essence.'[1] 2.0

The need for a formal definition of "bridge" based upon its physical characteristics and its origins in abstraction is necessary if the visual aspects of the bridge are to be explained. The visual aspects, both in the mind and in the eye of the designer, are the primary determinants of form, and are shaped by the constraints. How the designer recognizes and responds to the constraints is 2.1



George Washington Bridge
Fig. 16

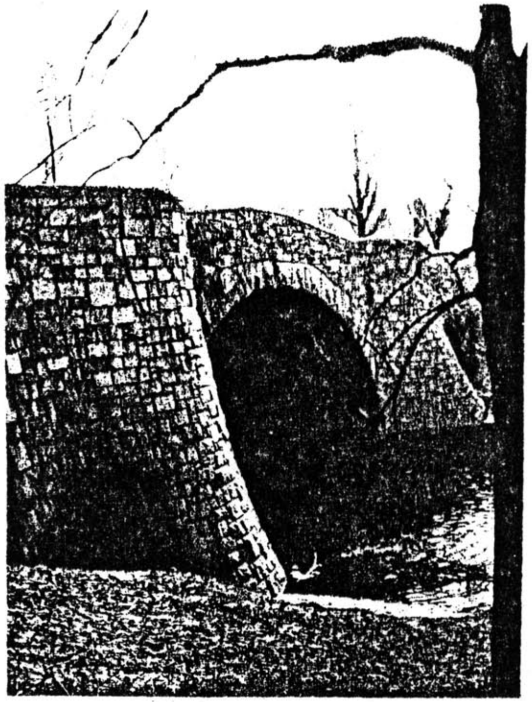
Brooklyn Bridge
Fig. 17

resolved in the bridge form. Design constraints vary, yet are location and time-specific; thus providing a unique basis and identity to each specific bridge. When, for example, limitations of space in the urban setting preclude the placement of the end abutments of the bridge without the designer's choice, these critical restrictions actually free the designer to express the bridge in a more exacting way. In another case, where the abundance of space exists, the attempt to locate the ends of the bridge sometimes leads to a loss in meaning. Unless the form can receive the identities (or create new identities) of the 'places' it has created at each end, the freedom in location is nullified. The George Washington Bridge, New York City, could have been spanning any river, not just the Hudson, in a number of different cities. But would the Brooklyn Bridge have been the same in St. Louis?

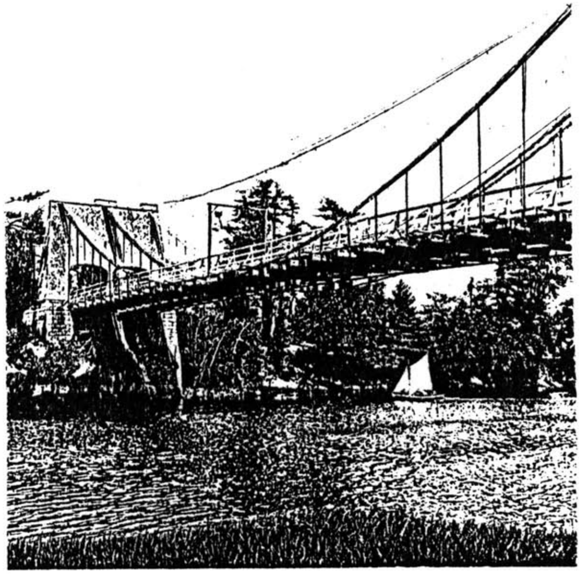
Constraints apply to all aspects of the design, from the span necessitated, the durability and stability of the material used, and the type of structural system chosen, to the personal constraints of the builder. From these restraints, the form is predetermined.

The visual aspects of the bridge form first depend upon the material. The material, whether dependent upon the personal preference of the designer, upon the availability and abundance, upon cost, or upon the 'state-of-the-art,' delegates the shape and magnitude (relative size) of the bridge.

From the material dictates result other visual aspects of the bridge. The size and scale of the elements (parts) of the bridge are relative to the material (and its inherent strengths) utilized. The steel girder would logically not be as deep as the timber beam to accomplish the same distance. The material's inherent strengths with its ability (or inability) to resist stress, delineate the appropriate size and form. Heavy masonry, for example, with its natural compressive strength and lack of tensile strength, resolves its possibilities only in the arch. Steel with both tensile and compressive strength adopts uses in various forms: the continuous beam, the arch, the truss, or the suspension form. Timber members dimensioned and sized to their abilities



Fenway Bridge, Boston
Massive stone bridge
H.H. Richardson
Fig. 18



Old Chain Suspension Bridge
Newburyport, Mass.
Fig. 19

(strong in both tension and compression) of strength and weight were first best utilized as beams and later in truss. Inherent in the nature of wood is the inability to span long distances. Thus in order to compete with other materials, the composite form (such as truss) was developed.

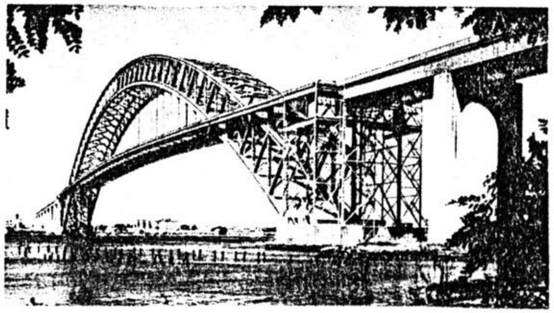
Therefore, the magnitude of the parts of a structural system is a function of the material, and an obvious contributing factor to the overall visual image of the bridge.

More importantly, the magnitude of the parts is a major factor in the relative strength to weight ratio of a particular material. This ratio is a determinant of the appropriate structure.

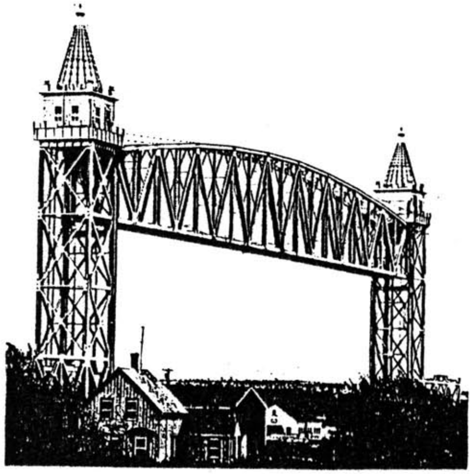
The realities of scale and span, consequently, preclude the upper and lower limits of the structural solution and dictate the form (or "the what") of the design. The weight of the material over a certain distance prescribes the upper structural limit. After 600 feet, for example, it has been noted "that increments of weight rapidly increase for every increase in span."[2] Therefore, the constraints of self-weight of the material and its form limit the use of particular structural solutions and demands another structure. This is true in any building, since once a certain magnitude has been achieved, the structural system must be changed. The upper limits, for example, of the simple steel truss is 720 feet, while the continuous truss has achieved 1000 feet. The steel arch span has successfully attained dimensions of 1600 feet in length, and the cantilever truss 1800 feet.

The lower limit of the structural solution is dictated by the efficiency in material and cost. Within a span of 400 feet or less, many structural types are possible, yet a steel suspension bridge would obviously be the least efficient. (Today, for the suspension bridge to be utilized efficiently, the bridge would have to be over 2,000 feet in span.[3])

Another visual aspect of the bridge which is material-dependent, and also inherent in the material, is the 'finish.' 'Finish' implies the final external appearance, whether natural or artificial. The resulting visual differences between the texture of a reinforced concrete masonry



Bayonne Bridge, N.J.
Steel-arched truss
Fig. 20



Cape Cod Canal Bridge
Buzzards Bay, Mass.
Vertical Lift Span
Fig. 21

Echo Bridge 'Aquaduct'
Newton, Mass.
Fig. 22

arch form and the sleekly painted steel of a truss, for example, create two distinct visual images without changing the definition of 'bridge.' (Historically, from the question of the material's finish many 'aesthetic' debates have arisen, not only in bridges, but in all aspects of building.)

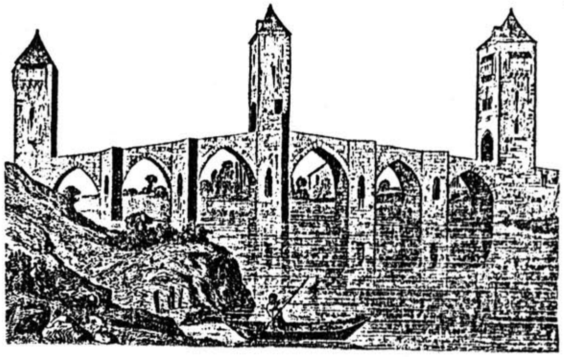
With changes in material and structural type, the visual characteristics of the bridge change. The profile or total image of the bridge is dependent upon the structural system which by its needs defines the use of the number of piers or supports, the anchorage, the cables, the vertical tower and the horizontal deck.

2.2 A bridge, however, is not determined by its materials and structural form alone. The use of the bridge whether intentional or "denoted" remains a primary determinant of its physical form. The utilitarian use of providing a passage or link has sometimes been an incidental function of the bridge. Changing social needs have dictated not only the change in the use of the bridge but also in the resultant change in design.

The origins of early Roman bridges were rooted in the need to carry water from city to city. The viaducts were transformed into aquaducts which combined the usual bridge functions with the water-carrying conduits. The best known Roman aquaduct lies outside Rome, the Pont du Gard, Nimes, France.

While the Romans judged their military strength on the number of bridges built, specific military needs were met by bridges in other ways. The pontoon bridge or floating bridge, for example, (first recorded in China as a "bridge of boats"[4]) answered the need for temporary and quick-assembly. An early precursor to the Bailey bridge[5] used during World War II, the early pontoon bridges provided access to or retreat from strategic locations. The contemporary ribbon-stress bridges originated from military needs in Germany.[6]

Another bridge built by military needs was the fortified tower bridge built throughout the middle ages to serve as protection. The towers, drawbridges and crenulated piers protected the bridge defenders from attack from all sides, land or water. The Pont de Valentre at Cahors, France, is an example of a strong fortification with three tall towers.



Bridge of Valendre
Cahors, France
Fig. 23

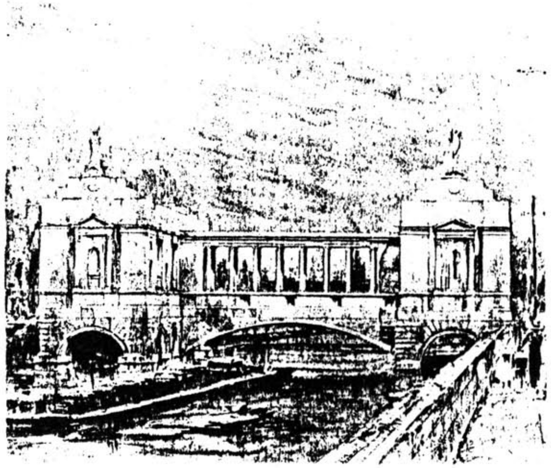
Beyond the military needs of the 14th century, the spread of Christianity influenced bridge form. The early English bridges usually erected chapels or shrines on the piers near the center of their bridges. The Old London Bridge (1176) built by a chaplain, Peter of Colechurch, included houses all along its length, with a drawbridge at each end and a chapel in the middle. France, with its founding of brotherhoods and priestly orders to build bridges, evidenced a departure from the physical forms of their Roman-precedented bridges. St. Benezet's Pont d'Avignon is one such bridge (now only three arches remain) with a chapel in the middle.

The Rialto Bridge
Fig. 24

The Renaissance bridges were generally urban bridges, built in cities which were rich and prosperous activity centers. The bridges similarly reflected the flagrant lifestyle, donned with shops and houses, each bustling with excitement and people. The Pont Neuf, Paris, the Ponte Rialto, Venice, and the Ponte Vecchio, Florence, each were typically Renaissance bridges.

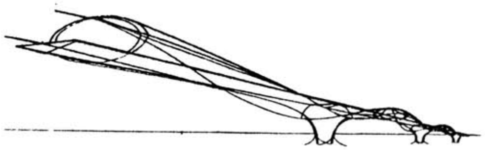
Bridges have responded in form to various social needs throughout history. In Blois, France, two mills were built on its bridge to respond to the needs of the manufacturing city.

In Dublin, Ireland, a different social need as well as cultural, was met by Edwin Lutyen's 'Museum Bridge' scheme. Proposed on a bridge near the site of today's Metal Bridge over the Liffey River, the design was meant to economize on the cost of land and to meet the needs of an expanding art collection.



Lutyen's 'Museum' Bridge
Dublin, Ireland
Fig. 25

Contemporary architects, such as Paolo Soleri, have similarly responded to changing social demands. Soleri's sketches for bridges are usually 'scientifically' modern reinforced concrete forms with overlapping curved edges. These elongated slender tubes tend to be sculptural in effect and denote a rapidness in motion, reflecting the increasingly faster-paced needs of the 20th century. Soleri sees his bridges as the vital city-to-city "intercommunication links" of society.



Paolo Soleri's bridge
Fig. 26

A major social need of the bridge is its cost. Toll bridges were an obvious solution, early in the history of bridgebuilding, to the problems of financial expense of construction. Users of the bridge were charged as they crossed the bridge. Sometimes, toll stations marked the entrance to the bridge as a gate, or otherwise defined the center of the bridge as a separate building.

Bridge inventions were not purely pragmatic. An American innovation, for example, the covered bridge lends another definition to bridge. Evolving from the need not only of physical protection, but also of social desire, (covered bridges are sometimes called the 'kissing bridges')[7] the covered bridge adds a picturesque image to the landscape. The first popular use of covered bridges began in the United States, particularly in New England, in the late 18th century. Due to abundance of wood, they were usually timber trestle or trussed construction. The Chinese, in Fukien, used timber bridges long before the 18th century, and were known to build covered pavilions in the center to promote 'gab sessions' and social meetings.

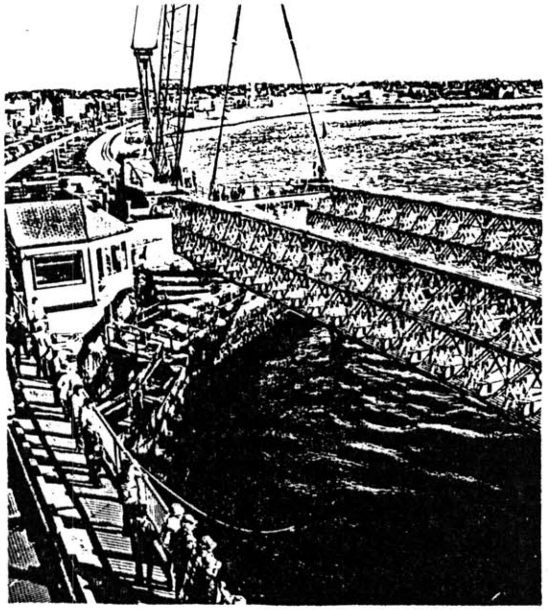
In history, some of the most appealing bridges are those which have responded to the social needs. The bridge hence, through changing social needs, has taken on "denoted" utility by making new functions possible.

2.3

The cultural aspects of the bridge design can be defined by evaluating the technological and economic factors which also are predeterminants of the form. Simply defined, the first order of technological factors would consist of the producer, the consumer and the product, acting in accord with the available materials, tools, and techniques, energy and theory. The 'intended' use (purpose) of the product (in this case, bridge) would be also a concern of the technology and a necessary predeterminant of its form. Each of these factors are interrelated and flexible within the economic and social constraints of the particular culture.[8]

Vermont Covered Bridge
Fig. 27

Each culture develops its technologies (if at all) at different rates depending upon its labor, capital and material resources. When a shortage of one material was prevalent, for example, the disadvantages could easily have prompted technology in another direction. The changes in material are obvious indications of technological change. The Roman brick was not the same size as the modulor standard sized brick used today.[9] As techniques changed, the materials



Moving panels into place:
Temporary Bridge
Gloucester, Mass.
Fig. 28

and their use were affected.

The controlling factor of a culture is its efficiency. Efficiency can be judged on various levels. The first and most obvious level consists of the economic factors relative to material and labor. Dependent upon the culture's proportion of these factors, the direction and impetus of technology can be interpreted.

Efficiency can also be evaluated as a means-end problem. As a means, efficiency is an advantage in design of the safest and most economical structural system. Yet as an end in itself, efficiency becomes a danger. Prefabrication leads to efficient, quick assemblage of standard parts. As a means, prefabrication eliminates tedious work and unnecessary manpower, allowing man to be more productible in another capacity. However, as an end, prefabrication produces routine and predictable form. The expandable standard panels (i.e., "acrow" system)[10] of the temporary bridge can be adapted to fit anywhere, thus losing the identity of the location and of the bridge.

Changes breed changes. The advent of the railroad in

America is a prime example. As a consequence of earlier advances in technology and science, the locomotive provided the hope of connecting every state in the country. This new transportation system carried with it not only technological advance, but also further particular demands upon bridge design. The culture and technology responded with timber truss railroad bridges.

The visual, social and cultural aspects of the bridge are not completely distinct definitions, as each is interrelated and include within each's requirements the basic physical elements of the bridge: the material, the form, the use, and its effect (or end result). Underlying these causes for the physicality of the bridge are the controlling principles of the idea, and sometimes the invention/innovation which predetermine the form. The bridge is not actualized by idea and invention, however, thus the definition of the bridge is incomplete. The 'mechanics' and 'construction' provide the critical dimension to the 'bridge' definition, along with supplying the underlying principles of the theory and technique of the "built" form.

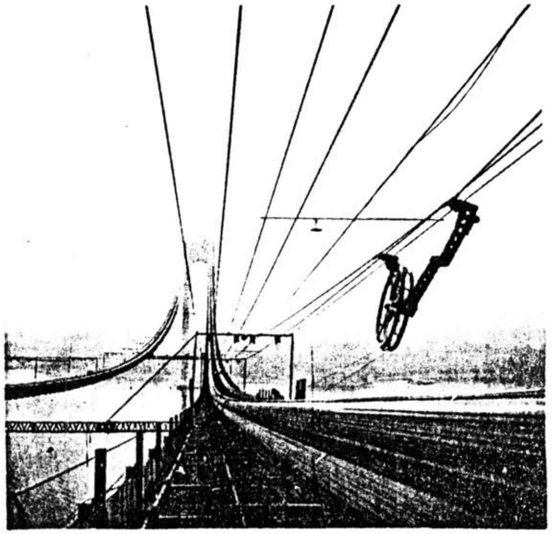
2.4 The mechanics of the bridge is the science of the forces acting on the bridge. How the bridge is designed relies not only upon the understanding of the action of the bridge's internal forces (denoted as the structural behavior), but also the action of the external forces acting on the bridge (denoted as the structural action). Using statical analysis, load-tests, or intuition, the bridge designer needs to understand both the structural behavior and action in order to determine structural adequacy. Structural adequacy assures the strength (calculated within allowable stress/strain) and stability (relative to stiffness/rigidity). Some bridge-builders recognize the dangers of relying too heavily upon calculation. When the science of structural statics dominates the design, and analytical calculations are too complex to solve, the mechanics limit the possibilities of forms.[11]

In the 19th century, however, technology triumphed by shifting the emphasis to the controlled observation and analysis of pure science, while still maintaining the practical approach to bridge design. Mechanics, using technology as its mediator, found its technique in construction.

Construction, the most necessary factor in the "bridge" definition, provides the method of actualizing the "built" form. With changes in constructional methods, the bridge's form, scale and magnitude is affected. The advances from rope (hemp) cable to twisted wire to high-strength steel cable document the achievements of increased spans in suspension bridges. As man's technological knowledge and technical expertise changed through his understanding of materials and tools, construction changed.

Though methods of construction naturally differ in cost and in process dependent upon the material, the inherent limitations of the method often define the bridge's form. The ability (or inability) to provide scaffolding strong enough to support a masonry arch determined the maximum span attempted.[12] Similarly, the thickness and depth of piers were dependent upon the sheetpiling technique and the perfection of the cofferdam.[13] Cast iron relied upon its moulded forms for shape.[14] More than any other material, concrete is the most obvious 'technique' intensive material, restricted by the method and expense of constructing its

Menai Bridge
Early suspension with wrought iron chains
Fig. 29



Verrazano-Narrows Bridge
cable-spinning
Fig. 30

formwork. By the constraints, the designer is actually free to more precisely control the designed form.[15] Thus as the most 'creative' material by the nature of its 'fluidity,' concrete requires foresight first in the design of its method of contruction.

Construction, aided by technology, provides the actual form of the bridge. As such, construction is the culmination of all aspects of the bridge's definition. Pier Nervi defines the synthesis stating:

> Construction springs from the material needs of the individual and society, but in satisfying people's needs it broadens to express their spontaneous and deep feelings. Construction gives in a unique synthesis the elements of manual labor, industrial organization, scientific theory, esthetic sensibility and great economic interests.... Because of its varied aspects, of its persistence in time, and the scientific, technological, esthetic, and social factors which influence it, construction may well be considered the most typical expression of the creativity of a people and the most significant element in the development of its civilization. 16

The visual, social, and cultural aspects of the bridge actualized through mechanics and construction present a logical order to the understanding of the physical characteristics and facts of the bridge. However, the causes for the physicality of the bridge and its function and its use as defined in this first set of definitions, do not explain the designer's intention and motivation, beyond the circumstances of the bridge. To define the bridge completely, it is necessary to understand the relationship of the bridge to its context, and the "nature" of the bridge itself.

A framework of 'essential-essence-Essential' has been proposed to proceed beyond the first set of definitions already assigned to bridge. The benefit of using this ontic-ontological level of definitions is found in the ability to extend beyond the casual connection, implied throughout history, between thinking and feeling, and between knowing and doing, by defining the underlying causal and controlling principles that have influenced the development of form (aesthetic, structural, architectural, etc., all being equal).

The ontic dimension deals with the physical characteris- 2.6
tics of the bridge through descriptions of the bridge within the context of time and place. The 'essential' and 'essence'

types of the three-part framework are within the ontic. The ontic dimension exposes the context-dependent factors of the bridge in order to penetrate the deeper relationships between man and nature. While informing about the particular, the ontic reveals little about the 'total' bridge.

The ontological dimension, the 'Essence' of the 'essential-essence-Essence' framework, is necessary to expand beyond the usual understanding of the physical context relationship. In the ontological, the relationship of the bridge to its context is not just physical as a 'link to the land,' but includes the 'self-showing of the bridge to its context' ("what is manifest") by its inherent nature. This definition of the bridge is not based upon man-to-man relationships by which the visual, social and cultural aspects of the bridge were defined, but is concerned only with how the bridge and its "nature" influence the context, and how the context in turn influences the bridge's "nature" (what it <u>is</u>).

2.61 The phenomenological framework, 'essential-essence-Essence' is based upon the theories of various architects, historians, a sculptor, and philosophers and is intentionally created to provide the necessary format by which the case studies could be selected and evaluated. The 'essential' is based upon the theories of Horatio Greenough, and Gottfried Semper; the 'essence' is understood through E. Baldwin-Smith's study of The Dome as a History of Idea, Erwin Panofsky's Art Theory as a History of Ideas, and the principles of 'essence-essential' as distinguished in Paul Frankl's The Gothic. The 'Essence' derives from the "Essence-Being" of the existentialist philosophy of Martin Heidegger, with supplementary ideas from the "existence-will" philosophy of Louis Kahn, and the Tao (order) found in Lao-tze's philosophy.

The'essential' is rooted in both the theory of aesthetics 2.71 proposed by Horatio Greenough and the equally compatible 'rationalist' approach of the German architect, Gottfried Semper. Greenough, an American sculptor at the turn of the century, in his espousals of 'organic aesthetics' exceeds the limitations of the loose 'form follows function' idiom by realizing that order and organization is based first on the understanding of the idea. He succinctly states in his definition of 'Beauty,' the reliance upon mastering the principles so that 'organized intention can pass to completeness.' (Truth) Greenough states: "Beauty: as being the promise of Function. Action: as the presence of Function. Character: as the record of Function."[17] This 'organic aesthetic' seeks nature for its subconscious conception and man for its understanding and fulfillment. The 'essential' is the idea nurtured by 'a priori principles' and formed by the evolutionary processes of its function.

Semper, with a similar evolutionary theory, clearly underscores the inherent idea upon which the action or development of form is based. He significantly avoids the confusion implicit in the belief that materials condition form by distinguishing the material dictates from man's appropriate selection of material. Semper proposes "that only the selection and treatment of materials is determined by the laws of nature, while forms and expression (in architecture) are dependent upon ideas inherent in every building and different from one kind of building to another."[18] This theory also helps clarify confusion caused by exceptions to the 'rule.'[19]

The 'essence' type supposes that the idea is not grounded in function as in the 'essential' but is inherent in the 'maker' with the material predetermined. The 'image' (of form) exists before the idea and is capable of existing as an anachronism or concept even after the form has disappeared. The 'essence' remains. 2.72

Baldwin-Smith's[20] derivation of this ontic dimension for the "Dome" recognizes that the "image" (or shape of the form) precedes idea, and acknowledges the process necessary for the development of the form from the idea. To advance, the idea is subjected to a cultural level where the idea acquires symbolic meaning vital to its continuance. The idea's existence is furthered by its 'socialization' during which period it receives the incentive, tools, techiques, and craftsmen, to become reality.

Panofsky follows this simple logic by similarly developing his theory for the history of ideas, by using the transition from abstraction to reality in art as basis. His descriptive process substantiates the theory that "essence" is achieved only through the hierarchical ordering of the parts. Panofsky's 'history of ideas' gives a conceptual basis of the idea from natural inception through historical interpretations to the eventual developed theory. This conceptualization accounts for the aesthetic and empathetic interpretations of objects in their expression, as well as the necessary reliance upon experience and the final understanding that 'unity' comes through synthesis. These steps are necessary for one to come "to know" yet does not guarantee achievement of the 'essence.'

Frankl[21] correctly concludes that 'essence' is never achieved, yet can be sought from a hierarchical ordering of parts wherein only when the creator has proceeded along the necessary path is discovery of significance realized. This 'essence' is not constrained by time, history, material, or process, but only man's limitations of creative power to unveil the possibilities. Thus 'essence' is impregnated in the necessary interaction of the parts, with harmony already understood as existing within the parts.

The 'essence' is not necessarily an experimentally or empirically-based theory but has acquired knowledge by way of the progressive steps necessitated in the attempt to achieve fulfillment. The 'image' that exists before the idea can be further described as the inner notion or cosmic spirit which exists within the parts of the object (itself) once conceived. Appropriately this 'essence' is immortal, and even after the image is gone, (and its maker) and the form disappears, the concept continues and the 'essence' remains.

The ontic dimension is still concerned with the particular, and the specific relationships of man to man, within a context of time and place. The function and the use of the bridge are its means of accomplishing order and harmony within the form. The "nature" of the bridge cannot be perceived on this level. The only way to define the "Essence-Being" of the bridge is to assume a higher order--that is the ontological dimension. The ontological dimension 2.8

proceeds from the more general to the particular to understand and define the bridge. 'Order' is already assumed as existing in the bridge. From this 'Order' the Essence of the bridge is defined.

2.81 Thus, the "Essence-Being" based upon Heideggerian philosophy, compatible in theory with the "existence-will" philosophy of Louis Kahn, provides the final framework in the 'essential-essence-Essence' thematic development.

Martin Heidegger,[22] a German existentialist philosopher, defines 'phenomenon' and 'logos' as the two necessary ways of understanding "Essence-Being." In his writings, <u>Introduction to Being and Time</u>, "phenomenon is defined as the self-showing in itself" (or "a distinctive way something can be encountered" i.e., "forms of intuition"). The phenomenon is "what is manifest" (i.e., the bridge). Logos is the necessary part to "letting something be seen," and provides the means for the phenomenon to develop. Both metaphysical concepts are aimed at revealing (truth) by the "a priori logic within the realm of Being" which is its "nature." This phenomenological approach is equally founded in more concrete terms in Louis

Kahn's statement, "Order is."

Suggesting that "being" transcends the actual reality of existence, Heidegger and Kahn enlighten our understanding of abstractions that words never can define. Kahn expresses this 'phenomenon' as the 'existence-will' meaning that an object has within itself a will-to-be. This "will" is only possible in form when it has been 'manifest' to the designer. (Kahn's "A House-A house-A home" framework exemplifies this order.)[23] Louis Kahn's belief in three important activities cultivate this "will-to-be": To learn, to meet, and to have well-being."

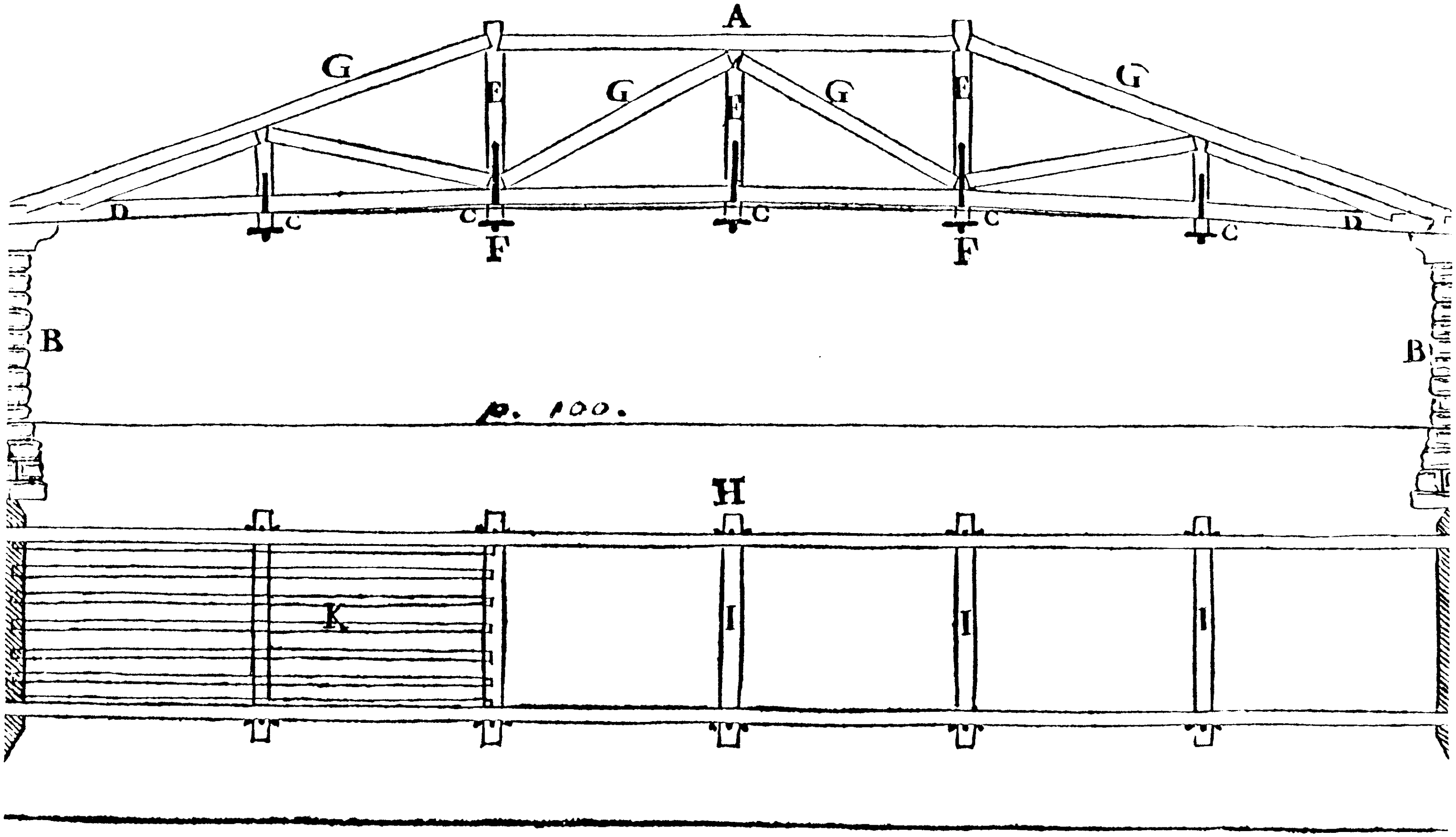
Lao-tze's Tao similarly complies with this explanation of the already existing "Order" of "Essence-Being" in his first chapter of the Way of Life:[24]

Existence is beyond the power of words
To define,
Terms may be used
But are none of them absolute.

And similarly in chapter 14:

Yet one who is anciently aware of existence
Is master of every moment,
Feels no break since time beyond time
In the way life flows.

ARCHITECT		ENGINEER	
	'essential'		
3.1	CISMONE TIMBER TRUSS BRIDGE	3.10	PONT DU GARD
3.2	ESSEX-MERRIMACK RIVER BRIDGE	3.11	PRINCE ALBERT ROYAL BRIDGE SALTASH
3.3	WATERLOO BRIDGE	3.12	GEORGE WASHINGTON BRIDGE
	'essence'		
3.4	SANTA TRINITA	3.13	PONT NEUF
3.5	IRON BRIDGE AT COALBROOKDALE	3.14	FIRTH OF FORTH BRIDGE
3.6	RISORGIMENTO BRIDGE	3.15	SALGINATOBEL BRIDGE SCHWANDBACH BRIDGE
	'Essence'		
3.7a	PONTE VECCHIO	3.16	PUL-I-KHAJU BRIDGE ISFAHAN
3.7b	PONTE RIALTO		
3.9	RUCK-A-CHUCKY BRIDGE	3.18	BROOKLYN BRIDGE



p. 100.

THE CISMONE TIMBER TRUSS BRIDGE at Bassano, Italy (1570)

Case 3.1 'essential'

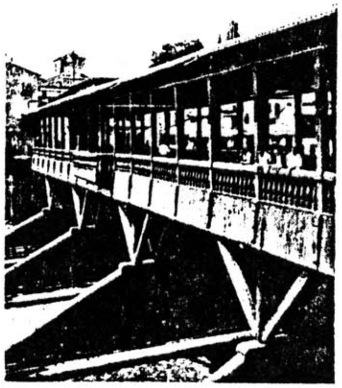
Andrea Palladio, Italian architect

Andrea Palladio's (1518-1580) writings on bridges acknowledge his understanding of the forces active in bridge design. His designs for wooden truss bridges, in particular, underscore this knowledge while recognizing that construction was possible without his knowing the magnitude of these forces.

Aware of Julius Caesar's timber trestle bridge over the Rhine River (55 B.C.) and Trajan's bridge over the Danube (A.D. 104) Palladio describes three 'inventions' relative to his own timber truss design in his Third Book on Architecture (Chapter VIII). The first 'invention' develops a form based upon each member bearing its own weight. An awkward and heavy stringer bridge form results with all the members of the same dimensions. The second 'invention' similar, but with a curved-arch chord, improves upon the first by proposing a truss wherein the weight is carried by the upper member and supported by the vertical members

Cismone Timber Bridge
Fig. 31

(collonelli). The final 'invention' with diagonal cross bracing is actually a beginning of a 'true' truss. The triangulated arched truss can be seen as a segmented, self-supporting unit. The advantages of these panels are in expandability and therefore the increased spans without additional piers.



Palladio's Covered Bridge
Bassano, Italy
Fig. 32

Palladio's general ideas on bridges include both stone and wood; yet it is, especially, through his understanding of the wooden arch-truss that he promotes as early as the 1550's (which is 300 years before these principles are physically utilized in built bridges) the ideas upon which rigid frame bridges are based.

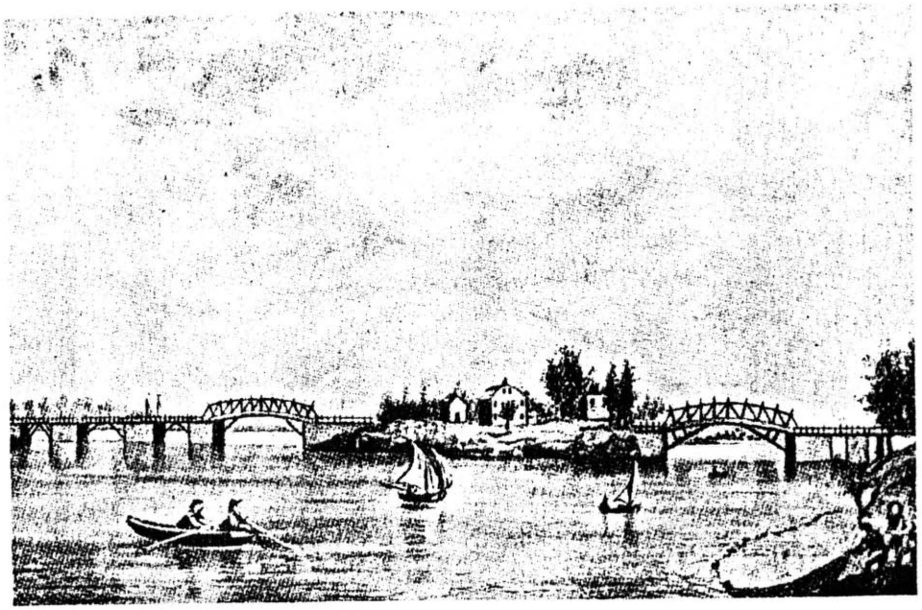
The decided advantage of having a bridge builder who writes about bridges is found not only in the inclusion of the design details but also in the revelation of the thought process and ideas that preceded the conception.

In 1570, Palladio built a wooden truss bridge over the Cismone River, in Bassano, Italy. No longer existing, as wood simply does not endure, the details of the construction can be found in Palladio's writings. The 180 foot span of the river was divided into five equal spans, with each part made up of eight oak timbers for the main beam members, each one and one-half feet thick and thirty feet long. The connections carry the weight to the vertical supports as explained in his earlier 'inventions.' The basis of a king-post framing except with an arched top chord, this Bassano del Grappa Bridge was the forerunner to the wooden trusses developed much later in America.

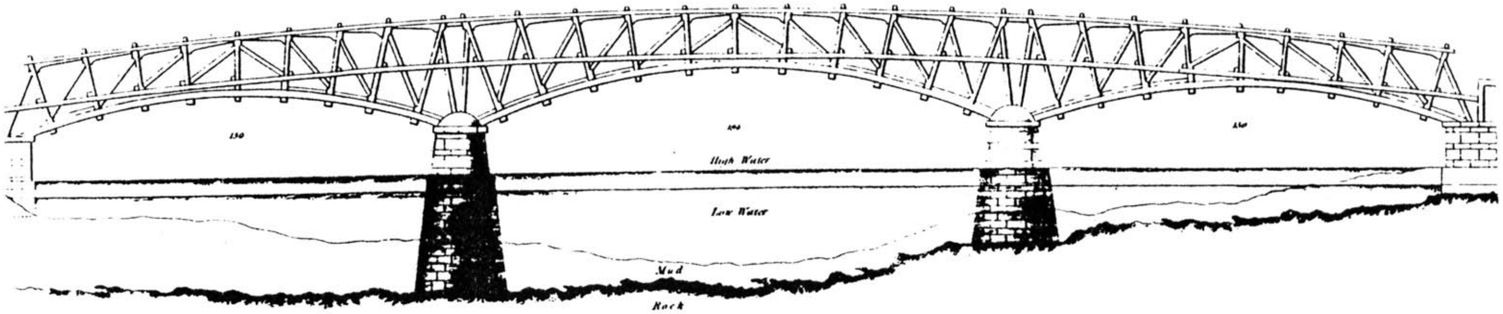
Palladio's lack of scientific knowledge with regard to his analysis of the forces and their magnitude in the trusses is amplified in a statement which nullifies the basic purport of his systematic descriptions of trusses. Palladio states:

> But because the particulars are infinite, no certain or determinate rule can be given about them (trusses), and therefore I shall present you with some draughts, and specify their proportions, whereby everyone as occasion offers, or his genius is happy may take his measures and perform what shall be worthy of praise. 1

Whether due to his vague approach, or his non-replicable method, Palladio's truss designs did not provoke any dramatic or immediate repercussions or reactions in bridge designs. In fact, in Europe truss design was not studied again until the middle of the 18th century with the advent of new municipal works brought about by the new interest in civil engineering as a profession.[2] Two hundred years after Palladio, wooden truss bridges were built by American housewrights as a natural outgrowth of their capabilities as carpenters, combined with the plentiful supply of the natural material: timber.



Essex-Merrimack Bridge
Fig. 33



THE ESSEX-MERRIMACK RIVER BRIDGE, Newburyport, Mass. (1793)

Case 3.2 'essential'

Timothy Palmer, American housewright

The disadvantages of wooden bridges may outweigh the advantages. However, due to labor and capital shortages, and the availability of timber, wood became America's most logical material for construction in general, and for, in particular, the early bridgebuilders. While England had its iron foundries with its ironmasters developing their iron arched bridges and tubular metal bridges, the Yankees were progressing in the wooden counterpart for bridges. A noted difference between the British and American cultures is discerned by the demand for expediency of construction. The American priority for quick construction was answered by wood.

The first major wooden bridge in America was across the Charles River connecting Old Brighton to Cambridge in 1662. A primitive structure of "cribs of logs filled with stone and sunk in the river--hewn timber being laid across it,"[1] this bridge lasted over one hundred years. The first

The "Permanent" Bridge
Fig. 34

wooden trestle bridge on piles was built by Samuel Sewell, in York, Maine, in 1761. However, the inadequacies of these short span bridges were soon realized, especially with the advent of the railroad in America.

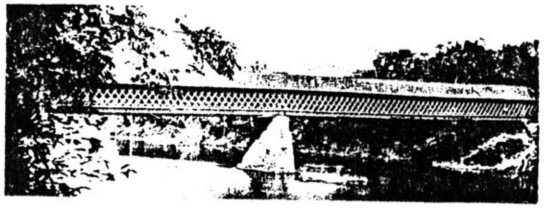

"Burr-arch" truss
Fig. 35

The first 'geometry-work' bridge across the Shetucket River near Norwich, Connecticut, is attributed to John Bliss and recorded as the first built on the truss principle.[2]

The first patent for wooden truss design is registered in 1793, to Timothy Palmer, (1751-1821), an American housewright. Whether Palmer was aware of Palladio's designs in the 1540's for arched-truss bridges of timber, or of the Swiss Grubenmann brothers' wooden truss bridges built in the 1750's over the Rhine River, is not known. What can be ascertained, however, is that as a housewright and carpenter, Palmer was familiar with the king-post truss typically used to support floors in mills, and the roofs in barns. As a self-educated man, he obtained most of his knowledge from practical experience gained through associations with the Newburyport carpenters and shipbuilders.

Palmer, a celebrated architect, by the merits of his successful design for a church and spire in Newburyport, Ma., is recorded in engineering history as the first American builder of long-span wooden bridges. Recognizing the limitations of the timber beam and pile trestle for longer spans, Palmer's first bridge, the Essex-Merrimack, proposed a composite truss of timber. Within fifty years of his building of this 'statically indeterminate' structure, American bridgebuilders would subsequently develop a more rational and mature form uniquely their own--the triangulated wooden truss.

In May, 1793, Massachusetts Magazine published a description and (plate) picture of Timothy Palmer's first bridge design. The bridge was composed of two unequal spans of trussed arch with typical beam and pile trestle approaches. Deer Island was located between the two spans. Overall length of the bridge was 1080 feet with a width of 34 feet.[3] Although criticized for costing twice as much as proposed, the bridge's rapid construction within seven months rectified the expense argument.



The Town Lattice Truss
Fig. 36

The methods used in construction of the Essex-Merrimack River Bridge were repeated in two subsequent bridges, the Piscataqua Bridge, in Portsmouth, New Hampshire, (1794), and the Haverhill Bridge, Haverhill, Massachusetts, (1794). Both constructions similarly consisted of three concentric timber ribs. The second rib carried the road and the third provided a railing. Theodore Cooper describes the construction in detail, in an 1889 report to the ASCE:

> The ribs were made from crooked timbers, so that the fibers were nearly in the direction of the curves, and they were connected by pieces of hard and incompressible wood, with wedges driven between. The ribs were mortised to receive these connecting pieces and wedges, thus keeping an equal and parallel distance between them. Each rib was formed of two pieces, about fifteen feet long, laid side by side in such a manner as to break joints. Their ends all abutted with square joint against each other, and were neither scarfed nor mortised, the two pieces of timber held together by transverse keys and joints. All the timbers were admirably jointed and freely exposed to the action of the air. Any piece might be removed for replacement without injury to the remainder of the structure. 4

Beginning with the "Permanent" Bridge scheme in 1804, a radical change became apparent in design, which continued in all Palmer's later bridges. Palmer was asked to expedite the construction of a wooden truss bridge over the Schuykill River, in Philadelphia, Pennsylvania, after a history of delays caused by changes in materials, (masonry to iron, finally resolved in wood) resulted in increased costs of earlier designs. Palmer's bridge consisted of three arched trusses which no longer required bracing between the arches but were continuous over the piers. Another 'first' for Palmer, and well-in-advance of European designs, found root in his desire to protect his wooden bridges from the weather. The "Permanent" Bridge scheme was the first recorded covered bridge of note. Discussing the "Permanent" Bridge, Palmer stated:

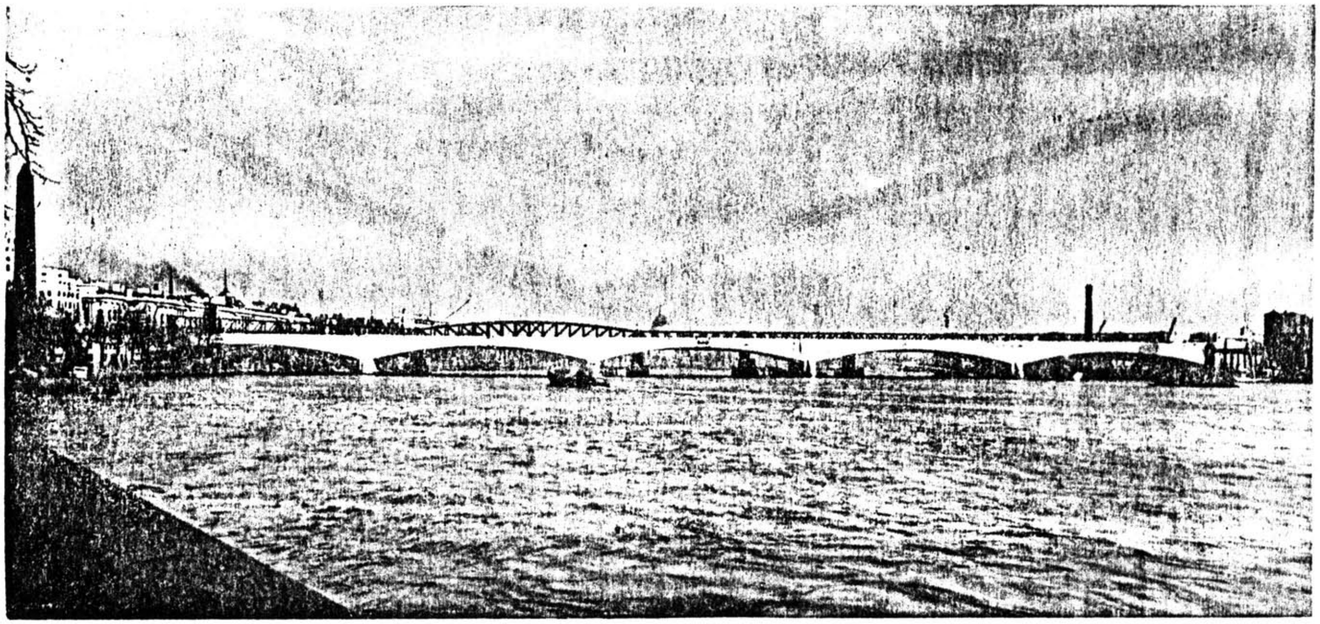
> I am an advocate for weather boarding and roofing, although there are some who say it argues much against my own interest....It is sincerely my opinion the Schuykill Bridge will last thirty and perhaps forty years if well covered. You will excuse me in saying that I think it would be sporting with property to suffer this beautiful piece of architecture, which has been built at so great expense and danger, to fall into ruin in ten or twelve years. 5

At best, Palmer's "Permanent" Bridge remained imitative of known masonry forms. The arched ribs, 20 feet at crown and

35 feet at the springing from the stone piers, were similar to stone voussoirs, and not necessitated by the nature of the timber.[6]

The construction of the piers and abutments by the engineers provided more innovative developments than the bridge itself. Cofferdams designed by William Weston, (from England) were used to achieve a stable rock bed of unprecedented depth of 41'-9". Thomas Vicker, the stone mason, developed an "ingenious method of strengthening the masonry work by stretching across the piers massive iron chains which were embedded in the masonry."[7]

The significance of Palmer's first bridge cannot be undermined. The Essex-Merrimack River Bridge, although not a 'true' truss, was the genesis that aided the development of the truss as a distinct structural form. The importance lies in Palmer's innovative attempt which is attributable to his experience and skill. Although Palmer's use of the composite truss form was not based on stress/strain calculations, by understanding the capabilities of timber, the natural need for the arch to be stiffened by the deck (or braced appropriately) was recognized. The submission of Palmer's arched truss form to the practicality of testing had a seminal influence on the development of the theory of the American 'true' truss.



The New Waterloo Bridge
Fig. 37

THE NEW WATERLOO BRIDGE, London, England (1939-1942)

Sir Giles Gilbert Smith, Architect
Buckton and Cuerel, Engineers

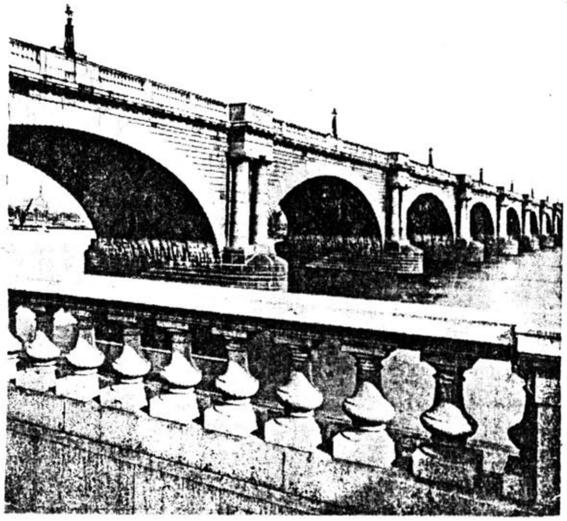
The beginning of the 20th century marked an advance in reinforced concrete, in Europe as well as in America, which dramatically affected bridge design. The singular use of concrete in the form of the arch was soon supplemented by the new material's adoption of the continuous beam and rigid frame. The use of reinforced concrete in continuous beams as in short-span highway connectors and elevated roadways is still prevalent today.

The most advanced theory and practice of reinforced concrete at the end of the 19th century had been found in the Melan principle[1] in which the reinforcing arch ribs were self-supporting I-beams or trusses, continuous over the length of the arch rib. This heavy use of steel with concrete sheathing, however, was soon outmoded by Ransome's system.[2] Ransome used the steel tie bars as 'wire-netting' to reinforce the tensile strength of the otherwise strong compressive material of concrete. The advances in the construction of reinforced concrete were now reality, and, when combined with existing cultural traditions, had far-reaching effects on the building industry.

The New Waterloo Bridge, over the Thames, London, built as a replacement to 'Rennie's masterpiece'[3] of 1817 evidences the adaptation of the new material to the known principles of the beam in a new form, the continuous twin-arch girder.

The demands placed upon the design by its succession to a 'noblework of engineering' in stone cannot be understated. The Rennie bridge had, from 1817 until 1933 when it was taken down, served not only the functional requirements but also the aesthetic obligations as reflected in its accepted classical style. The engineers, Buckton and Cuerel, of the bridge engineering firm of Rendel, Palmer and Trilon, and the architect, Sir Giles Gilbert Scott, realized the traditions set by precedent, and attempted a scheme which would remain consistent within the still present Victorian image of the city of London.

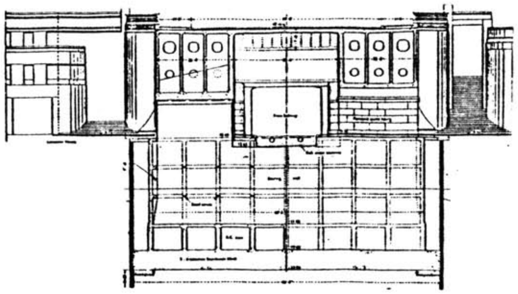
Unfortunately, the designers chosen were more popular than experienced. Buckton and Cuerel were accepted leaders in bridge design, who at the time of the Waterloo, were also involved with the construction of the Wandsworth and the Chelsea bridges. Sir Giles Gilbert Scott was the appointed City Architect. The collaboration of the architect and the engineer was seen as a prodigious factor in the bridge's design. However, the difficulties in construction and the complications in structural solution actually prove the counterproductiveness of this collaborative design approach. The form of the construction "imposed by aesthetic reasons" was costly due to extensive use of welding, complex detailing, and the conglomerate scheme evolving from rehabilitative necessity.



'Rennie's Masterpiece'
Fig. 38

The simple stone-faced facade of the five eliptical arch span, (which reaches from the Victoria Embankment to the Surrey side of the Thames) subtly conceals the complex structure of the reinforced concrete girders. Elizabeth Mock, understandably, underestimates the difficulties in construction by describing the bridge as consisting of "long-leaping curves (which) are executed with such easy grace."[4]

The architect, Sir Giles Gilbert Scott, restricted the width of the beam girders by determining the form of the curve. Scott contended that in the 1930's, there was a revival of interest in 'line and form' that had not occurred since Telford's time. This attention was obvious in the "motor cars with a keen eye for line" as well as "ships and aeroplanes."[5] Scott, thereby, felt the need to evoke similar 'eyeable' qualities in the New Waterloo Bridge. By adopting twin-girder construction, the wide arches and tunnel effect were alleviated. "The first pier well out in the water opened up with the striking effect of an uninterrupted view of the sweeping lines of the embankment."[6]

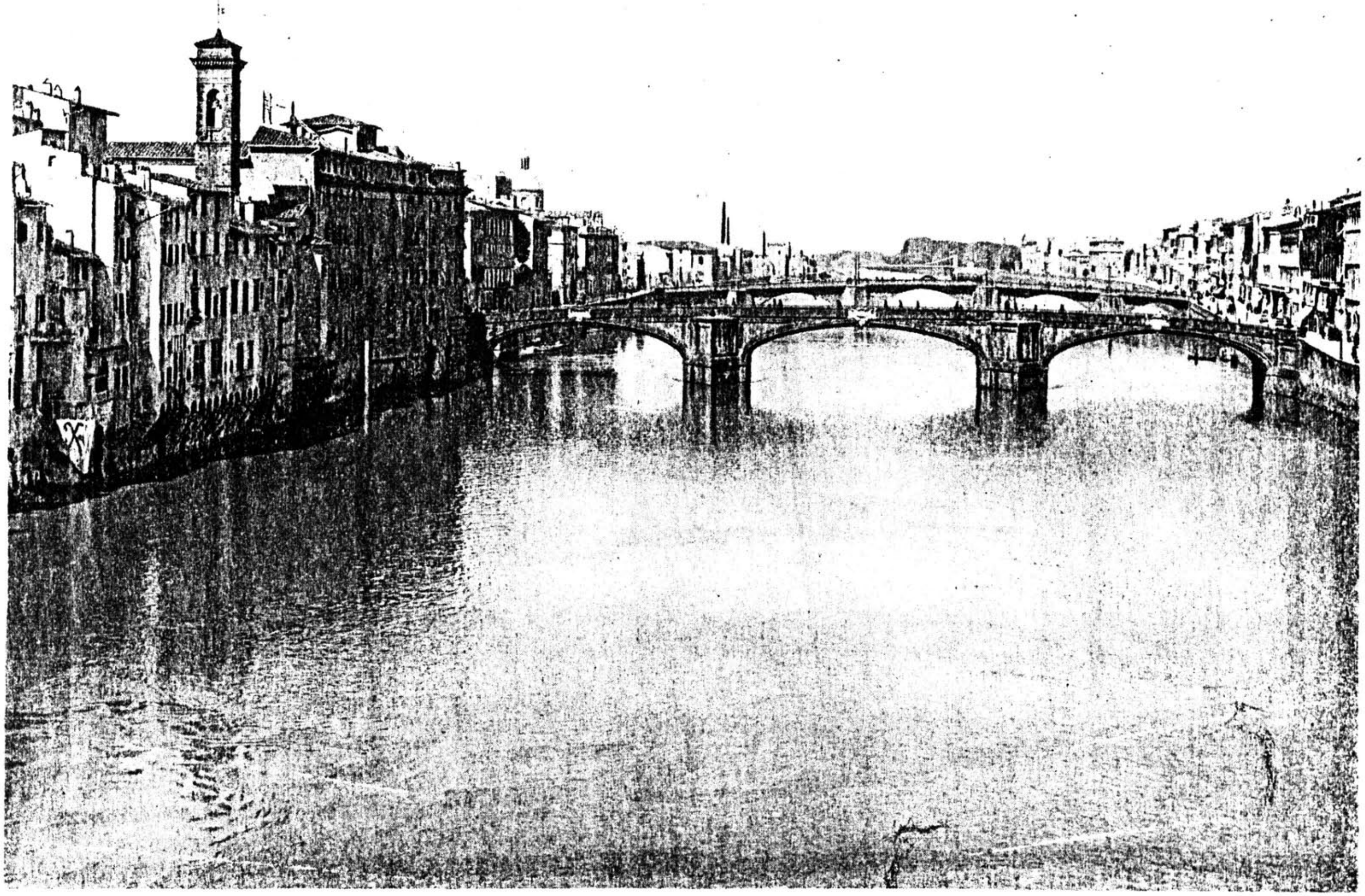


Cross-section of
Continuous Beam
Fig. 39

Functional aspects of this structural solution also made the twin-arched beam girder the best choice. The long and low profile of the continuous beam would not impose a huge superstructure upon the city. Instead, the elimination of pier supports, which allowed more navigable river, and the five-arched spans (each approximately 240') simplified the form and complimented the skyline.

Scott's overzealous desire not to be utilized as a 'decorator' of the bridge was actually a preoccupation which led to his performance as such. Covering the bearing walls of the bridge with vertically-applied (not to be confused with masonry) granite facing material because of the 'unpleasing and unfinished' texture of the concrete, the architect admitted strong claims to the past traditions of the classical approach.

The New Waterloo Bridge represents the 'growing pains' of a new material searching for permanence in a new form. The reinforced concrete arched ribs with trusses gave way to lighter continuous box beams and eventually to prestressed concrete forms.



SANTA TRINITA BRIDGE, Florence, Italy (1566-1569) Case 3.4 'essence'

Michelangelo, Italian architect and built by
Bartolomeo Ammanati, Italian sculptor

The new spirit of the Renaissance period in Italy encouraged the 'discovery of stucco as a plastic medium' and simultaneously 'a love of ornamentation.'[1] These new ideals and aspirations of the Renaissance, while freeing the builder from Antiquity, also developed into a separation from the medieval processes. The artistic appeal and philosophical approach taken by Renaissance designers provided the transition period that aided the shift from medieval empirical craft to the development of a theoretical science of building. Understanding this spirit, sculptors, Michelangelo and Ammanti were appropriately chosen as the architect and builder respectively of the new design for the Ponte Santa Trinita, over the Arno, in Florence.

Santa Trinita
Fig. 40

"Michelangelo, one of the greatest creative geniuses in the history of architecture, frequently claimed that he was not an architect." This statement reiterated by James

Ackerman, in his book, The Architecture of Michelangelo, prefaces his presentation of Michelangelo's architectural ideas. To appreciate the Ponte Santa Trinita, the necessary distinction between the new Renaissance ideals and Michelangelo's variance from these ideals must be clarified. Ackerman concedes that "to visualize any of Michelangelo's designs we must seek to capture not a determinate solution, but the spirit and goals of the process."[2]

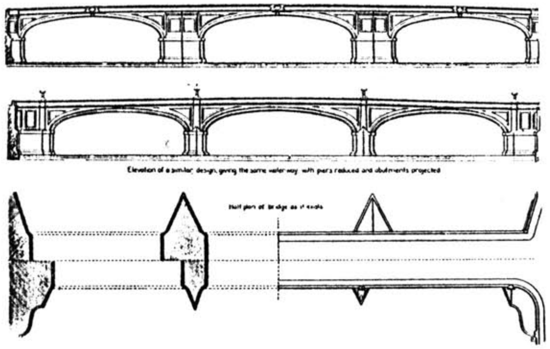
Michelangelo's sculptures, particularly The Slaves, readily admit this truism. As an 'unfinished' sculpture, the figures of the slaves are more complete and emphatic in their struggle to exist free from the uncarved marble. As his sculpture, Michelangelo's buildings are similarly seen as structures that can be shaped and changed within the context of light, shadow and movement. Instead of using the human figure as the basis for the geometry of proportion as the humanists did, the human body to Michelangelo meant motion, function, and change.

Ackerman claims that if Michelangelo had written a treatise on anatomy his theory would have emphasized the human "moti" and "apparenze." ("moti" suggests emotions as well as motion; "apparenze" implies the'psychological and visual effects of bodily functions.')[3]

The Ponte Santa Trinita, an early Renaissance bridge, in Florence, (1570) depicts a departure structurally from the typical Roman bridge and an admission sculpturally to Michelangelo's and Ammanti's creative ideals. The semicircular arches, the Roman precedent, were replaced by elliptical arches. "Using the curves of Michelangelo's sarcophagi on the Medici tomb to give shape to his arches, Bartolommeo Ammanti designed the elliptical arches"[4] to give more navigable freedom on the river Arno. After World War II, when the bridge was reconstructed engineers could not solve the arch problem to replicate Ammanti's unprecedented span to rise ratio of 1:7. The flattened curve at the crown defied the analytic's calculations, "suggesting that there is a limit in intuition and the artistic eye."[5]

Elliptical Arch
Fig. 41

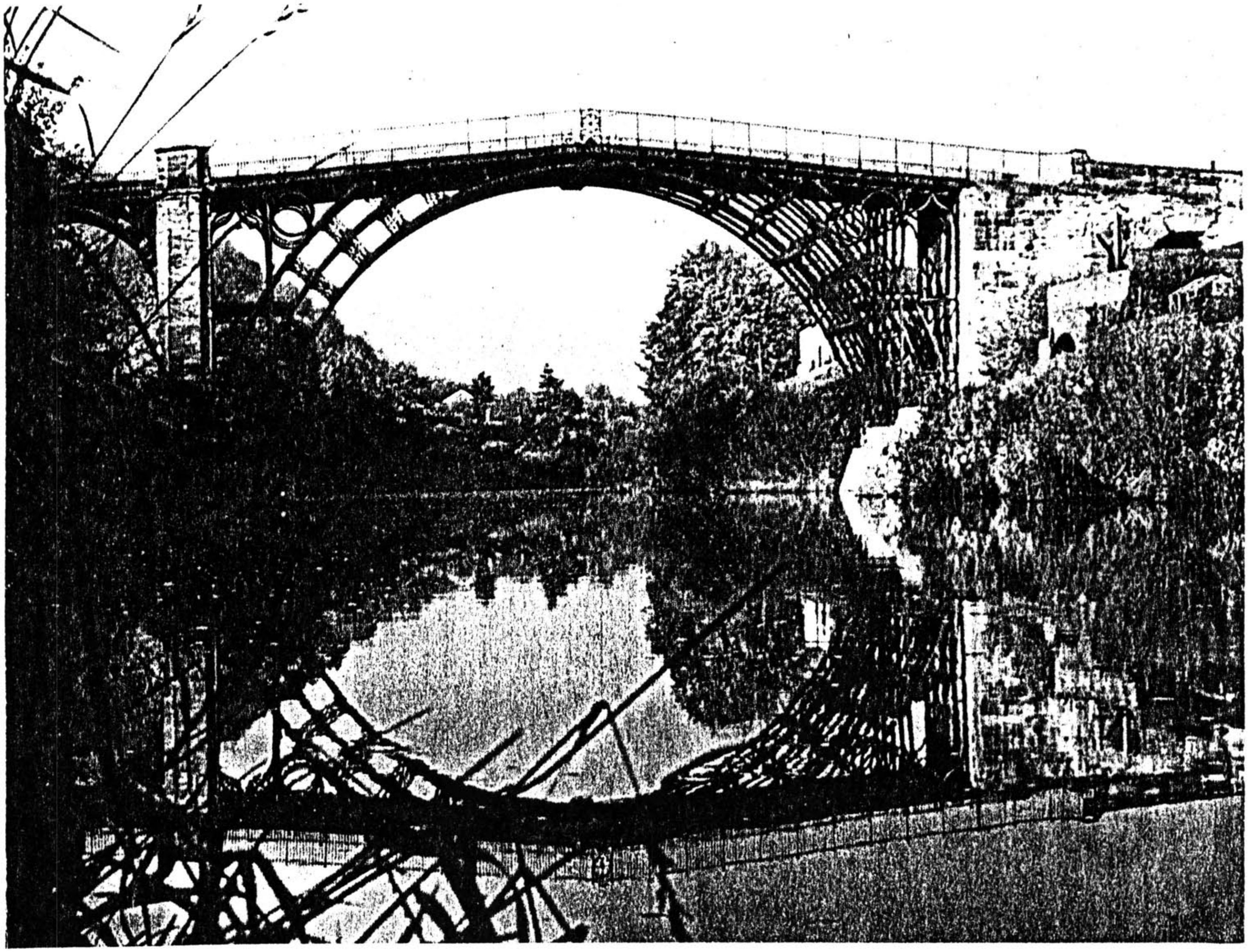
The original engineers, Alfinso and Guilio Parigi,



Similar Elevations and
Half-Plans with Piers
Reduced
Fig. 42

solved Ammanti's foundation problems for the Santa Trinita, by building two concrete walls seven feet thick by ninety feet long to act as sheet piling. Filling between with concrete, and then setting two walls parallel to the river's flow, provided the 'compartmentalized' abutments upon which the piers were built.

The 17th century sculptor Francavilla, later added a decorative feature to the Ponte Santa Trinita with four sculpted statues, one for each season. The value of these statues to the bridge users, both spiritually and traditionally, was emphasized by the world-wide search that took place after the bridge's destruction in 1944. Only three statues were found immediately. Not until 1961 was the final head of the last (season) sculpture found in the river. The Florentine newspapers gloriously proclaimed: "E tounata la primavera!" (Spring has returned.)[6] reinforcing the importance of the bridge and its features as a recognizable part of the people's everyday life.



THE IRON BRIDGE AT COALBROOKDALE, Shropshire, England (1775-1779)

Case 3.5 'essence'

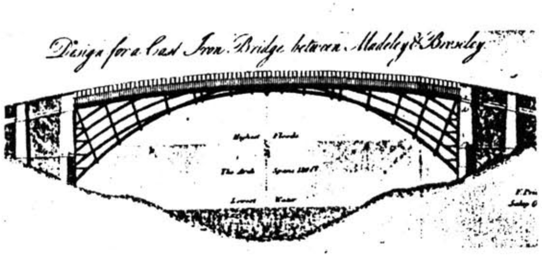
Thomas Pritchard, English architect

Abraham Darby III, English iron founder/builder

When in 1773, Thomas Farnolls Pritchard, a Shrewsbury architect, developed the design for the first iron bridge at Coalbrookdale, he had no way of realizing the resonant effects this combination of two distinct traditions, one of stone and the other of iron, would have upon the professions of both the architect and the engineer. Not a prototypical cast iron bridge nor the world's first,[1] the cast iron bridge at Coalbrookdale represents a critical technical transition intellectually and materially, from old to new tradition.

As a successful architect, and the son of a joiner, Pritchard's background and practical experience led him to the fitting development of such a design. As a surveyor of stone bridges, Pritchard gathered the necessary knowledge of the techniques of stone masonry. Working with highly skilled craftsmen as part of his architectural practice

Iron Bridge Coalbrookdale
Fig. 43



Bridge design
by Thomas Pritchard
Fig. 44

he was also aware of the 'techne' involved. In the 1760's through his involvement with fireplace designs, Pritchard became familiar with the craft of the iron masters. Thus Pritchard, handily, combined the experience and knowledge of both traditions. Unfortunately Pritchard died in 1777 and never saw his design actualized. One of the bridge proprietors, Abraham Darby III, an iron works founder, without bridge building experience, agreed to build the Iron Bridge.

The form of the cast iron arch inversely models the form of a masonry arch, with webs for the joints, and voids for the solids. As the use of cast iron became better understood, as a structural material strong in compression yet not as reliable in tension, the profile of the arch was reduced. Thomas Telford's bridge proposal for a 600' span cast-iron arch at the site of the London Bridge correctly interpreted the new material as distinct from stone. Although never built, low-profile arches in cast iron were built later. This reduction in the arch profile alleviated the need to incline the road platforms while producing a structural advantage by reducing the "effective depth of the arch ribs without the likelihood of the thrust line passing outside and inducing tension on the other side of the rib."[2]

The Coalbrookdale Bridge, consisting of six semicircular ribs, has no rivets or bolts for its numerous connections, but was a mortised assembly as if timber jointed. Whether poured into molds directly from the blast furnace, or cast in half from nearby foundries, the total length of the rib castings is seventy feet long.[3]

Telford's proposal
over Thames
Fig. 45

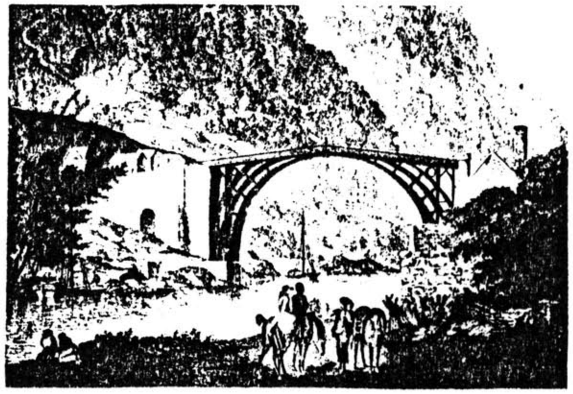
Many accounts have recorded the construction period of the Iron Bridge, yet none are widely published. The best sources seem to be the accounts in the Shrewsbury Chronicle. From this newspaper's records, the fact that all the bridge's major parts were erected during a three month period concluded in November, 1779 when the scaffolding was removed, is well documented. From Darby's accountant's records of the cash flow, it was deduced that a model was constructed in order to prepare for the construction method and process. The only acknowledgement of the model's existence was the amount received when it was privately sold.

One fact that need not be published was the obvious change that the Iron Bridge had on the Severn River Gorge region. Originally planned and built to meet the local need for a connection between the turnpike road and the county of Shrewsbury, the bridge was geographically situated and proposed to span 101.6' across the Severn River. The resulting rerouting of the stage coach, and the frequent appearance of interested tourists accelerated the commercial development, and at the very least increased the hotel trade of the once sleepy county. The bridge proprietors properly aggrandized themselves in the new market by charging tolls.

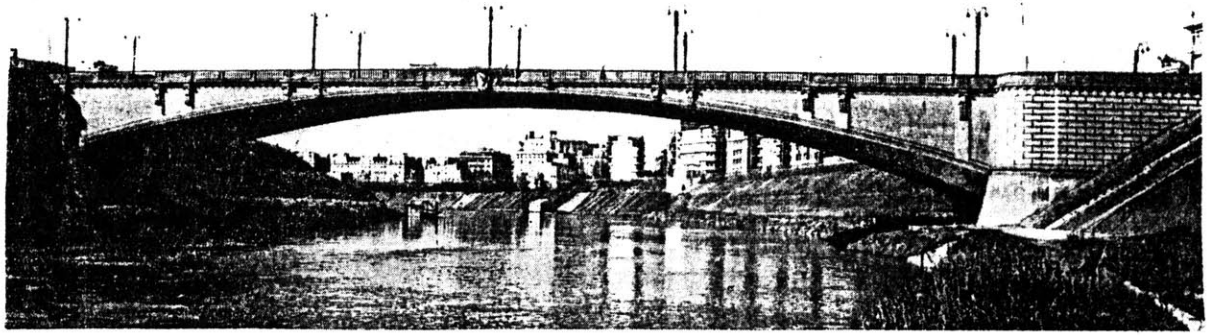
A long history of repairs and continuous study of the stability of the abutments maintained the workable use of the bridge until 1934. As recently as 1971, the tollhouse at the south abutment was renovated into the Gorge Museum and information center. The Iron Bridge, at Coalbrookdale, now a national landmark, has become a resort, with landscaped parks adjacent to its approaches and a convenient car park. The tourist easily can combine in a day's activities a trip to a nearby iron foundry and a visit to the famous bridge.[4]

Immortalized in paintings, designs for iron grates for fireplaces, bill heads, ceramic pieces, tankards, jugs, the symbol of the Industrial Age lost its original attraction by the mid-nineteenth century when the ill effects of the industrialization diminished the bridge's acclaim.

A lasting effect of the Coalbrookdale Bridge is the dichotomy that it represents with regard to its use of iron in its arch form, and to its need for its own empirical basis. Although intrinsically representing a culmination of old and new traditions, the Coalbrookdale Bridge concurrently signaled a departure from the past's empirically-based bridge forms. The use of cast iron as a structural material celebrated a new birth of exploration into its strengths, weaknesses, properties, uses. However, instead of developing its own structural identity experientially, the emergence of a new material founded by science simultaneously brought about the increased reliance on analytical calculations and on the developing scientific theory.



Painting of the Iron Bridge
by George Robertson, 1788
Fig. 46



Risorgimento Bridge
Fig. 47

RISORGIMENTO BRIDGE, Rome, Italy (1913)

Francois Hennebique

As the theory of reinforced concrete was developed in the late 19th century, it took until the early 20th century for its practical advance. French builders, in particular, such as Francois Hennebique, Swiss-born Robert Maillart, and Eugene Freyssinet were major contributors to the advance and use of reinforced concrete.

Francois Hennebique (1842-1921), a self-taught builder who as a young man apprenticed as a stone mason, was responsible for the advancement of slender forms, particularly thin slabs, as the most economical means of utilizing reinforced concrete. His ability to visualize concrete structures as monolithic form was readily apparent in his continuous beam bridges.

The Risorgimento Bridge, Rome, with its smooth elliptical curve evidences his visual ability along with his familiarity or understanding of the new material.

Hennebique, accustomed to large scale projects such as churches, bridges, railways, and viaducts was able to recognize the marketability of his expertise, and thus set up his own building contractor's office. A businessman of sorts, Hennebique maintained design authority but had local concessions for various projects. The power of his ability to promote and build is obvious from the sensational figures. In 1892, Hennebique had six projects under his control, and by 1902 this number had escalated to 1501 projects.

Aside from his enterprising success, Hennebique's technical advances in reinforced concrete demand attention. The Risorgimento Bridge with its 328' span rising only 33 feet at the crown (almost 1:10 ratio of height to span) expresses the daringness and possibilities of the reinforced concrete through its form.

Hennebique's Ponte del Risorgimento represents experience with reinforced concrete, as well as an understanding of the structural behavior. Nervi records in his book, Structures, the fact that German theoreticians, upon calculating the allowable stresses in the Risorgimento Bridge obtained a figure which exceeded that allowed by the theory of elasticity. These scientists would not renounce their calculations even in the face of the fact that the bridge existed and did not fail. Explaining why discrepancies can occur between the calculated and the built bridge, Nervi confesses that

> A system in elastic equilibrium is in a limiting condition of equilibrium. All actual states of equilibrium are the result of a happy tendency, common to all structures, to find the state of equilibrium which best suits their shape and nature, beyond and above our limited knowledge. 1

In the design of reinforced concrete structure, research and experience show their vitalness to the design. Hennebique's one hundred bridges built before 1900 confirms the experience, while his patents and 'agents' attest to his accomplishments in research.

The Risorgimento as a 'progressive product' in Hennebique's personal development remains timeless in the history of structures. Although the architecture was reminiscent of the Ponte Rotto (nearby on the river), the structure was a prototype for the future.

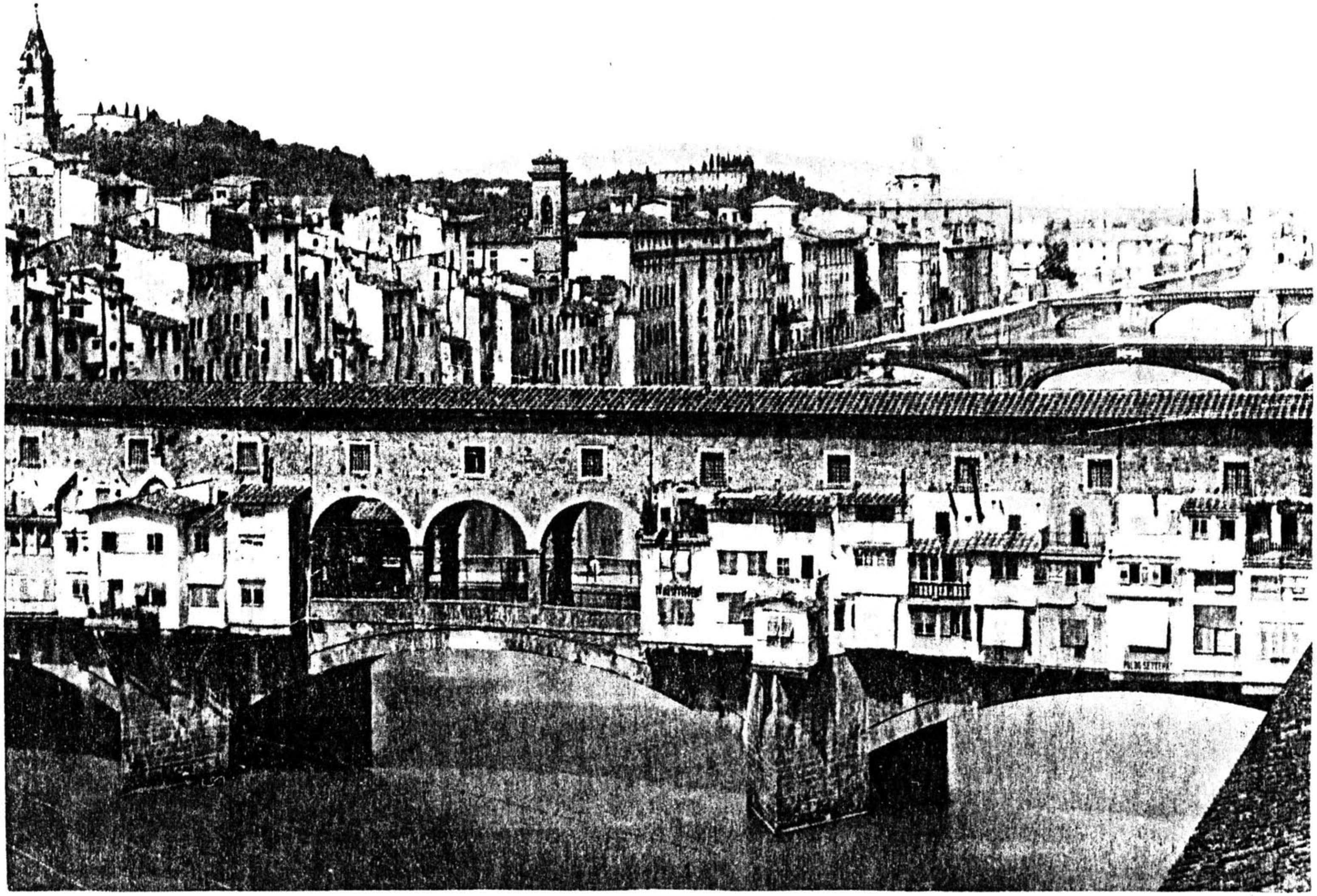
The structure, a lightweight hollow reinforced boxed girder, with a hinge at the middle, is more readily described as two cantilevered arms (8" thick at center) reaching from end supports (20" thick).

Hennebique's influence was a major contributing factor to the development of reinforced concrete. Maillart and Freyssinet, among others, continued his interests with their own in reinforced concrete.

One note of interest with regard to reinforced concrete is that the bridges at the turn of the century differ very little from the designs of today. One reason can be the unique procedure for design that was characteristic of Hennebique's time. Concerning the known practices, Hopkins states:

> Attention was directed towards the real rather than the assumed properties of the material, thus providing sound information upon which intuitive geniuses could base their design. 2

Although the practices of the early 20th century builders credit the reasons for the advances in reinforced concrete, the question remains why the latter part of the century has not excelled further.



PONTE VECCHIO, Florence, Italy (1345)

Taddeo Gaddi, Italian architect

The endurance and perseverance of names of bridges through connotative use, identify and perpetuate qualities of the particular bridge by association with commonalities. The Pont Neuf in Paris, for example, although not the newest bridge in France, thrives colloquially as 'pont-neuf' is frequently used as a term of strength, health and rigor.[1] Conversely, the 'Pontevecchio'--the Old Bridge, has carried with its name the traditional meanings and qualities of its history. The Old Bridge has been the Ponte Vecchio since the first timber construction in 972. The history of the succeeding bridges complies with the social needs and elicits the motive sources of the times, while struggling to withstand nature's indifferent floodwaters of the Arno.

The richly endowed creative climate of 1345 in Florence provided the social inspiration and the financial wealth necessary for the present Ponte Vecchio to develop as an attractive commercial shop area for jewelers and artisans.

Ponte Vecchio
Fig. 48

When the Ponte Vecchio was built at the end of the fourteenth century, it originally housed a marketplace of butcher shops. Two centuries later, reflecting the current social values and importance of fine arts, Cosimo I ordered the 'vile arts' out and the artists to move into the shops on the bridge.[2]

Shops and houses on bridges were a marked change from the medieval stone-arched bridges which expressed their existence through their feats of stability. The Ponte Vecchio (old even when new) announced not a radically new structural form of bridge design but brought a new meaning to bridges. The projecting shops, added as businesses thrived and needed to expand, create an assorted array of color and solidness to the once flat elevation of this covered bridge. The Ponte Vecchio is two stories high, with the first level consisting of its double row of shops, and its second level, the gallery denoted by small square windows cut repeatedly into the elevation, providing the connective link between the Pitti Palace and the Uffizi. The new bridge acclaimed its noted popularity as a place to shop and spend money.

Structurally engineers have marveled at Gaddi's use of the segmental arch. Similar in form to the arch form of Santa Trinita, the Ponte Vecchio was the first to use arches that were wider than a semi-circle. Obvious reasons such as fewer pier obstructions in the river, and the aesthetic effect of symmetrical arches matching the arched opening in the upper story, could have led to the desire for such unprecedented arches. The ability of the architect, nonetheless, to know that the segmental arch would support the weight of the bridge and its shops and occupants is beyond simple explanation. "Gaddi had to act on intuition or experience, and of the latter he could have had very little."[3]

The only successful influences that may have been known at this time for single-span stone arches were short-lived. The weakness of the single-span stone arch was its susceptibility to destruction. The potential of these arches is illustrated by the clear spans of the Ponte Vecchio, 100 feet in the center, and 90 feet at each side span. In 1370-7, a single-span stone bridge was built over the Adda River at Trezzo, Italy, for Visconti. This bridge, with a span longer than Trajan's timber arched

The "segmental" arch
Fig. 49

bridge, similarly did not endure. "It was not before the second half of the 19th century that similar spans were again attained. They were excelled only after the advent of modern concrete and reinforced concrete bridges."[4]

The Ponte Vecchio, or 'The Golden Bridge' as jewelers came to call it, became a lasting tribute to an early age of the Renaissance spirit. Longfellow's Poem about the Ponte Vecchio allows the bridge to speak for itself and to share the experiences and history that it has endured.

Ponte Vecchio Poem by Longfellow[5]

Taddeo Gaddi built me, I am old.
Five centuries old. I plant my foot of stone
Upon the Arno, as St. Michael's own
Was planted on the Dragon, fold by fold
Beneath me as it struggles, I behold
Its glistening scales. Twice hath it overthrown
My kindred and companions. Me alone
It moveth not, but is by me controlled.
I can remember when the Medici
Were driven from Florence; longer still ago
The final wars of Ghibelline and Guelf.
Florence adorns me with her jewelry;
And when I think that Michael Angelo
Hath leaned on me, I glory in myself.

Henry Wadsworth Longellow, Poems.
(also cited in Watson's Bridges in History and Legend. p. 157)

Antonio Da Ponte, Italian architect

Whereas the Ponte Vecchio may suffice in purporting the spirit of the early Renaissance artists, it cannot reveal the maturity and changes in ideals that were reflected in the later designs of the High Renaissance. The Ponte di Rialto (1588-1592) as a product "of the period of intense economic activity on a more sophisticated level"[1] supplies the additional dimensions of this change. By the end of the Renaissance, engineers were turning from practical experience to a more experimental and theoretical basis for design. Inventions such as treadwheel and various pulley devices were tested on new constructions. This shift to a scientific method was also evidenced by the fact that design competitions were held for the Rialto Bridge.

History documents the continual saga of repairs and reconstructions to the 'early' Rialto. Originally know as the 'Money Bridge,' located at the narrowest point of the Grand Canal in Venice, the timber construction was a toll bridge

Ponte Rialto
Fig. 50

until 1458 when the enlarged plan included shops with rent revenue. The name was subsequently changed to Rialto ("Rivo Alto" or High Bank). Up until 1524, the Rialto was still a frequently repaired timber bridge with two bascule spans.

View from Above.
Fig. 51

The banks of the Grand Canal supporting the Rialto Bridge thrived physically and financially during the many timber bridge's reconstructions. Venice, a city of commercial prosperity, due to its shipping, was ready for a more permanent and prominent bridge. In 1570, a design competition was held for a stone-arched bridge. Among the submissions were design proposals by architects Sansovino, Vignola, Palladio, Scamozzi, and Fra Giocondo. Andrea Palladio's scheme was selected yet so delayed in building by the Turkish war that it was never realized.

The Rialto Bridge of 1588 was the result of a second design competition. The selected designer, architect Antonio Da Ponte, proposed a simpler design both in detail and decoration than Palladio's original scheme. The technical details of Da Ponte's scheme acclaim the astute experiential knowledge of the later Renaissance builders.

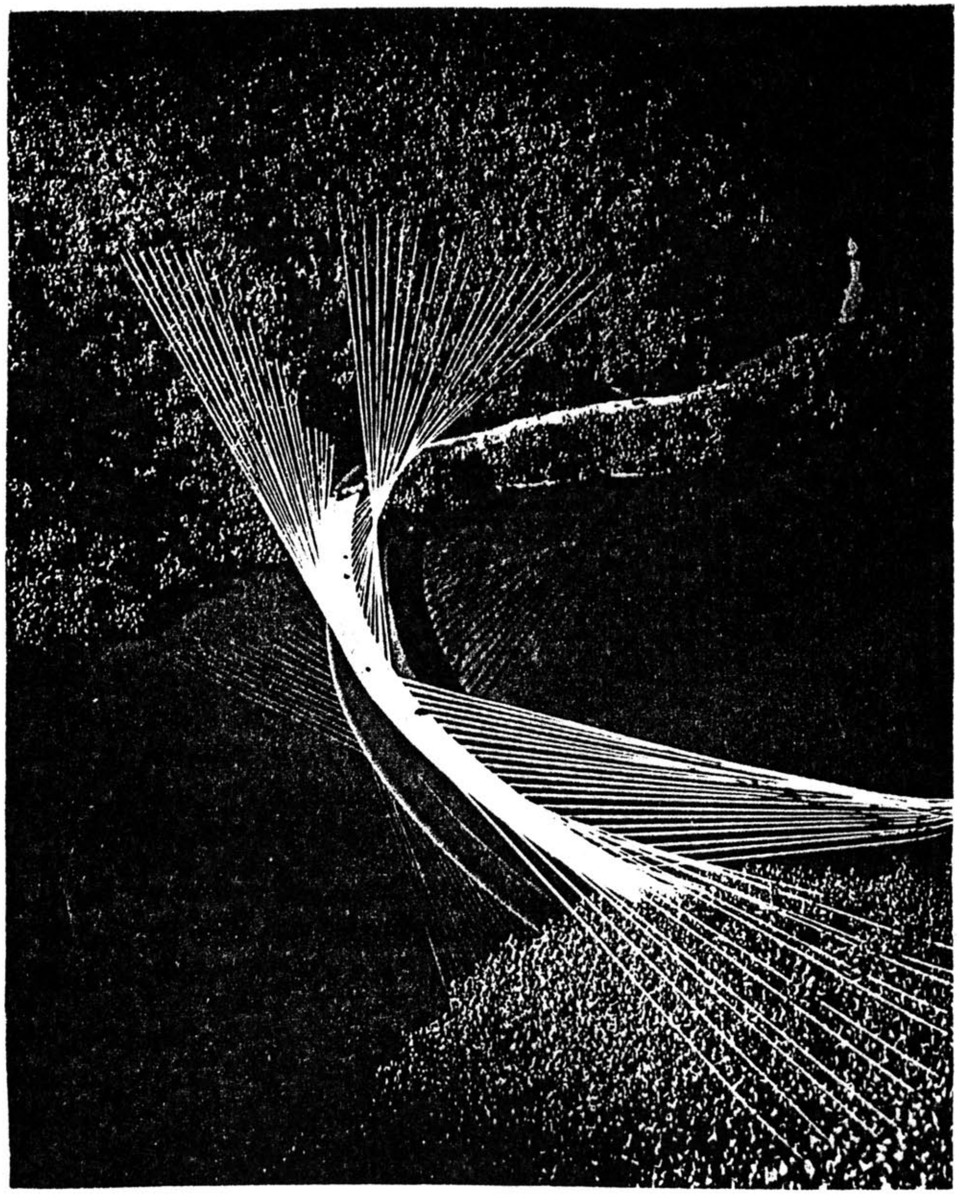
The lateral stability of the built-up banks of the canal at stake, 6,000 timber piles (6 inches in diameter, 11 feet long) were driven into the silty Grand Canal. Heavy timbers were laid across the top as capping elements upon which the piers were built up.[2] Knowledgeable of these methods for pile foundations since Virtruvius' Ten Books of Architecture, the Renaissance architect appropriately utilized the technique.

The classical revival influences of the later Renaissance style are evident in Da Ponte's arcaded symmetrical arches and the ornamented details of the balustrade. The larger central arcaded-arch which raises above the other lesser arches creates a recognizable middle plateau on the bridge, where the pedestrian can linger and view the enframed Grand Canal. However, unlike Palladio's decorated scheme, Da Ponte's austere Rialto Bridge marks a departure from the humanists' interpretation of the Vitruvian-based architecture and epitomizes a more rational design approach. Antonio Da Ponte not only designed but also built the Rialto, recognizing that the 'new' Renaissance man had to master both theory and practice.

The single-span stone arch leaps eighty-eight feet across the canal with the grandeur that only a single segmental arch profile allows, and with the strength which the stone's mass and its compression forces demand. This unity of structural achievement and inherent form creates a natural harmony and order in the bridge design.

Statistics indicate the practicalities of the design. Da Ponte's proposal was the most economical scheme priced at 250,000 ducats (approximately $375,000). The dimensional details of the covered promenade provide a visual assessment of the plan. The 66' wide arcaded walkway is divided into three walkways, with the central path the widest, 18'-6", and the two side aisles each 9'-3" wide. Four separate rows (or blocks) of shops open out to all three paths of travel.[3]

For centuries, the Rialto was the only bridge on the Grand Canal. Today it continues to proclaim its original eclat by its visual prominence and its perpetual spirit.



THE RUCK-A-CHUCKY BRIDGE, Auburn, California

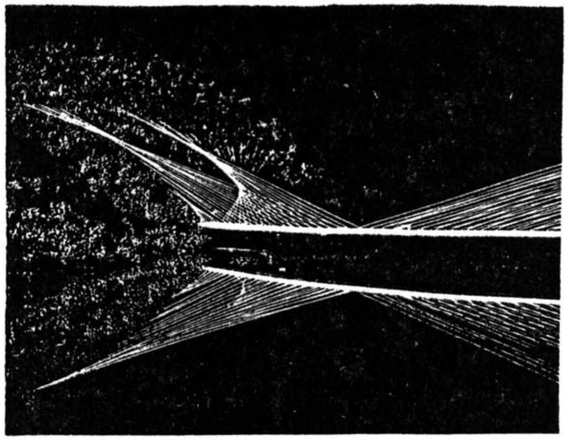
Case 3.9 'Essence'

Myron Goldsmith, Skidmore, Owings & Merrill
T.Y. Lin Engineers, International
American architects and engineers (198?)

When and if built, the Ruck-A-Chucky Bridge, over the American River, in Auburn, California, will suspend in time and space an unprecedented sculpture of engineered technique, and a creation of place never before experienced. This proposed vehicular connector to a local country road, which evolved from strict site constraints, answers more than the bare rudiments of river crossing. Because of the increased depth of the river to 450 feet when the American River Dam is built, bridge supports or piers were assumed uneconomical. Also with the steep mountains (40^{o} slope) on either bank, a straight bridge with conventional anchorages and abutments would have necessitated the additional effort and expense of tunneling into the mountain. Thus the proposed 'hanging arc' scheme of high strength steel cables with a curved plan and ends tangent to the existing road approaches on

The Ruck-A-Chucky Bridge
Fig. 52

the mountainsides, was presented. The parabolic form, with its dramatically arrayed cables, visually and physically displays the forces at work. The tensile forces in the cables carry the deck and attach the bridge to the canyon walls by boring through and using the mountains themselves as anchorages.



Side View of Model
Fig. 53

The Ruck-A-Chucky Bridge, proposed by T.Y. Lin Engineers, San Francisco, and Myron Goldsmith of Skidmore, Owings & Merrill, Architects, Inc., New York, is based upon conventional engineering practice, yet answers to a new need with vitality. The 1300 foot span with potential seismic faults below required consideration of fifteen different bridge solutions of varying structural types. Finally, the 'hanging arc' scheme evolved.

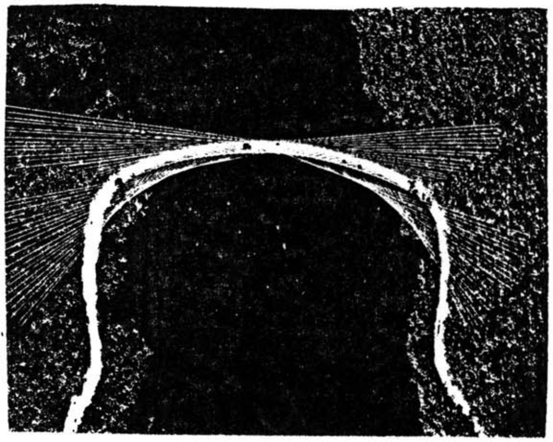
For the cable layout and design, computer optimization studies were attempted. Due to the irregularities of the topography and the resulting variances in locations of possible anchorages, the typical mathematical solution was not practical. So the designers relied on a trial and error approach, with simple guidelines. The basic guidelines included: "1.) structural efficiency, 2.) aesthetic considerations, and 3.) methods of simple construction."[1]

Once the cable formation was decided, then tests on the forces computed under different loadings were done. These tests aided the basic decisions for the type of cable to be used, and the specific anchorage method. The deck was proposed in both steel and concrete with both schemes evaluated to their advantages and disadvantages.

The cables are at 30' intervals for both aesthetic and structural reasons. The need for horizontal erection techniques have been recognized as the construction stresses are bound to be very high for this bridge.

Both model testing for seismic reactions and wind tests were performed on the basis of the proposed scheme. The results of the dynamic analyses and model tests affirm the bridge's effectiveness in resisting horizontal and vertical ground motion. The wind tests' results also support the bridge's aerodynamic success without repercussions caused by "flutter" or "vortex-oscillation."[2]

This unique scheme proposed through a collaborative



Aerial Perspective of Model
Fig. 54

effort of architects and engineers achieves more than technical success through its technology. The components of the design: the high-strength steel cables, the dramatic curve of the deck, the suspension system, and the beautiful site boundaries, create an overwhelming visual experience for the viewer and the user.

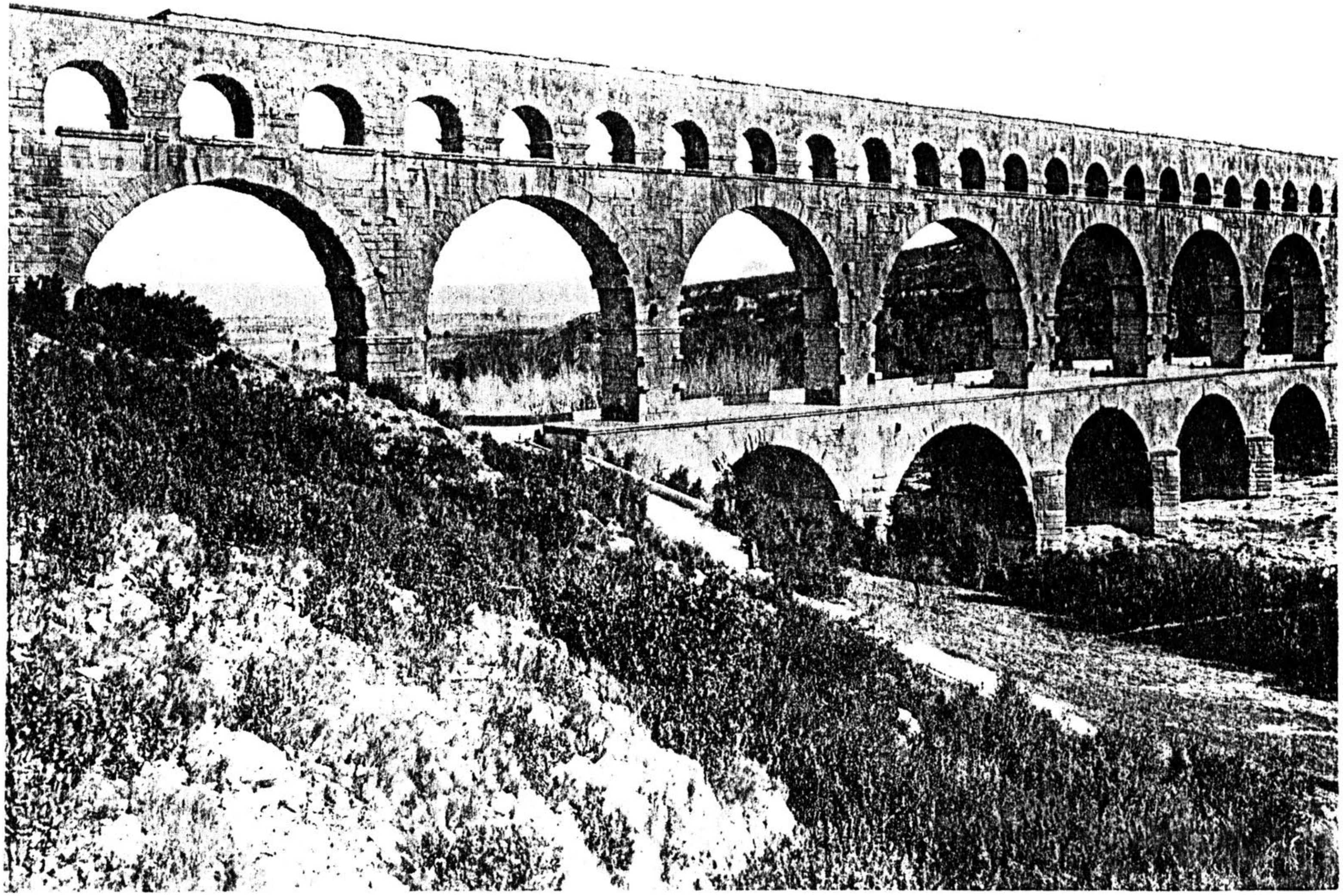
The achievement of design excellence was recognized publicly when Progressive Architecture magazine gave its "First Award for Architecture" to the Ruck-A-Chucky Bridge, and its designers, in 1979. The jury's comments expressed the unique attributes of this proposal and commended it upon its merits of aesthetic as well as dynamic structural solution, and its compatibility with the site.

One jurist, Barry Elbasani, Vice-President of Elbasani, Login, Severen & Freeman, in San Francisco, stated:

> Architecture is the making of objects and spaces which are events--in this case, a river crossing. Ruck-A-Chucky was awarded the First Design Award not only because of the technology of solution but also because of the spatial event in crossing the span which is created by the technology.

Fred Dubin, P.E., of Dubin-Bloome, Associates, New York, another jurist realized the inherent qualities of this bridge design and simply stated that "It comes out with what it is looking like and how it acts because that is simply what it wants to do."[3]

Until actually built and used, history will be unable to assess the life and existence of this modern bridge.



PONT DU GARD, Nimes, France (14 A.D.) 3.10 'essential'

Agrippa, Roman engineer

David Steinman, in his book Bridges and Their Builders, proclaims:

> Never before, nor since--(unless perhaps it be our own)--has there been a whole nation of builders; the Romans produced the first true engineers of our civilization. They built not from necessity, not from the urge of aesthetic idea or concept, not from a desire to possess material objects, but from the sheer joy of building, for innate delight in engineering accomplishment. 1

The reasons for building aside, Steinman's undaunted belief in civilization's first engineers' capabilities is easily recognizable and has been proliferated by the endurance and appearance of Roman works beyond the Roman Empire.

The Romans, without formal theory, or precedents, knew empirically how to build. Amazingly, they knew how to build to last. Over 2000 years old, the magnificent Pont du Gard, Nimes, France, with its dramatic profile against the French countryside, immediately demands our attention.

Pont du Gard
Fig. 55

"The magnitude of the Roman achievement can only be assessed by bearing in mind that, "statistically speaking, it is virtually impossible for a bridge to last 2000 years."[2] The local materials, having already survived the effects of weathering, provided a durable basis from which the Romans could build. The 'soft' stone may not have lasted outside the Province of France, but for the Pont du Gard, the use of local materials was more than appropriate for reasons of ease in transport and of durability.

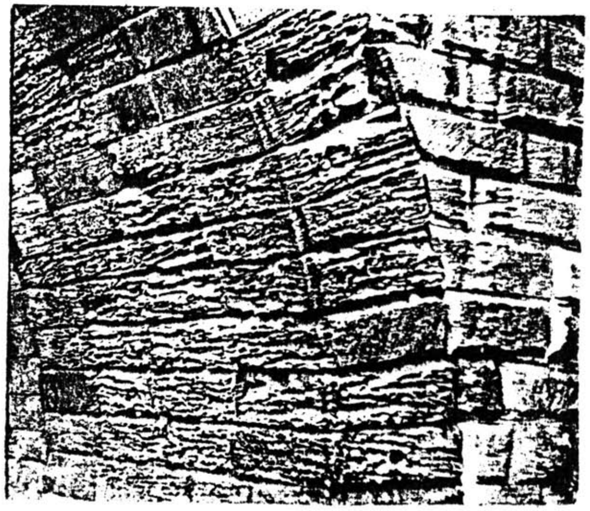
Examining the construction details affords one way of comprehending the vitality and creative power of the builders of the Pont du Gard. The semicircular arch profile repeatedly used in the Pont du Gard, most logically arose out of the convenience of setting the pre-cut stones with minimum of framework. Natural compressive action of stones lent itself empirically to the arch form. Recognizing the stone's ability the Romans cut it into appropriate wedge shapes and numbered each part in order to assemble the pieces exactly as cut. The Romans' system of 'prefabrication' of certain units limited their choices of overall form.[3]

Visual reminders of the Romans' centering process are the projecting corbels on the face of the Pont du Gard. Built permanently into the facade, perhaps to facilitate maintenance, the stones' original use during construction was as anchors for framework to support the arches. The arches, due to the compressive strength of (mass) stone, became self-supporting after the keystone was in place. This eliminated the need for the heavy centering and supports.

Vitruvius, writing in the first century B.C., in his Ten Books on Architecture, recorded the need for thicker end piers to provide the arch with stability.

> ...when there are arches composed of voussoirs with joints radiating to the centre, the outermost piers at these points must be made broader than the others, so that they may have strength to resist when the wedges under the pressure of the load of walls, begin to press along their joints toward the centre and thus to thrust out the abutments. Hence, if the piers at the ends are of large dimensions, they will hold the voussoirs together, and make such works durable.
>
> (Vitruvius, Book VI, Chapter VIII)

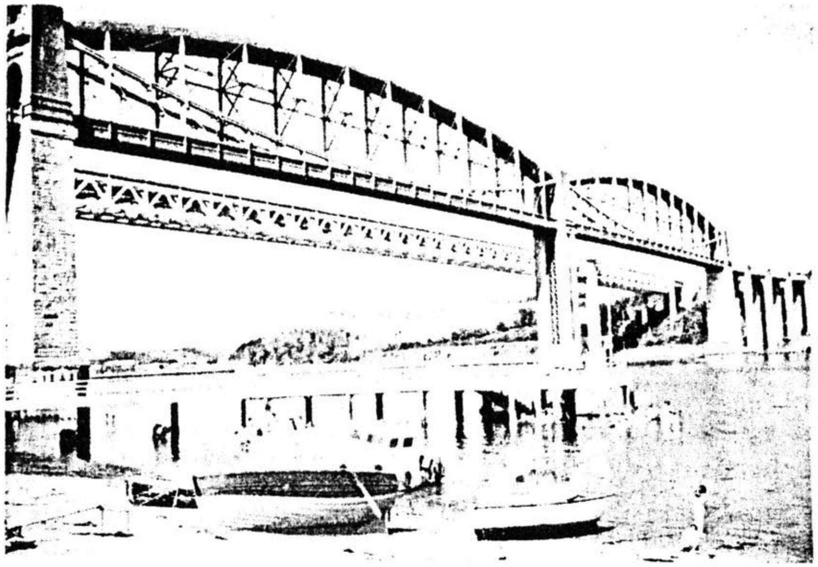
The repetition of the semi-circular arches over the three tiers of the Pont du Gard, which achieves a height of



Weathered stone of arch
Fig. 56

155', presents a magnificent edifice. The six spans of the lower level (roadway) range from 51 to 80 feet, with the longest one spanning the river. The second tier has eleven arches, and the third has thirty five, smaller semi-circular arches.

Built by Agrippa in 14 A.D., the Pont du Gard also records the socio-political atmosphere of the time of its birth. Marcus Vipsanius Agrippa was Augustus' military administrative aide (also his son-in-law). Military strength was dependent upon the roads, bridges, and aquaducts. As a vital link, bridges were recognized as a strategic means for control. The Romans understandably devoted their energies to the construction of more roads and bridges as the source of more power.



Prince Albert Royal Bridge
Fig. 57

PRINCE ALBERT ROYAL BRIDGE, Saltash, England (1856)

Case 3.11 'essential'

Isambard Kingdom Brunel, British engineer

The mid-nineteenth century marks a transitional period in bridge design which reflects the changes that were occurring in both the United States and England as a result of the events of the earlier decades of the 1800's. With the use of the steam engine, and the resulting increased output of coal, came an increase in production of iron. Iron, self-aggrandized, developed its further need and production. The railroads increased the need for a new development in bridge design. The increased weight from railroad traffic made metal-arch bridges and suspension types structurally unfeasible, and demanded a more rigid system for support. Cast iron, not being as strong in tension as it is in compression, would not answer the rigidity requirements of the new heavier live load. Wrought iron, due to its strength in tension and its ductile quality became the applicable and progressive material.

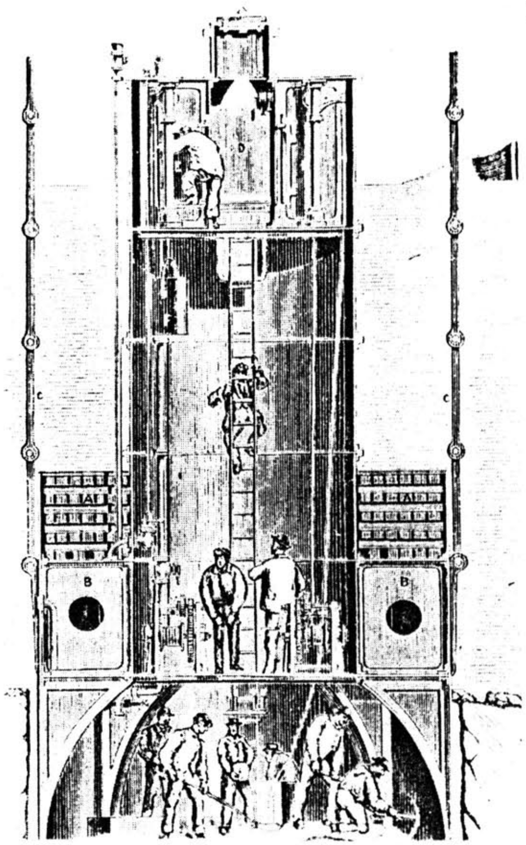
The resulting development of wrought iron for use in plate-girders provides the transition from wood to iron in bridge design, and similarly parallels the shift from a practical to theoretical ideology. The development of the truss, though still empirically based, led easily to analysis by nature of its form. The British bridge builders, as opposed to their contemporaries in France, were not yet theoreticians. The British still remained pragmatic designers who tested by observing and learning on the job.

I.K. Brunel, however, foreshadows the change that was to take place in the education of the engineers in England. Up until the middle of the 19th century, housewrights, mill designers, and mechanical engineers all were and felt that they were equally qualified to be called bridgebuilders. Brunel's background marks the beginning of a new emphasis on more 'educated' technical training which soon would affect the approach taken in design as well as the bridge construction.

Isambard Kingdom Brunel (1806-1859) was born into an 'engineering' family. His father, Marc, (1769-1849), a distinguished engineer both in England and the United States, had established his own factory for the manufacture of technical equipment for ships. I.K. Brunel 'apprenticed' with his father and in 1824, in particular, was involved in a tunnel project under the Thames. Injured during the tunnel construction, I.K. Brunel turned adversity into good fortune. While recovering from his injuries, Brunel entered a bridge competition in Clifton, in 1829. After much debate, and a second competition, Brunel's scheme for the Clifton Bridge was selected. Without previous bridgebuilding experience Brunel's career began.

With a natural interest in railroads, he opened his office, Great Western Railway, in London, in 1833. Ambitious Brunel successfully built "the world's longest railway tunnel in 1841 and the world's longest brick arch bridge in 1839."[1] Involved with tunnels, ships, bridges, Brunel had acquired invaluable experience which helped in his "stuggle to find new forms appropriate to metal construction."[2]

Brunel's Prince Albert Royal Bridge, over the Tamar River, Saltash, England, exemplifies his success in finding the appropriate new form. The Saltash Bridge actualizes the possibility of union between theory and practice. As



Early pneumatic caisson
Fig. 58

a reminder of its scientific basis, the Saltash Bridge of 1856 did not resist analysis or existing theory. Brunel undoubtedly was aware of the analytical methods known at the time. Metal trusses had been built in the 1840's in the United States, and in 1845 in England (lattice-type). In 1846, the Warren truss was patented, and in 1847 S. Whipple's "Essay on Bridge-building" published existing knowledge of truss design. Karl Culmann, a German engineer, had also published results of his studies of American trusses in extensive reports. Thus by the 1850's knowledge of analytic methods of truss design was widely publicized.

However, the Saltash Bridge, while utilizing the theory and basic 'Pauli' girder truss, uniquely expresses the imagination and empirical knowledge Brunel needed to evoke such an emphatic solution. Hopkins, author of A Span of Bridges, characterizes the Saltash as the climax of "Brunel's thinking out loud--the progression in bridge design from Windsor, Chepstow to Saltash."[3]

The railroads incurred live loads larger than those ever designed for before. This load capacity requirement combined with the problem of increased dead weight due to the increase in span further compounded the search for the appropriate structural solution. Brunel, aptly, realized that the span at Saltash necessitated a 2-span plate-girder truss (each 455' long).

> Each span of Brunel's main superstructure is formed by an immense hollow oval tubular arch 16'-9" wide, tied at either end by two cables of wrought iron chain links. Vertical hangars support the single track rail deck. 4

The light-weight arches of the ellipse (top and bottom chords) keep the axial forces constant over the span and carry the load without substantial effect to the weight. The ties handle the thrust of the arches. The masonry vertical supports add the final contrast which enhance the overall appearance.

Brunel's tunneling experience distinguished his technical advance with respect to the foundations of his bridges. Using an early form of caisson to sink foundations, Brunel's procedures can be considered the precursors of the modern methods. The diving bell for underwater works had been known for centuries. Romans had even sunk hollow monoliths, as a primitive form of caisson. Brunel advanced the practice by introducing the air compression chamber. Despite the superstitions associated with the mystery of the undiagnosed 'bends' the caisson procedure continued to be used in later bridges. (Eads Bridge, St. Louis, Telford's Menai Straits, England, Fowler's First of Forth, Scotland....)

As the Saltash Bridge, empirically introduced a new form, by understanding the implementing the plate-girder truss, later truss forms developed analytically. The advent of this theoretical basis for design can be visually documented by the truss forms that evolved in the late 19th century. The structural statics of the first half of the 1800's led to the development of graphic statics in the later decades. This change is responsible for the shift from mathematical analysis to a geometrical analysis as the basic method for later truss form development. (Later variations: Schwedler, Gerber,...simple beams to cantilevers.)[5]

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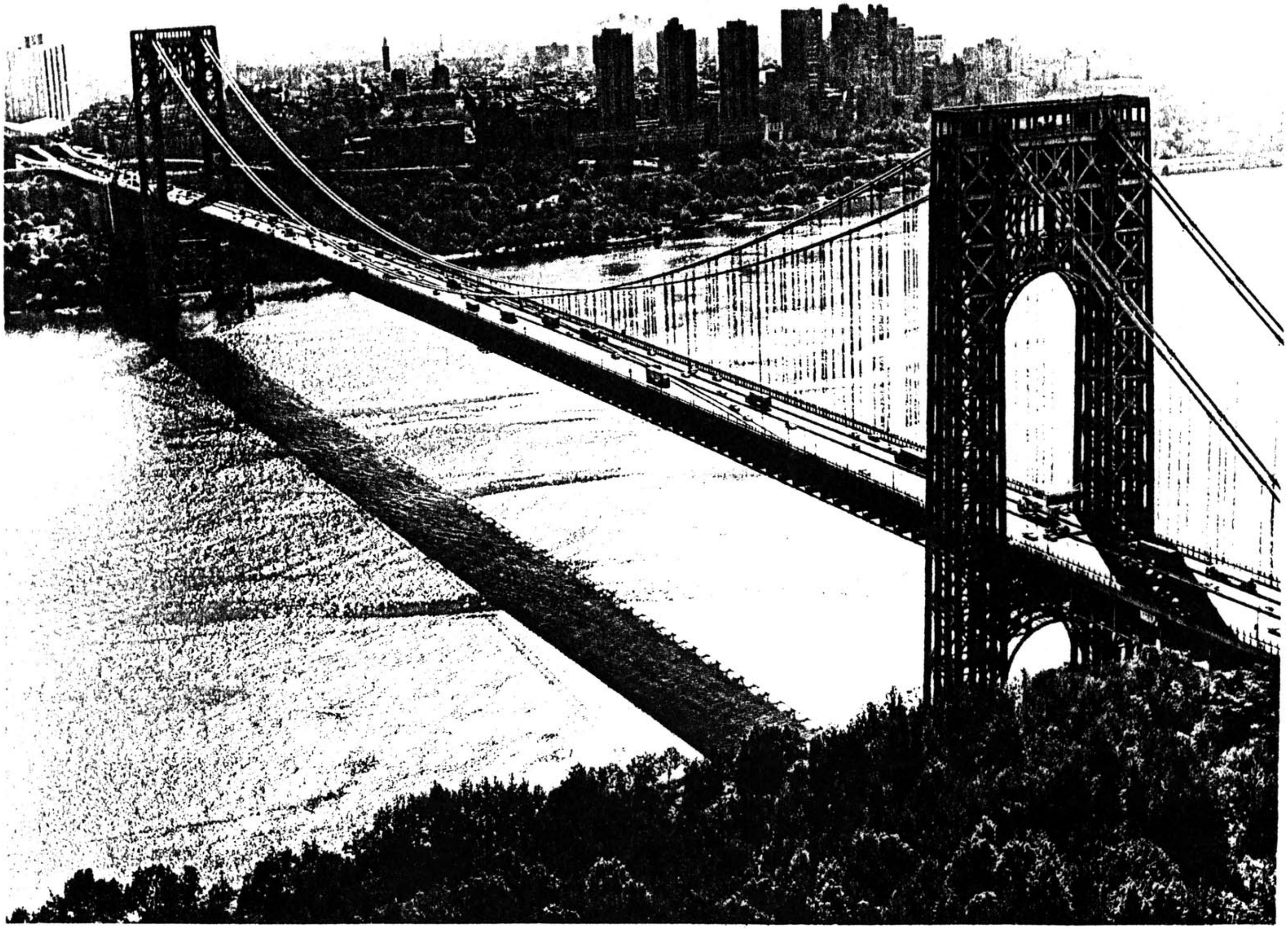


THE GEORGE WASHINGTON BRIDGE, New York City, (1927-1931)

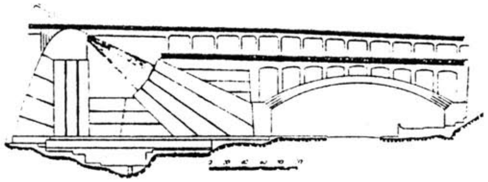
Othmar H. Ammann

Le Corbusier has written that "The George Washington Bridge on the Hudson is the most beautiful bridge in the world....It is the only seat of grace in the disordered city."[1] To be paid such a tribute, especially by an architect as influential as Le Corbusier, is an honor not frequently bestowed on a bridge. Yet the design which prompted this praise was perhaps more accidental than intentional.

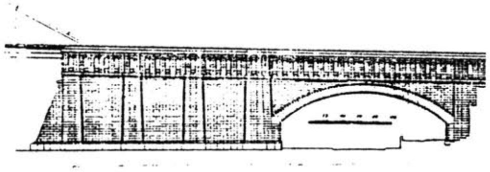
When Othmar H. Ammann, the Swiss-born and trained engineer, originally designed the George Washington Bridge, he had his architect, Cass Gilbert, design a concrete and granite facing for the two 604' high towers, as an independent self-supporting structure. The unexpected visual appeal of the 'naked' steel skeleton, however, proclaimed that structural form, which was dictated by function alone, was sufficient to express 'Beauty.' Thus, the towers were left unsheathed.

George Washington Bridge
Fig. 59

Ironic that this 'accident' occurred on an Ammann



Proposed design for
anchorages
Fig. 60



Cass Gilbert's design for
anchorages
Fig. 61

bridge, since unlike other contemporary engineers, Ammann was one of the few who felt the need to associate with architects for all his bridge projects. By doing so he therefore acknowledged a separation of his architecture and his engineering. This 'aesthetic' vs. 'structure' issue is curious also because Ammann's Neo-Platonic 'aesthetic' is contrary to people he worked for such as Gustav Lindenthal.[2]

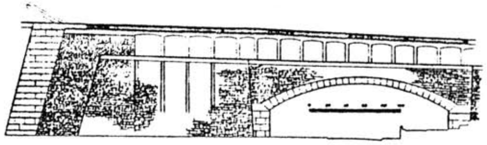
The design of the anchorages represents the architect's similar traditionally held convictions. Instead of wanting to 'purely embellish,' the architect wanted to demonstrate 'engineering.' Cass Gilbert proposed to express the stresses in the anchorages with smooth concrete 'strokes' of form that paralleled the lines of tension of the underlying steel. This scheme did not conform to the existing masonry buildings near the site and therefore was rejected. The accepted anchorage design was the conventional stone facade with an arch over the highway.

Ammann's training at the Federal Polytechnic Institute at Zurich influenced his method of design. He readily visualized total developed schemes to the refinements of the details. Each part of the design marked a progressive advance in the design of long-span suspension bridge. The unexpected yet simple expression of the towers contributed to the powerful visual appeal of the thin parabolic cable stretched between the towers, as well as to the simplified overall form. Ammann's deck design departed from the conventional deck-stiffened trusses, which up until the 19th century had become heavier and heavier in order to resist the effects of wind. Ammann was convinced that a rigid system was not necessary.[3]

Ammann's design intentions for simplified form were clearly in response to "favorable and well-defined" conditions of the site. Ammann wrote:

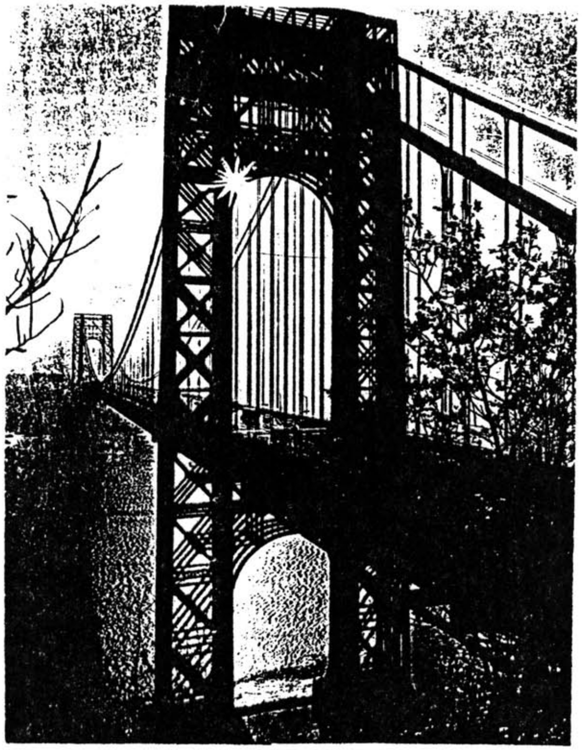
> In fact, so clearly are the location, the general proportions, and the type of structure indicated, that the engineer, who can visualize the completed bridge, has merely to adapt its various parts to the requirements of utility, safety and esthetics. 4

The George Washington Bridge not only received praise for its appearance, but also for its utilitarian accomplishments. Opened in October, 1931, the George Washington Bridge was the longest suspension bridge in the world,



Accepted design for
anchorage
Fig. 62

(doubling the span of its predecessor) with its 3500 foot (tower to tower) length. As a connection over the Hudson River, between Fort Lee, New Jersey and 178th Street, Manhattan, the George Washington carries an unprecedented 14 lanes of traffic. The two levels of travel carry yearly traffic at a near capacity of 38,800,000 vehicles. "In 1980, the bridge carried 41,395,900 vehicles in the eastbound (toll) direction."[5]



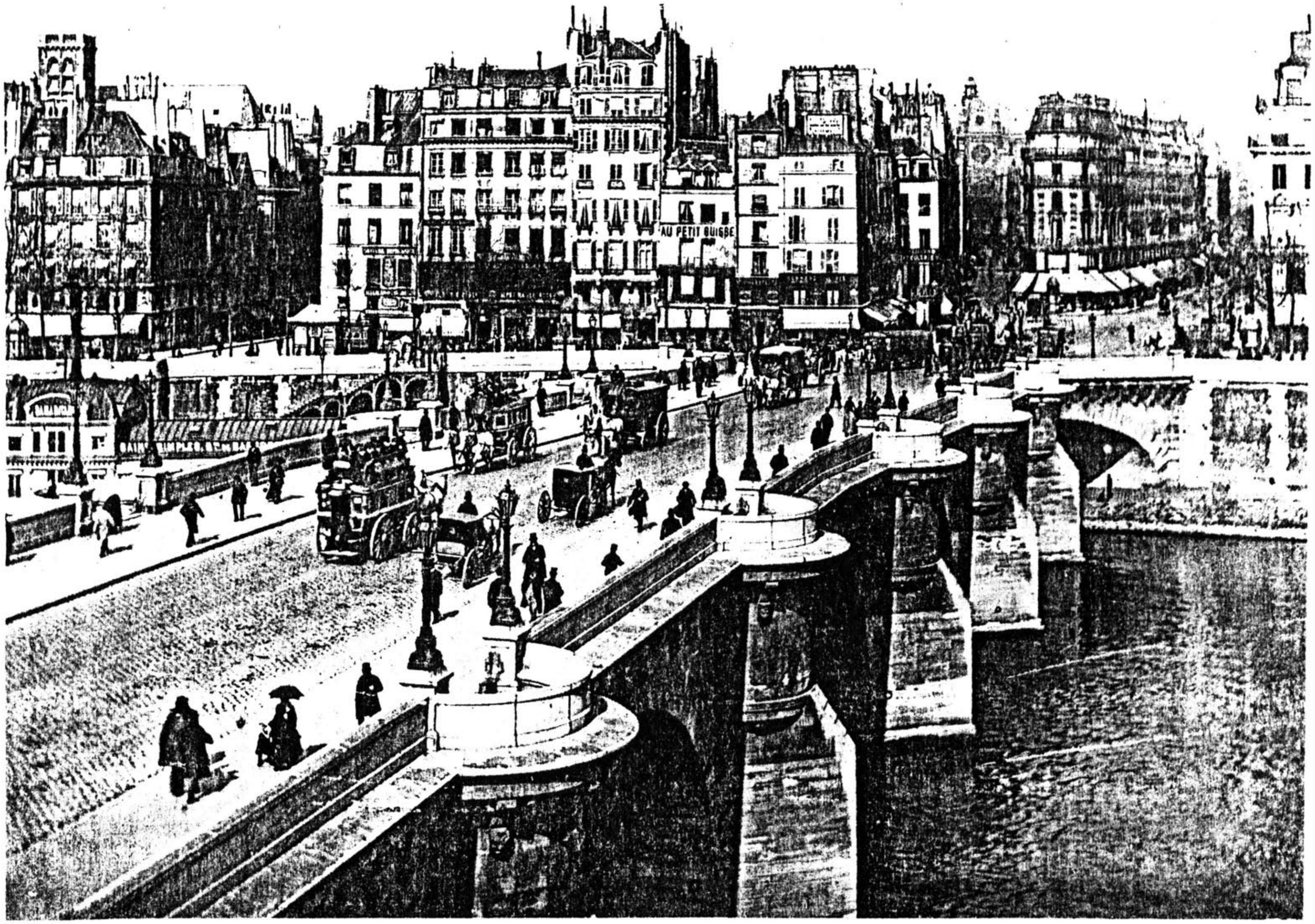
Tower design
Fig. 63

Other facts about this bridge which enhance its uniqueness are the events that have occurred with each celebration of its origins. Its 50th birthday celebration in 1981 included a 'cavalcade of cars,' representing model years 1931-1981, across its span as well as other ceremonies.[6] Amidst the celebration, the American Society of Civil Engineers awarded the George Washington its highest honor, the designation as a National Historic Civil Engineering Landmark (October 25, 1981).

Other interesting facts about the George Washington denote its ceremonial yet delightful qualities. Appropriate for a bridge named in honor of our first President, the George

Washington displays the largest flag (60' x 90', and probably the heaviest; banner weighs 80 pounds) from its New Jersey tower on special occasions. Novels have been written about the George Washington Bridge throughout history,[7] but a definite first is the symphony composed by William Schuman in 1950 to the George Washington Bridge. It is still a popular band piece today.

Having survived its first 50 years, the George Washington Bridge is a lasting tribute to the 'new beginnings' of the 20th century engineers and architects.


AU PETIT SUISSE

PONT NEUF, Paris (1578-1607)

De Cerceau and Marchand, architects & engineers

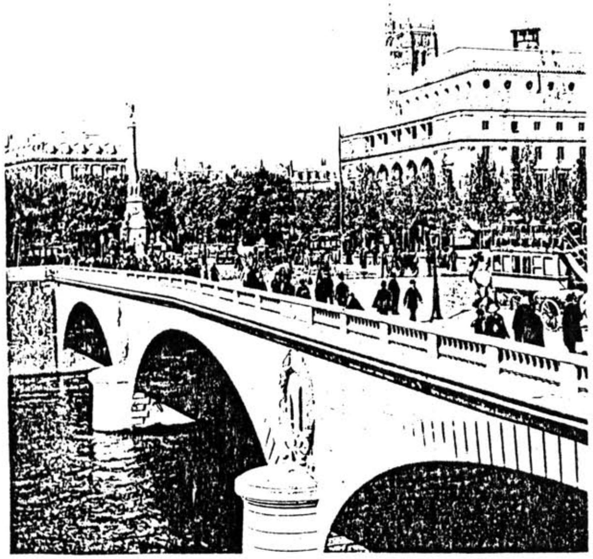
If the twenty-eight years of construction are not an obvious enough indication of the struggle that the Pont Neuf underwent to reach actualization, then the reams that have since been written about the events, people and incidents which occurred during those years provide an accurate account. M. Edouard Fournier provides such a thorough depiction in his two scholarly volumes, Histoire du Pont Neuf.[1]

The Pont Neuf was built by contractors, masons, and artists and designed by the Royal Architect, Androuet Baptiste de Cerceau and Ile de Pierre. As a Renaissance bridge, it is understood as engineering. Guillaume Marchand, who with du Cerceau supervised and built the Pont Neuf, was accepted as the chief mason. From 1584 on, Francois Petit assisted Marchand in the construction.

History honors the Pont Neuf as an exemplary engineered structure. "When built the Pont Neuf was the finest specimen of modern engineering, employing the latest theory and technique." The bridge's progressiveness was not confined to

Pont Neuf Bridge
Fig. 64

the technical, however. David Steinman comments on the social impacts and the inspirational aspects of the bridge's construction as the contributing causes to Paris' transformation "from a medieval town to a splendid Renaissance city."[2]



Pont au Change
Fig. 65

The need for a new bridge was recognized by Henri II in 1550, when the commercial stalls on the Pont au Change became overcrowded and the foundations of the Pont Notre Dame began settling. The first bridge proposal considered triumphal arched gates at each shore with a two-storied pavilion on the Ile-de-Cite. This design was fortunately never built. The City of Paris unable to finance, delayed the bridge through the reigns of Francois II and Charles IX before continuing in 1578 under Henri III. Henri III sent the design out for bids three times before settling on the most economical contractors to begin constructing the piers and foundations of the five-arched span to the Left Bank.

Androuet de Cerceau's original design did not provide for houses or shops on the bridge. However, in 1579, 'motive-powers'[3] of social life were emphasized, the desire to include shops became a necessity and the increase in width to sixtysix feet became a reality. As the piers and abutments had already been built on the shorter (left) side of the bridge, the widening necessitated the use of corne-de-vaches ("cow's horns") which were actually splayed false arches in front of the true arches. The corne-de-vaches (attributable to Fra Giocondo[4]) were used, instead of lengthening the pier, for the purpose of carrying the arches out over the ends of the piers. As the long arm (seven arches to Right Bank) of the bridge had not yet been built, the corne-de-vaches were not added; and the piers themselves were lengthened to accommodate the width change. Ironically, the houses and shops were never built on the Pont Neuf, although Henri IV allowed temporary stalls to be used on the bridge in later years.

The bridge construction was delayed for another eleven years during the religious and political wars and not continued until Henri IV-s reign. In 1601, the king ordered that the 'forever under construction' Pont Neuf be finished within three years. Not even Henri IV's command could accelerate the bridge's completion. The Pont Neuf, finally, was opened in 1607.

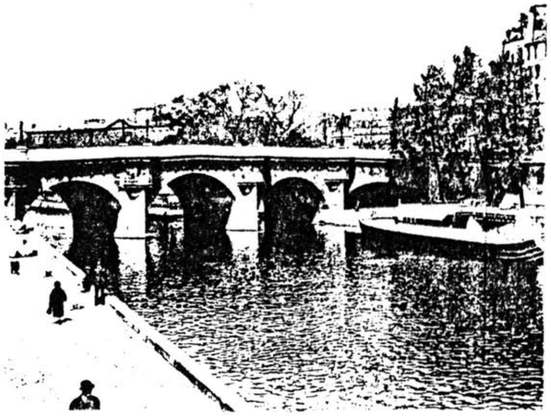
The details of construction as the years evidenced were not simply uneventful either. None of the bridge's semicircular arches are identical, as the lengths vary from 31 to 61 feet. Nor are the downstream and upstream sides of each arch identical as there is a ten per cent skew. Each arch is carefully constructed with columns intervening to provide widened niches periodically along the course of the bridge's road.[4]

The Long Arm
Fig. 66

Perhaps the most troublesome aspect in construction for the Renaissance bridgebuilder was the inability to drive the pile footings below the scour level. (Scour is the abrasive action caused by sand movement underwater.) The cofferdams used for the Pont Neuf were primitively constructed using two wooden enclosures jointed together with the space in between filled with clay. Pierre Lescott, the foundation engineer, investigated and proposed a 'stepped-back' cofferdam which unfortunately was not enough to withstand the srong current of the Seine. By the time the bridge was nearing completion the foundations needed replacement.[5]

"Le Pont Neuf C'est Paris!" This popular saying evokes the feeling of humanity and of revelry through strife that has been a part of the Pont Neuf's 380 year history.

> It is curious how, in connection with Paris, there is a tendency to envelop every place and feature with a romantic interest, at times redolent of the studied stateliness of an old aristocracy, at times stridently alive with the new enthusiasm of glory under the great emperor, at times tragically reminiscent of the wild fury that transformed a jocund populace into a mob of demons. 7



The Short Arm
Fig. 67

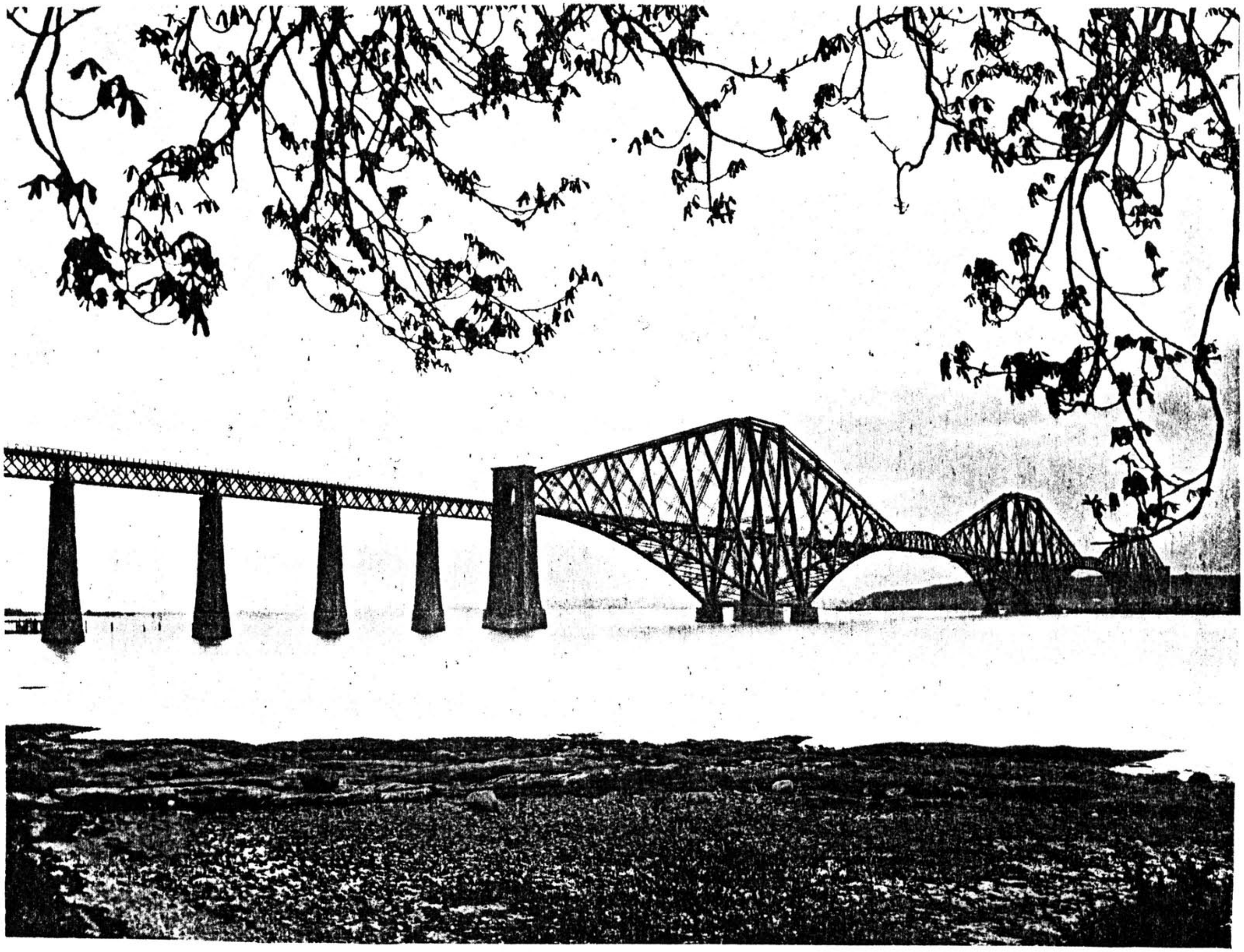
The bridges of Paris, in particular, the Pont Neuf, supplies endless associations of old with new romantic recollections. Joseph Gies personifies the Pont Neuf stating that "good or evil, it was there (on Pont Neuf) the heart of popular Paris beat...."[8] Steinman agrees with Gies' interpretation of the spirit and life embraced by the Pont Neuf:

> The Pont Neuf played a vital role in Parisian life for many generations, taking most of the traffic to and from the crowded island and the famous Left Bank. There was a proverbial saying that, from a niche in the roadway, one could contemplate a cross-section of Parisian life--the French children with their nursemaids, the prostitute, the eager art student, the haggard peddler, the wily beggar, the pompous man of business, the

> housewife with her marketing and so on 'ad infinitum.' 9

The Pont Neuf lacks nothing. Confirming its picturesque qualities within the urban context, Whitney romantically describes the visual impact the Pont Neuf's presence achieves.

> Crossing the two branches of the Seine at the lower end of the Ile de la Cite with the little Parc du Vert Galant below it, framed between the wooden embankments and the city on each side, it is one of the most beautiful sights of Paris. 10



THE FIRTH OF FORTH BRIDGE, Scotland (1888-92)

Sir John Fowler and Sir Benjamin Baker, English engineers

If 'sensational' and 'magnanimous' could quantify the varying aspects of the appearance, the constructed form, the performance, the history, and the cost of the Firth of Forth Bridge (1882-1890) in Edinburgh, Scotland, then 'magnificent' would understate the reactions and impact that this cantilevered truss bridge had upon successive bridges and their builders.

The equal spans of steel truss, carrying the North British railway line from South Queensferry to Garvie Island and North Queensbury, Scotland, have been "likened to two elephants standing in the Firth of Forth" pronouncing the 'Gargantuan' image that greets the viewer. Yet seen as the best solution to the specific needs, utilizing the current engineering methods, the Firth of Forth Bridge represents a critical step in the progressive development of structural steel, and the engineers' technical training with regard to use of this new material. The two spans,

Firth of Forth Bridge
Fig. 68

each 1710 feet, could not have been achieved by a continuous beam or suspension bridge, as the first with many piers would have obstructed the navigable waters below the bridge, and the later would have been too flexible to resist the horizontal and increased vertical loads caused by the railroad trains. Fowler and Baker, English engineers, proposed a solution that would not only bring the roadway to a clear height of 150' above the river, but also limit the number of piers to three major supports from which the cantilever arms would project.

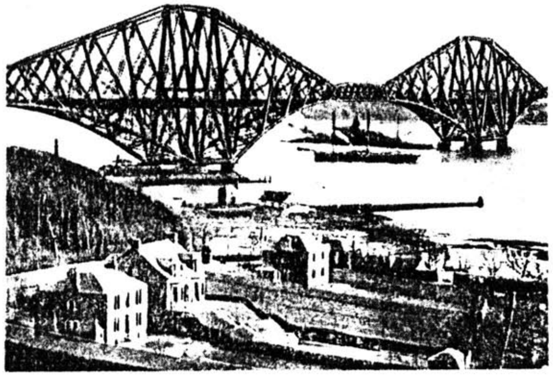
Fowler's and Baker's design is a perfectly analyzed statically determinant structure which enabled every element to be preconceived. Prior to railroad bridge construction, the engineers had to approximate the weight of the structure on the basis of past experience and then adjust the design and redesign by the requirements imposed as the bridge was built. In the Firth of Forth, the strict specifications for each steel member based on stress (not more than 1/4 of the ultimate strength of the material) and strain (in compression: tensile strength of 34 to 37 tons, and in tension 30 to 33 tons) allowed the weight of the structure to be calculated and led further to more accurate calculations.

The details of construction, all analyzed and calculated to the last joint, now could be prefabricated. At the Firth of Forth bridge site, fifty acres was set aside for the purpose of bending the steel plates into tubes. William Arrol, the steel contractor, fabricated the steel tubes, then re-erected them on the bridge. Using the piers as support, the cantilevers were swung out and constructed self-supported without additional framing.[3] The differences in construction methods from previous bridges which required heavy framing or scaffolding become readily admissable.

One minor problem was the final connection in the middle of each of the cantilevered arms. The event actually highlights the advances in structural statics and strength of materials rather than demeans man's intelligence or foresight.

> The plates overlapping each other at the middle joint were drilled in the shop; and the bolt holes were calculated to come fair at an even temperature of 60°F, at the time of erection. But when the closure was attempted, the temperature was

> only 55°F, and a chilly northerly wind was blowing, so that the holes did not meet. By lighting fires of wood shavings and oily waste over a distance of some 50 feet on each side of the middle span, the steel was made to expand so that the holes came fair and the bolts securing the two halves of the suspended span could be inserted and drawn. 4



Bridge with Fabrication
Site in Foreground
Fig. 69

Significantly, the understanding of the structural behavior of beams enabled Fowler and Baker to conceive the unprecedented cantilever truss form. A continuous beam with maximum moment at midspan requires increased depth at the center (if ends fixed). This increase in depth increases the dead load and therefore increases its own limitations by further increasing the bending moment. A bridge with cantilevered spans overcomes the limitations of maximum moment at midspan by transferring the moment to the support.[5]

Fowler and Baker as well practiced bridge engineers learned the capabilities of steel and understood its applicability to a trussed cantilever form. Mainstone tributes the Firth of Forth as "a structural masterpiece. Breathtaking in these giant leaps and impressive in its manifest strength; it was, at the same time a remarkably clear and legible structure."[6]

However, the cost of materials and construction would prevent any continuance of such a bridge form. Whether overdesigned from the resulting cautiousness of its engineers after the Tay Bridge[7] disaster (1879) or out of sheer desire for monumentality, the Firth of Forth used ten times as much steel as the Tay Bridge, and cost four times more than that of its contemporary, the Eads Bridge in St. Louis. The 42,000 tons of steel combined with construction costs set the price at $16 million (in 1882 dollars). (Even the Brooklyn Bridge, including the price of land, was built for less!)[8]

Other statistics of the Firth of Forth which add to the 'sensational' aspects in evaluation would be the large number of fatalities of workers. However, if the fifty-seven deaths are callously proportioned to the total number of 4500 employed at the height of the bridge's construction, the fact would not be so shocking, but accepted as a natural risk incurred by progress.

The Firth of Forth evidences that the British theory was beyond the development of America's at this time. The cantilever bridge of the Firth of Forth held the world's record for longest span (8200') for 28 years until the Quebec Bridge was built in 1917.

THE SALGINATOBEL BRIDGE, Schiers, Switzerland (1930)

THE SCHWANDBACH BRIDGE, Hinterfultigen, Switzerland (1933)

Robert Maillart, Swiss engineer

Robert Maillart's bridges and his writings with regard to his use of reinforced concrete provide an exceptional resource for exposure to the Swiss traditions of building as well as for a succinct explication of the technical and aesthetic standards involved in design. Although this Swiss engineer built over 30 bridges in the last twenty years of his life alone, two in particular, the Salginatobel Bridge in Schiers, and the Schwandback Bridge, near Hinterfultigen, will be investigated as exemplary of his two distinctly different yet complimentary solutions in bridge design.

As a student in the Swiss tradition of the Federal Institute, Maillart was influenced by the teachings of Wilhelm Ritter (1847-1906), a German-educated engineer. Ritter, who succeeded Karl Culmann (1821-1881) as professor of structures, was interested in teaching the 'visual methods of analysis' with regard to structural behavior.

Salginatobel Bridge
Fig. 70

Ritter even followed up Culmann's earlier writings, Graphic Statics, with his own four volumes on Application of Graphic Statics. Ritter's role in Maillart's development extended beyond academia to his professional career. Ritter frequently judged bridge competitions (Swiss traditional method for awarding 'cantonal' projects) which Maillart had entered, or actually consulted with Maillart on the commissions.[1]

Ritter's promotion of full-scale load testing also had a permanent effect on Maillart who used load testing as one of the primary criteria in his bridge design method.

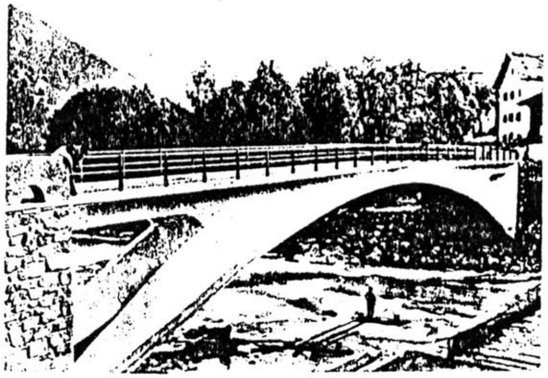
"The Swiss tradition tended to be less certain of the emerging mathematical theories in engineering and more open to the need for visual demonstration of performance."[2] Respecting this tradition, Maillart sought simplified methods of calculation and the practical experience of testing to prove his designs. Ritter had always condemned complex mathematical analyses for 'obscuring design potentialities.'[3]

Many historians, including Giedion, Huxtable, Max Bill and others have credited Maillart's ability for combining art and science in his 'artistic' bridge designs. David P.

Billington's book, Robert Maillart's Bridges: The Art of Engineering, is similarly based, developing the theme of "structural form as it arises out of aesthetic feelings and scientific ideas." Billington furthers this supposition with examples, by specifically equating Maillart's ideas and development of the 3-hinged arch bridge form to "structural engineering as a visual art" while interpreting the deck-stifferened arch bridge idea to "scientifically based engineering."[4] These parallelisms reawaken the traditional arguments of aesthetic vs. scientific as the basic pre-constituents of form. Although the two bridge forms are distinctly different, they are complimentary and congruent and not specifically art-based or science-based.

The Salginatobel Bridge (1930)

If experience was Maillart's guide, he had many examples from which to thrive. From 1902 to 1913, he built seventy-four works, (buildings and bridges); two of these in particular are of notable influence in his development of a new bridge form: the Thur River Bridge at Billwil (1903-1904)



Tavanasa Bridge
Fig. 71

and the Rhine River Bridge at Tananosa (1904-1905). Practice led Maillart to the design of a hollow box section, with longitudinal walls and a horizontal curved arch slab, all of reinforced concrete. The knowledge of this form, although implicit in the analytical understanding of each component's dead and live load carrying capacity, had never been 'analyzed' empirically. Maillart tested his theories by cutting out parts of the wall (reducing the dead load and stress) thus visually making the wall seem like part of the arch. Although the wall was not acting as the arch in flexure, but was carrying the vertical loads, it gave a new visual unity to the parts.[5]

Billington realizes the merit in Maillart's effort to combine seemingly precedented forms in an original and new structural totality. "Perhaps the clearest expression of his mature style, the Salginatobel Bridge, also happens to be his longest arch, spanning 294 feet; it possesses that deceptive simplicity of appearance which can conceal an intrinsic complexity of structural behavior."[6]

Maillart made three choices in his design of bridges.

First, aware of the bridge as a public structure, Maillart consciously designed with the overall image of the bridge in the context of the environment in mind. As a second factor, he already selected reinforced concrete as his material. He wrote, studied, and experimented extensively with reinforced concrete. Realizing that concrete's fluidity was its own limitation to form, Maillart designed consciously to minimum cost with minimum of materials. His efficiency developed into his own style which won him many competitions. This personal style, however, necessitated a resolution of conflicts.[7] Billington states:

> Maillart strove for minimum use and minimum costs, but field labor costs can be high when thin sections are designed, because forming and castint require more precision. Along with minimum curves, he sought maximum expression of the overall form; and to minimize applied decoration, he tried to achieve detailed shapes and textures within the structural form itself. 8

Maillart's style found resolution of these conflicts in the Salginatobel Bridge. The three-hinged arch form with the hollow box girder solved his problems of weight, creep, shrinkage, and moment. The slender crown, made possible

Thur Bridge
Fig. 72

by the light weight concrete arms cantilevering from each end, with its exposed concrete texture was not a typical or traditional Swiss bridge design. Even though Maillart's methods were not exceedingly revolutionary, his new 'products' of design were.

His construction procedure advanced previous practice by the nature of the design. The heavy scaffolding of the past could be lessened by the fact that the cantilevers were hollow and lighter in weight, and also by the fact that the horizontal slab (the road) helped carry the road and the superstructure.

Perhaps the difference in Maillart's bridge forms from traditional precedents can be attributed to his keen sense of the material and its behavior, which he developed through years of experience working with reinforced concrete. His writings elucidate this understanding:

> Reinforced concrete does not grow like wood, it is not rolled like steel and has no joints as masonry. It is most easily compared with cast-iron as a material cast in forms, and perhaps we can learn something directly from the slowly discovered cast-iron forms regarding the avoidance

> of rigidity in form by a fluid continuity between members that serve different functions. The conditions of this beautiful continuity is the conception of the structure as a whole....It is not only the feeling for beauty which makes desirable the conception of the whole primary to that of the single elements. Seeing the structure as a whole nearly always brings economical advantage as well. 9

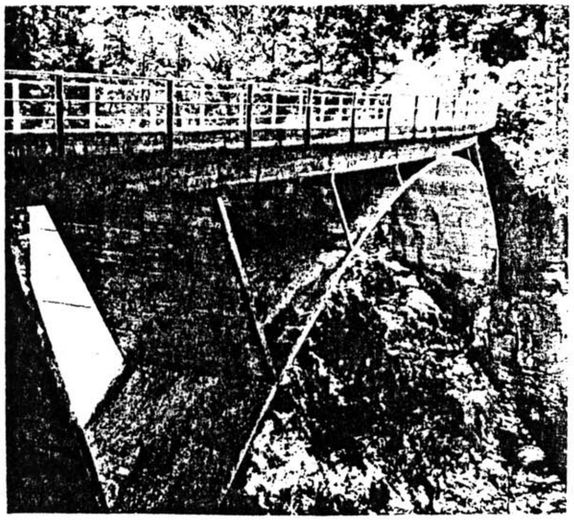
The Schwandbach Bridge (1933)

While the Salginatobel evidences the achievement of Maillart's personal style, the Schwandbach Bridge enhances this design achievement. Built in 1933, the Schwandbach Bridge, with its deck-stiffened arch, continues Maillart's search for his ever-evolving new form. "The typical bridge features: the plan, the approach, the parapet and deck, and the arch itself, reveal substantial changes, and each time these differences marked the unfolding of design ideas freed from concern about analysis."[10]

Schwandbach Bridge
Fig. 73

It is not surprising to expect the Schwandbach Bridge to represent the culmination of Maillart's style. His progressive gains in each work contributed successively to his yet unrealized projects. As Maillart never limited his design thinking to his simplified analyses, his freedom in form (within material limitations) was unabated. This approach earned him the title of "tanzboden" ("dancefloor") engineer[11] among his contemporaries, who criticized his simpleton's calculations from which he proposed seemingly unorthodox solutions in form.

What distinguishes Maillart's method from his contemporaries is the fact that he chose the material and form first, then analyzed the forces within the form. The assumptions to which Maillart responded were based on his understanding of the 'live load analysis' and the capabilities of the deck-stiffened arch to uniformly carry the dead load by axial forces.[12] Instead of determining the form based therefore on the external forces (loads) using structural analysis, Maillart was interested in the structural behavior of the form, and was able to analyze the actions of the internal forces (i.e., how it reacted, carried its load). This approach was harder to document without experiential knowledge. Many engineers, including Americans who simultaneously had produced a comprehensive analytical study on concrete arches, neglected to understand the overall behavior of



Outer edge of arch.
Schwandbach Bridge
Fig. 74

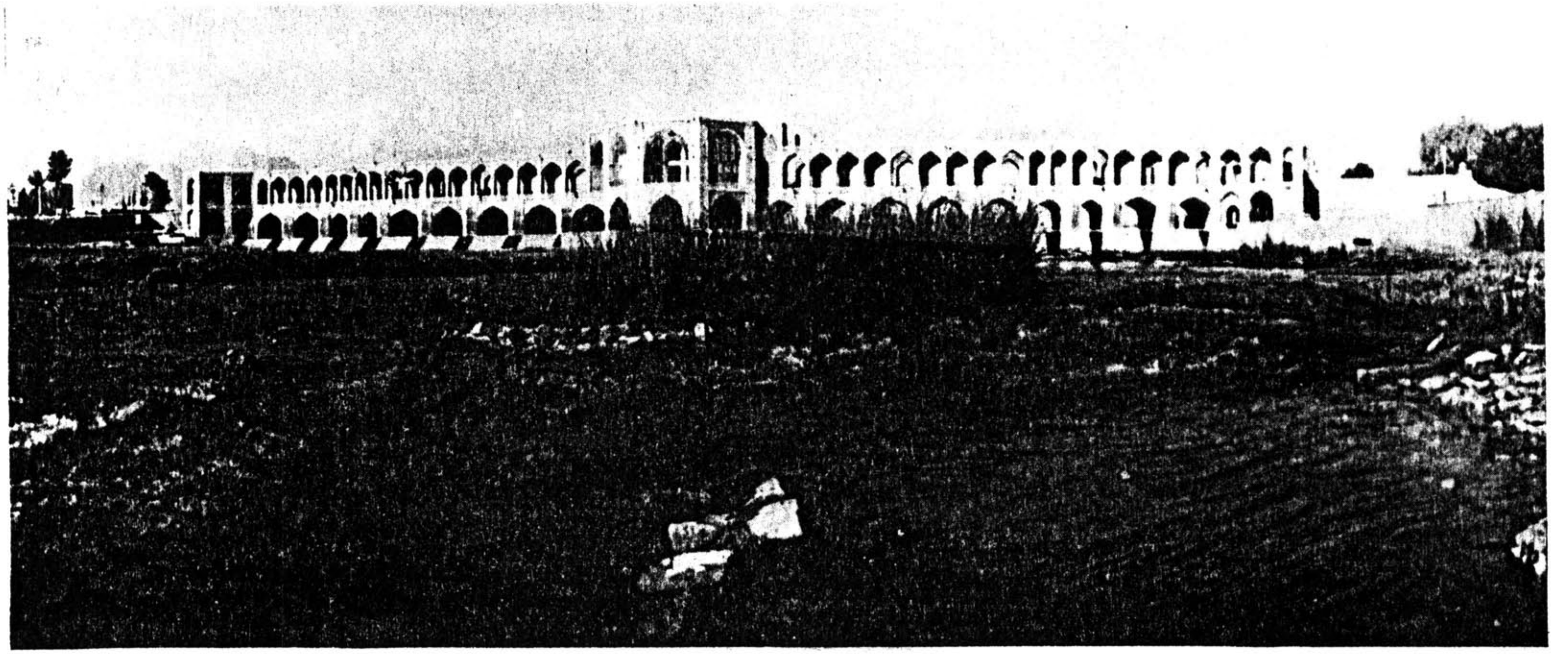
the structure, and concentrated the entire bulk of the study on calculations of the external forces only.

Between 1930, when the Salginatobel was completed, and 1933 when the Schwandbach was built, Maillart constructed eight deck-stiffened bridges. Each bridge was a physical test of his ideas. Billington thoroughly describes the attributes of the Schwandback by taking each of its major features: the curved elliptical plan, the approaches, the parapet, the deck girder, and the arch, and individually revealing the decided departures they achieved from the traditional forms.[14] These unique individual differences though not visually recognizable as distinct components, combine with a simple order so implicit that the form seems almost monolithic.

The meaning in Maillart's bridges, clarified by realizing the choices he made, and the mdethods of analyzing structural behavior, assists in the understanding of the unmeasurable and inherent factors which play a critical role in design. Billington, too, concludes that Maillart's bridges are based on recondite factors as well.

> What we are forced back to is the persistent feeling that Maillart did not consciously make aesthetic

choices any more than say a naturalistic portrait painter or sculptor who set out to make pretty likenesses. A Maillart bridge, a Leonardo portrait, or a Michelangelo sculpture, are highly representational; they look like what they represent. Yet, beyond that, they are unique, so characteristic of the personality of their originator, so symbolic of their contemporaneous culture, and so technically spectacular, that gradually the general public confers on them the accolade, 'great art.' Clearly there is more to it than that, but the crucial factor to emphasize here is that the designer is trying to represent something in a prototypical way; i.e., in the only way it can possibly be for him. 12



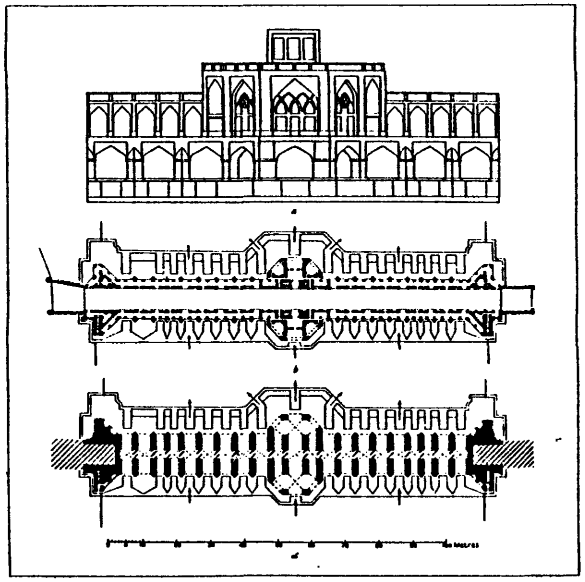
Pul-I-Khaju Bridge
Fig. 75

PUL-I-KHAJU BRIDGE, Isfahan (1644-1666)

Shah Abbas II reign (engineer unknown)

Persian bridges of the 17th century require attention not as structural feats, (as their form was possibly mathematical yet not distinctly unique[1]) but for their 'inner' purpose. An understanding of Islamic culture and its underlying principles of development provide the necessary basis for appreciation of Persian architecture. The bridges of Isfahan are clearly understood as necessities within the ordered and organized patterns of the cities. The bazaar, old square, and bridges provide the means of creating levels of primary and secondary movement within the city as well as from city to city. The order created attested to a culture uniquely endowed with an understanding of existence on various levels (i.e., natural, geometric, harmonic[2]). The natural harmony inherent in this order became realized in the places (and spaces) created.

Recognizing that "the Safavid Dynasty marked an outstanding example of harmonic order"[3] it is not surprising



Elevation and Plans
Fig. 76

then that during the reign of Shah Abbas II, the Pul-I-Khaju bridge was built in Isfahan, Persia. This bridge, built of stone, with twenty-four main arches, also functioned as a dam over the Zendeh Rud. The bridge was constructed in three levels; each level having its own purpose. The basement was the length of the dam (154'). The second level consisted of the main roadway (24' wide) and was accompanied by a covered gallery. The terrace walk was on the third story.

The bridge actually looked more like a building because of its four projecting two-storyed pavilions; one at each end and two at the middle. The pavilions were decorated with paintings and gildings, thus attracting users to the bridge to admire art while relaxing and lingering on the walkways of the bridge.

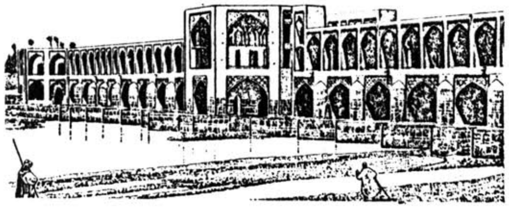
The bridge was an event; a place for relaxation or in later decades as a source of amusement. The Pul-I-Khaju bridge became the focus of an annual ritual which was more a public spactacle than a respectable occurrence within the context of the bridge's origins. Lord Curzon's <u>Persian History</u> records the original meaning of the bridge while bemoaning the fact that the only surviving event is the spring ritual of watching the floodwaters.

> In olden days this bridge was a favourite resort in the evening, where the young gallants of Isfahan marched up and down, or sat and smoked in the embayed archways overlooking the stream. Now it is well-nigh deserted save in the springtime, when the snows melt in the mountains and in a few hours the Zendeh Rud is converted from a petty stream into a foaming torrent. Then the good folks of Isfahan crowd the galleries and arcades of the bridge and shout with delight as the water rushes through the narrow sluices, then mounts to the causeway and spills in a noisy cascade down each successive stairway or weir, and finally pours through the main arches, still splitting into a series of cataracts as it leaps the broken dam. 4

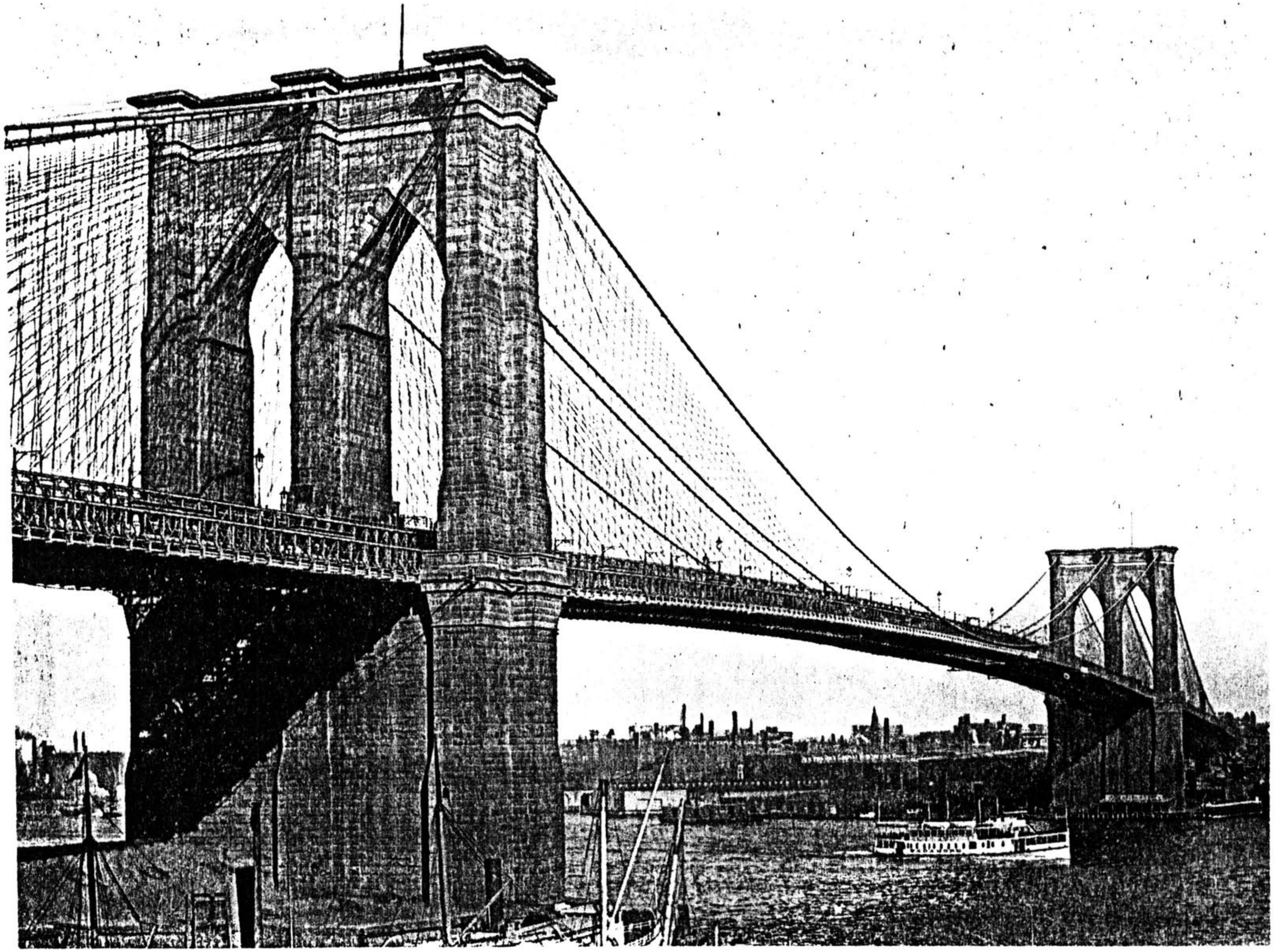
Although debased in meaning and degraded in function over time, the Pul-I-Khaju Bridge still remains physically and symbolically a reminder of the order that it once represented.

Nader Ardalan and Laleh Baktiar, in their study of the Sufi traditions, proposed the bridge as an 'encounter point.' Bridges, by their natural function are logically placed at intersecting roadways or other paths of travel, thus creating 'encounters' or 'memorable city nodes.' Sometimes the bridge was located at the entrance to the city and served as a gate as well.[5]

Describing the pointed arches of the Pul-I-Khaju Bridge, or its two-directional brick work would not enhance the reasons for its existence, but rather would describe the physicalities of its being, and inform one of its builders' culture, and their understanding of the available knowledge and the material resources. The Pul-I-Khaju Bridge represents the perpetuation of a spirit, not as an anachronism, but as a quality of its inherent nature. The significance of the Pul-I-Khaju lies in what it is.



Perspective of Bridge
with Pavilion at center
Fig. 77



THE BROOKLYN BRIDGE, New York City (1869-1883)

John and Washington Roebling

Lewis Mumford writes that there are three ways of 'modifying and humanizing the visible landscape.' Simply stated: one is by agriculture and horticulture; the second is by city development and architecture; and the third way is by works of engineering--bridges, viaducts, canals, highways, docks, harbours, and dams.[1] It is impossible to separate these three 'intermingled modes' as each interacts with the other in a civilized world. If we needed to find a man who embraced this power to 'modify and humanize the visible landscape,' we would not have to look beyond John Roebling, the designer and builder of the Brooklyn Bridge.

As a unique case, perhaps, John Roebling experienced all three ways in his lifetime. Roebling, born in Germany in 1806, and educated as a civil engineer at the Polytechnic Institute, Berlin, came to America in search of fame and fortune. He settled first on a farm in 1831, in Saxonburg, Pennsylvania, where he cultivated fields until his restlessness

The Brooklyn Bridge
Fig. 78

caused him to accept a job as a State engineer. In 1841, he established his own factory and business for spinning wire cables from hemp.

In 1844, he entered and won his first bridge competition, and his works of engineering began. Roebling (1806-1869) who not only studied architecture, bridge construction, and hydraulics, but also philosophy under Hegel in Germany, personified the enthusiastic yet confident engineer that the late 19th century America needed. He approached his work with a commitment which adhered to Hegel's statement that, "Nothing great in the world has been accomplished without passion."[2]

Roebling's earlier experiences with bridge designs, including the Niagra River Railway Bridge (1855), Allegheny River Bridge, Pittsburgh (1858) and the Ohio River Bridge at Cincinnati (1856-65) led to the successful culmination of old with new technical skills and materials in the Brooklyn Bridge proposal.

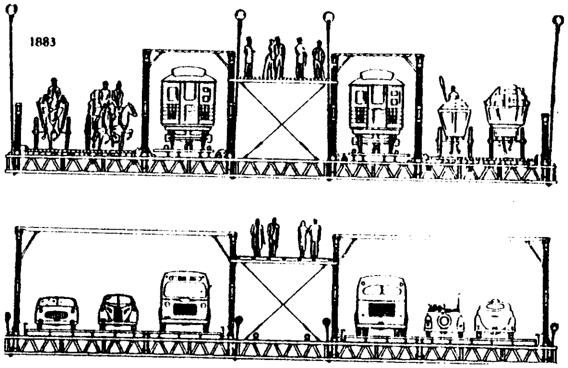
The Great East River Bridge, as the Brooklyn Bridge was first known, with fourteen continuous years of construction, provided the 'stunning act' that America needed to incite renewed faith and interest in man's ability to utilize new materials (steel) and new techniques. The unique qualities which make the Brooklyn Bridge distinct from the other suspension bridges that presently accompany it in spanning the East River, are the reasons for the attraction by writers, poets, historians, artists and the resulting wealth of documented sources.

The significance of the Brooklyn Bridge becomes apparent when the social and political climate of America in the late 1800's as well as the specific changes that were transpiring in New York City are realized. With the rise of industrialization came the shift from rural to urban, and the consequent increase in population in the cities. The need for bridges, tunnels, dams were a natural result of the urban changes. Change came, however, at a depressed time. Mumford calls this period--after the Civil War and before the positive aspects of America's new technology became utilized--"the Brown Decades"[3] as a latent yet transitional epoch. Engineering works up until this time "still left the landscape clear; and at its best, gave the land comeliness."[4] The Brooklyn Bridge emerged perfectly timed but not without a 14 year struggle. "To many the Brooklyn Bridge became the apotheosis of a bridge; to others a symbol of the best America could achieve, a thing of simple straightforward eloquence."[5]

Confident in his design proposal for the masonry towered, steel cabled suspension bridge, Roebling prophesied:

> The contemplated work, when constructed in accordance with my designs, will not only be the greatest bridge in existence, but it will be the greatest engineering work of the continent and the age. Its most conspicuous features, the great towers, will serve as landmarks to the adjoining cities, and they will be entitled to be ranked as national monuments. As a great work of art, and as a successful specimen of advanced bridge engineering, this structure will forever testify to the energy, enterprise and wealth of that community which shall secure its erection. 6

John Roebling's proposal for the Brooklyn Bridge was not the first. Other engineers such as Thomas Pope, (1811) with his 'Flying Pendent Lever Bridge' had considered the connection between Manhattan and Brooklyn. Yet Roebling's scheme, first presented in 1856 and again in 1857, was the most sound. Roebling's design encompassed all aspects of concern; technical, social, aesthetic and visual, and revealed a perceptive capability for understanding the needs of New Yorkers as well as the spirit of the times. The Brooklyn Bridge design was based on three separate lanes of travel: the common lane for cars, another land for "bridge trains" on rails to speed commuters across the river, and the third completely separate upper level for the pedestrian. Instead of the pavement adjacent to the traffic lane, the pedestrian had a second level "to allow the people of leisure, and old and young individuals to promenade over the bridge on fine days, in order to enjoy the beautiful views and pure air."[7] Roebling considered amenity to be of "incalculable value in such a crowded and commercial city."[8]



New and Old Traffic Lanes
Fig. 79

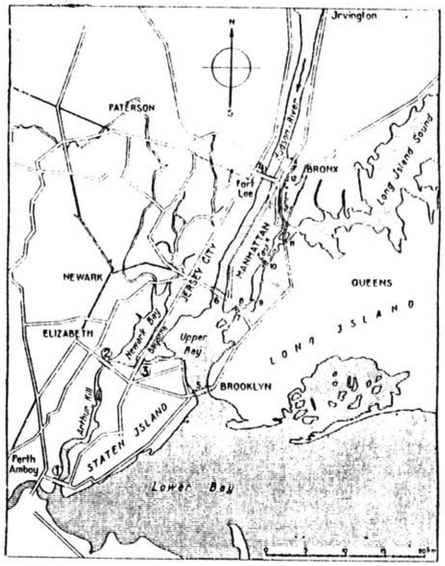
Ten years later, when the New York Bridge Company finally decided to go ahead with the construction, they approved Roebling's scheme, not on the basis of its design but relying on Roebling's genius. Mumford enunciates: "Nothing but Roebling's experience, his personal power, and his immense authority could have made a plan go through: a suspension bridge with towers 276 feet high and almost 1600 feet in the central span had not been built anywhere in the world."[9]

John Roebling did not live to see even the beginning of the construction. In July, 1869, he died as a result of an accident on the site. Roebling's son and engineer-in-training, Washington became the Brooklyn Bridge's next chief engineer. Washington Roebling, educated at Renessaler Polytechnical Institute, had built two suspension bridges (one at Fredericksburg, Va., and the second at Harper's Ferry) prior to his involvement with his father's practice. In 1869, knowledgable of every construction detail, Washington took charge.

The construction events have been narrated by many authors. David McCullough's The Great Bridge, and Alan Trachtenberg's Brooklyn Bridge: Fact and Symbol, in particular, are two novels which dramatically present a full documentation. Mario Salvadori presents another perspective of the construction in his chapter on the "Brooklyn Bridge" in his text, Why Buildings Stand Up: The Strength of Architecture.

The Bridge

Not spectacular as the first steel suspension bridge (the first recorded was built in Vienna in 1828), the Brooklyn Bridge was most outstanding of three exemplary American cases of sophisticated steel use in bridge design between 1874 and 1883. Nine years earlier the Eads Bridge in St. Louis had been built with steel arch ribs, and the Glasgow Bridge, in Missouri, had a main span constructed of steel. But the Brooklyn Bridge with its new light and flexible cables and trusses entirely of steel in combination with its heavy masonry towers, created a prominent new form.



Map of New York Bridges
Fig. 80

David Billington evaluates the Brooklyn Bridge through an analysis of its structure based upon efficiency, safety, and endurance. Concluding that the cables perform their functions as tension members, and the towers by their massiveness serve the dual function of adding compresion loads and strength while adding weight to help sink the caissons, Billington substantiates the scientific meaning of the bridge.[10] Billington by emphasizing the correctness of Roebling's decision to use the heavy stone towers, denounces

Montgomery Schuyler's earlier criticisms of the functionless and 'Gothic Revival' masonry towers and evidences how 'mechanical' the towers are.

The significance of the Brooklyn Bridge extends beyond its scientific accomplishments. The fact that the Brooklyn Bridge was not a prototypical design since its technical features were soon outdated is evidenced by the later bridges on the East River alone. Stone towers and diagonal stays were not used on any later suspension bridges.[11]

The city of Brooklyn "transformed" by the existence of the Brooklyn Bridge, "from insignificance into metropolitan importance" can be quantified by the extreme change in population. At the beginning of the nineteenth century there were about 5,000 people living in Brooklyn. Within a lifetime the population jumped to 400,000. The borough of Brooklyn, although still only half the population of New York City, was considered the third largest.[12]

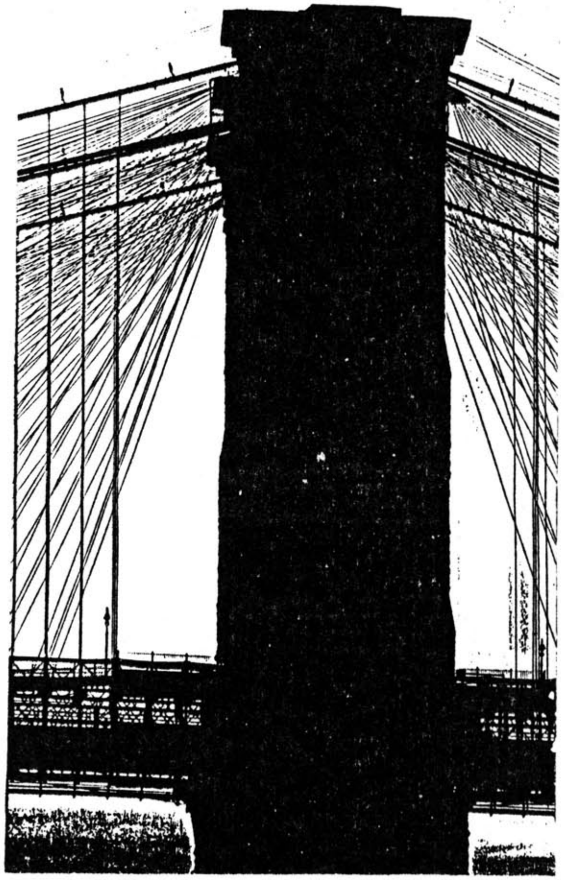
The symbolic power of the Brooklyn Bridge is perpetuated by the many artists' depictions, poets' epics, and authors' studies. Some have even called the Brooklyn Bridge "the Eight Wonder of the World." The recognition as a Historic National Landmark in 1964, formally pronounced the Brooklyn Bridge as a monument. Yet these facts do not recognize the 'unmeasurable' qualities of the bridge.

Mumford senses the intrinsic qualities of the Brooklyn Bridge and, by comparing it with other suspension bridges, states:

> If anyone doubts that a bridge is an aesthetic object, if anyone doubts that it reveals personality, let him compare the Brooklyn Bridge with the other suspension bridges on the same river. The first bridge is in every sense classic. Like every positive creative work, the Brooklyn Bridge eludes analysis, in that its effect is disproportionate to the visible means, and it triumphs over one's objections even when it falls short of its highest possibilities. 13

Alan Trachtenberg, in his "Prologue," states the 'parallax' effect of experiencing the Brooklyn Bridge. This is the best written account of the movement, change, views, feelings that the Brooklyn Bridge is capable of evoking in its users. Describing a walk across the promenade of the bridge, Trachtenberg realizes the users' participation.

> But the walk is narrow enough for the promenader to reach over and touch the large, round cables, wrapped in wire casing, or the rough wire rope of



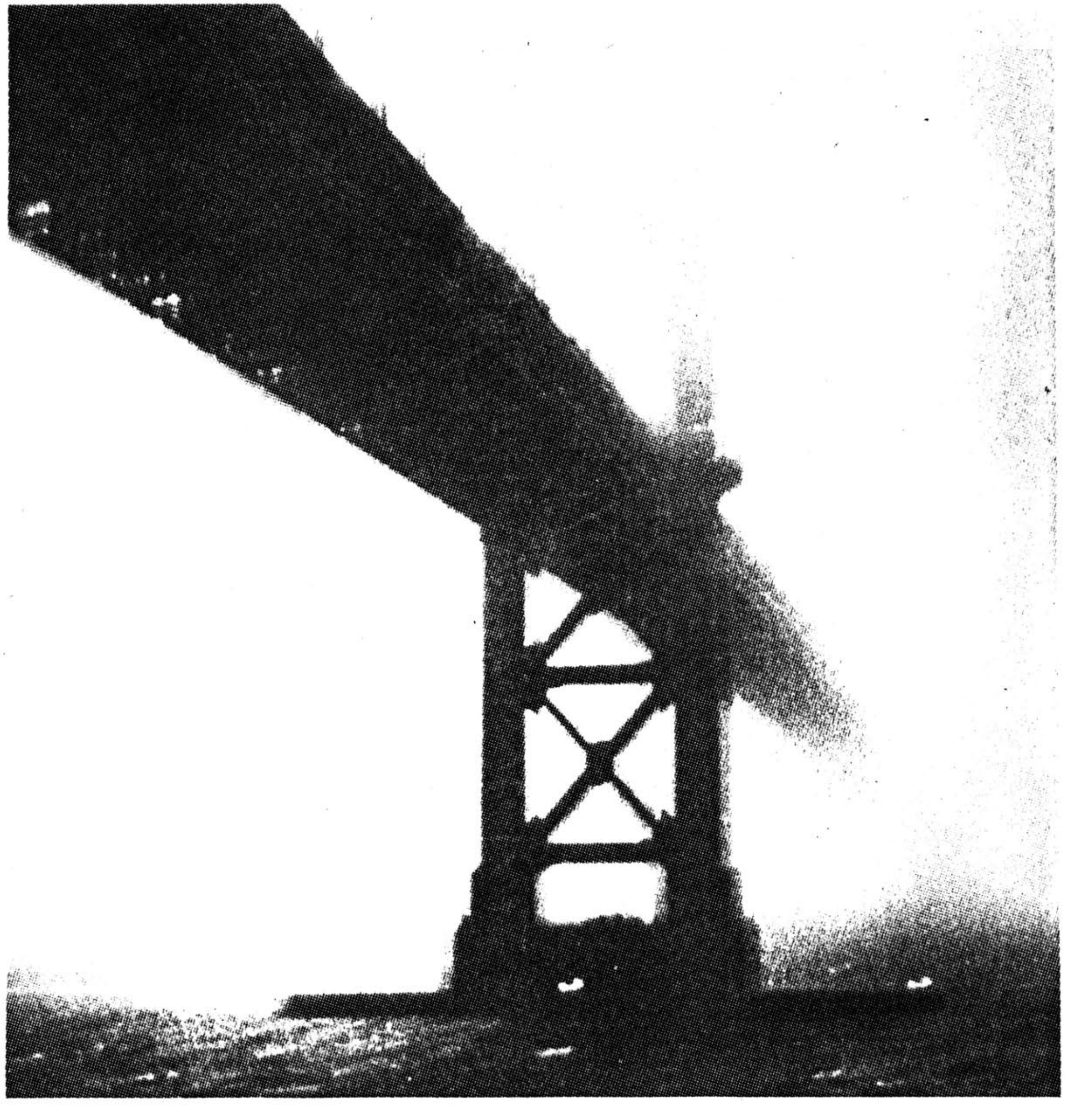
The Towers and Cables
Fig. 81

> the vertical suspenders. Crossing the verticals is a rigging of diagonal wire ropes--stays, attached somewhere to the floor of the roadway below.
>
> One has the illusion of enclosure. The web formed by the diagonals and the verticals captures the walker's attention; it is a diagram of the physical forces of the bridge. 14

Trachtenberg here acknowledges the enframed view of the Manhattan skyline provided at the highest point of the promenade.

> It is tempting to linger on the balcony, to walk around the center pier, to gaze up at the underside of the arches, to feel the coarseness of the Maine granite, or to read the plaques attached to it. But another experience lies ahead, and one soon descends the few steps back to the promenade. The diagonals and their knots now swoop down toward the center of the bridge. But at the same time the roadway slopes upward: its bow has become more pronounced, an upward counterpoint to the descending knots. At the very center of the bridge, the main cables and their smaller ropes drop out of sight altogether, somewhere below the railing. The walker has a clear plateau to himself at the highest point of the promenade. He has a view of the harbor on one side, the Navy Yard on the other side. He has the New York skyline, the Bay, the Statue of Liberty. Sea gulls wheel and dip into view; one may fly across the bridge and pivot out of sight. 15

The Brooklyn Bridge reliquishes a power and a control (even if only transitory) to its users, that would not be possible unless a participant of the bridge.



Chapter Four: CONCLUSION

Alfred Whitehead, author of the Function of Reason, proposes that 'Solomon's dream' provided the best example of the "antithesis between the two functions of Reason." Whitehead defines these two functions: 4.0

> The speculative Reason produces that accumulation of theoretical understanding which at critical moments enables a transition to be made toward new methodologies. Also the discoveries of the practical understanding provide the raw material necessary for the success of the speculative Reason. [1]

Within this speculative Reason, the significance of the issues of each case study is contained.

Each bridge in each case depended upon an 'order,' on a system for determining 'Form.' ('Form' means the act of 'making' not the physical or structural form.) This 'order' is derived in different ways as the case studies illustrate. A summary of the case studies is possible by applying the definitions as a framework, illustrating the varying constraints and possibilities within each. Using the first set of definitions (visual, social, cultural,

The Golden Gate Bridge
San Francisco
Fig. 82

mechanics and construction) to evaluate each case, the physical circumstances are revealed and provide a basis for general observations over each time frame. If the second level of definition is used independent of the first, the results would not be similar but distinctly different within the same time constraints. The best way to apply the two levels of definition to each case would be combined in a matrix, with the ontic-ontological dimension on one axis and the 'causal' definitions on the other. By developing the interrelationships and interaction of each set of definitions, the particular observations are summarized. From these particulars, the controlling principles can be determined.

The case studies revolve around the historical events of the 1750's. Each phenomenological definition has a 'before,' 'during' and 'after' the "schism" prototype (with the exception of "Essence" which does not exist during the "schism"). The time constraint, therefore, provides the comparative basis.

The separation of cases into two frameworks: one for the architect and another for the engineer was necessary to transcend the architect vs. the engineer arguments. The similar differences of both the architect's and the engineer's cases, demonstrate that each responds to similar constraints and needs.

The matrix provides the most comprehensive means of comparing and contrasting the facts 'within time' (i.e., Before "schism:" 'essential-essence-Essential') and 'over time' (i.e., 'Before, During and After,' 'essence:' 'Before, During and After,' etc.)

4.1 "Within time" before "schism"

Comparing the bridges 'within time,' hastens the discussion of the particular bridge-dependent needs, as the context and time are constant.

Before "schism" (prior to 1750) means that the material was either stone or timber, and the form (structural) was most likely an arch or a beam. The similar physical circumstances end there. With the purpose and use the 'essential,' 'essence,' and Essence are differentiated and are discussed "over time."

During "schism," the material was either metal or timber and the form was a more sophisticated beam (i.e., continuous truss, cantilever beam) form. The 'essential' and 'essence' still exist distinct from each other during "schism." The 'Essence' was not possible during the "schism" as man and his relationship to nature was disrupted by the shift from the empirical traditions of the past to the neo-scientific methods. Man needed to reorganize his knowledge of himself and of nature. With regard to 'Essence,' therefore, the state of flux of the "schism" represents a transitional stage.

After the "schism," the material was predominantly high-strength steel, and reinforced or prestressed concrete. The new forms (structural) were a culmination of the science and practice of the day: suspension, or continuous lightweight reinforced concrete beams.

These brief generalities summarize the causal differences within time without answering to the "imminence" of the bridge itself. By applying the ontic-ontological dimension 'over time' the purpose and use of the bridge is exposed.

4.2 'essential'

The 'essential' bridges as defined by the architects' and engineers' cases (3.1, 3.2, 3.3, 3.10, 3.11, 3.12) are designs which achieved 'Beauty' by answering to 'Function.' Culture usually dominated the social and visual aspects so as to make the shift in material (from before to during "schism") ineffectual until man, the creator, was able to distinguish between 'remembering' and 'thinking.'

The 'essential' bridges were prototypical statements of their epoch's technology and culture. Whether the mechanics were experiential as in the Pont du Gard, or empirical as in the Essex-Merrimack, or scientific as in the George Washington Bridge, the success in form illustrated the capabilities of the designer to use his methods and tools to his advantage. The possibility of the bridge to be other than it appeared did not exist. The meaning of the form was clear in its visual aspects, with its "idea" embedded in its function as a bridge. The visual dominated in the 'essential.'

4.3 'essence'

The 'essence' bridges (3.4, 3.5, 3.6, 3.13, 3.14, 3.15) are significantly distinct from 'essential' not only in the builders' humanistic approach to the ordering of the 'Form,' but in the physical form. The inherent harmony of the parts was an accepted necessity sought by the builder, and perceived in the visual totality only by the unity of its parts.

In the 'essence' bridges, the cultural needs dominated. The technology and its efficiency were measured through experimental use of new materials such as cast iron as at Coalbrookdale, and reinforced concrete in Maillart's Swiss bridges. The shift from qualitative to quantitative use of materials, and the resultant increase in scale and size of the bridge are noticeable in the comparison of 'essence' before "schism" to the 'essence' during "schism." Attributable to the parallel shift from empirical method to scientific methods, the bridge 'form' was ordered on new principles.

The designer's constraints directed his attention to a material, or technique as the material dictated. How the designer met his changing cultural needs depended upon not only his experience and knowledge, but also his personal style and creative daring. The most successful 'essence' type in terms of daring are Hennebique's Risorgimento and Maillart's Salginatobel and Schwandbach. Each bridgebuilder relied first on visual analysis and load testing of the bridge 'form' and secondarily on the analytical calculation. The development of the science of reinforced concrete had advanced enough to give a material that lent itself freely to new testing and new 'form.' The 'essence' was found imminent in the result.

4.4 'Essence'

The 'Essence' bridges (case 3.7a, 3.7b, 3.9, 3.16, 3.18) are the bridges which develop the relationship of man to nature and nature to man by 'manifesting' what they are. By creating 'A Place,' the 'Form,' (not understood as the physical or visual aspects of these bridges) reveals the order that comes from within.

What dictates 'Essence' can be understood by the absence of an 'Essence' case study during the "schism." During the "schism" the possibility for the 'Essence' was eliminated by dominant shifts in ideas, theory, materials, and practices as well as the upset of the social and cultural needs as well.

Although 'Essence' is beyond the circumstances that led to its form, i.e., material, use, effect, the 'Essence' is concerned with the relationship to nature. Creating a space in which 'nature' can be revealed is the purpose of coming to this hierarchical order. The 'Essence' bridge uses its relationship to its context to inform its own 'nature,' and in return to further inform the context about 'bridge.' Visual expressions do not inhibit the bridge's 'Essence-Being.' The 'Form' is the manifestation of its 'bridgeness.'

The three phenomenological types have led to three distinct responses to bridge.' The essential was the 'engineered' or 'architected,' the 'essence' was concerned with 'people' and the social needs, and the 'Essence' created 'Place.'

The underlying theme in each case is the implicit understanding of these three phenomenological dimensions as 'Form determinants.' To discover the realm between the idea and the reality, an awareness of the unmeasurable and hidden potential, is necessary. Whether this is called 'Order,' or Intuition, is not critical. What is significant is man's recognition of this potential.

The distinct differences between each case study clearly state that architects and engineers answer to more than the causal dictates of 'Form.'

Through this documentation of the changes in bridge-building, technology has proven to be the mediator between theory and practice, and has given 'Form' to each of the bridges.

NOTES

GENERAL

preface: Stussi quoted from Eduardo Torraja, Philosophy of Structure (Berkeley, CA: University of California Press) 1978, p. 207.

Title: Louis Kahn stated, "...the intuitive being the odyssey, or the record of the odyssey, of our making through the untold billions of years of making". My thesis title is contrived from Kahn's philosophy, but is meant to have two meanings. The first use of "Odyssey" simply means a continuance (journey) over time. The use of Intuition was intended to express bridge building as "making". As an "Odyssey of Intuition", the combined terms, serve to document and follow changes in the "making" of bridges as a way of interpreting technology. "Non-reductive" in the first meaning is used not to assume an accepted negative attitude of some toward technology, but to qualify the dangers of reducing technology to the technical. The second meaning is the implicit understanding of intuition, suggested from the framework developed within the thesis. The "odyssey" now has the meaning Kahn states. "Non-Reductive" is used in the second case to specify the 'unrestricted' possibilities of technology.

FOOTNOTES

Chapter One: INTRODUCTION

[1] Webster F. Hood, "The Aristotelian versus the Heideggerian Approach to the Problem of Technology" in Mitcham and Mackey, Philosophy and Technology. (New York: The Free Press), 1972.

[2] "Novelty" is differentiated from change in Gesalt psychology. See discussion in Nathan Rosenberg, The Britannia Bridge: The Generation and Diffusion of Technological Knowledge. MIT Press. 1978.

[3] C. S. Smith, "Structural Hierarchy" from In the Aesthetics of Science, MIT Press 1971, p. 51. Smith's intention is to discuss the different orders of change within art and science through a hierarchy which illustrates "the interplay that gives unity and character to an assembly even when the parts are invisible — , and to the assembly as a larger aggregate."

[4] Lewis Mumford, Technics and Civilization. (New York; Harcourt Brace Jovanovich), 1934, p. 220.

[5] James Ackerman, "'ars sine scientia est' Gothic Theory of Architecture at the Cathedral of Milan," Art Bulletin, Vol. XXXI, 1949, pp. 84-111.

[6] Class notes, MIT 4.409 Fall '81, "Philosophy of Building Technology" given by Peter McCleary.

[7] Sigfried Giedion, Space, Time and Architecture. (Cambridge: Harvard University Press), 1954, pp. 5-28.

[8] Erwin Panofsky, Idea: A Concept in Art Theory, (Columbia, S.C.: University of South Carolina Press), 1968.

[9] Mumford, op. cit., p. 109.

[10] Ibid., p. 52.

[11] Ibid., p. 133.

[12] Ibid., p. 211.

[13] Ibid., p. 263.

[14] Ibid., p. 265.

[15] Erwin Panofsky, Gothic Architecture and Scholastics. (New York: The World Publishing Company), 1951, p. 15.

[16] Hegel, Aesthetics, p. 41. The medieval builders presented the dilemma of empiricism to the scholastic logic. That is why medieval thinkers could not raise these questions at all. Panofsky's explanations of the scholastic says that "the individual was thrown back to resources of private sensory and psychological experience." p. 14.

[17] José Ortega y Gasset, "Thoughts on Technology" Mitchum and Mackey, Philosophy of Technology 1972. p. 293. If technology were a separate and independent entity, then the bridge could be defined by its technology alone. However, technology deals with needs, and concerns and is not independent of man.

[18] Peter Collins, Changing Ideals in Modern Architecture: 1750-1950. (Montreal: McGill-Queen's University), 1965, p. 185.

[19] Helene Lipstadt and Harvey Mendelsohn, Architectes et Ingenieur Dans La Pres: Polemique, Debat, Conflict. (Paris and Cambridge, MA: MIT Press), 1979.

[20] Collins, op. ci., p. 192.

[21] Ibid., p. 182.

[22] Hans Straub, A History of Civil Engineering, (translated by E. Rockwell) (London: Leonard Hill Limited), 1952, p. 49.

[23] Drexter, (ed.) The Architecture of the Beaux-Arts.

[24] Collins, op. cit., p. 187.

[25] Drexler, op. cit., 223.

[26] Ibid., p. 223.

[27] Ibid., p. 223.

[28] Ibid., p. 231.

[29] Ibid., p. 231.

[30] Ibid., p. 218.

[31] R. Krautheimer, Acts of the Twentieth International Congress of the History of Art., II (Princeton, 1963) p. 42-52.

[33] Straub, op. cit., p. 126.

[34] In 1801, JamesFinley built first suspension type bridge in America, in 1816 patented wire cable and became the first to use wire cable instead of iron chains. See Mock, op. cit., p. 54.

[35] Charles S. Whitney, Bridges: A Study in Their Art, Science and Evolution. (New York:

William Edwin Rudge Publisher,), 1929, p. 23.

[36] Lewis Mumford, The Brown Decades: A Study of the Arts in America 1865-1895. (New York: Dover Publications, Inc.), 1931, p. 26.

[37] Ibid., p. 47.

[38] Montgomery Schuyler, "Monumental Engineering," Architectural Record, Vol. 11, (July-August, 1901-1902) p. 615.

[39] Montgomery Schuyler, "Brooklyn Bridge as A Monument", American Architecture and Other Writings. Atheneum, 1964. Also summarized in Mumford's Brown Decade, pp. 44-46.

[40] Ibid., p. 47.

[41] Montgomery Schuyler, "Bridges and the Art Commission", Architectural Record, vol. 22. (December, 1907), p. 469.

[42] Ada Louise Huxtable. "Progressive Architecture in America: Eads Bridge," Progressive Architecture, v. 38 (April 1957), pp. 139-142.

[43] William Wordsworth, "Composed Upon Westminster Bridge", Benet's Anthology of American and English Poets.

[44] Max Weber, Hart Crane: A Bibliographical and Critical Study. (New York: Russell and Russell), 1948, p. 349.

[45] Irma Jaffe, Joseph Stella (Cambridge, MA, Harvard University Press), 1970, p. 79.

[46] Eduardo Torraja, Philosophy of Structures. (Berkeley, CA: University of California Press,) 1958. p. 81.

Chapter Two: DEFINITIONS

[1] The development of the 'essential - essence - Essence' framework was prompted by Peter McCleary. As written, it was interpreted through reading, and any fault was with the author.

[2] Myron Goldsmith, "The Effects of Scale", AIA Journal, October 1980. p. 60.

[3] Ibid., p. 61.

[4] Wilbur J. and Sara Ruth Watson, The Bridge in History and Legend, (Cleveland, Ohio: J. H. Jansen), 1937, p. 77.

[5] Bailey Bridge: temporary bridge formed of interchangeable, steel truss panels bolted together. Named after British engineer, Sir Donald Bailey (born 1901). See Article "The Famous Bailey Bridges" in Architect and Engineer (April 1945), pp. 25-27.

[6] "Stress-Ribbon Bridge Concept in Steel" Structural Engineer J 55. n. 5, 1977. pp. 223-229.

[7] Wilbur, op. cit., p. 179.

[8] "producer, consumer, product, tool," discussed in Ortega's description of three main phases of technology; the technology of chance, the technology of the craftsman, and the technology of the technician, as a means of explaining the evolution of technoloty. Ortega, op. cit., p. 293.

[9] Peter McCleary, "Structures and Intuition", AIA Journal, (October, 1980) p. 57.

[10] "Acrow" System is not a generic name, but may soon become one. This is a manufacturer's name for a standard 10' x 2.5' steel truss panel. Today these panels are frequently used in bridge construction to replace (temporarily) bridges that are under repair.

[11] Wilhelm Ritter, Maillart's professor at Federal Polytechnique Institute in Switzerland. See David Billington, Structures and the Urban Environment. C E Lecture Notes. (unpublished), 1978. p. 109.

[12] Example of arch: Pont du Gard & other Roman bridges usually were semicircular arches due to limitations of framework and inability of arch to self-support.

[13] Cofferdam technique was evolutionary. Early Roman bridgebuilders used inter-locking tongue and groove piling to close off and underwater the bed of the stream. —Thus bonded masonry could be laid up directly from piling. See Carl Condit essay "Technology: Its Branches, Building and Civil Engineering" in Technology and Culture (1971). By the mid-19th century, the pneumatic caisson was developing. Brunel's Saltash Bridge, and the Eads Bridge, St. Louis were early bridges to test out the air compression chamber.

[14] The Iron Bridge at Coalbrookdale was moulded in two pieces, dependent upon the form of the cast.

[15] Maillart's 3 hinged arch bridges demonstrate the 'fluidity' of reinforced concrete: Zuoz, Tavanasa and Their Bridges. Hennebique's Bridge over the Ourthe, Liege, Belgium (1905) and Freyssinet's Bridge over the Seine at St. Pierre du Vauray, France. (1922) See Mock. op. cit., p. 98.

[16] Nervi, op. cit., p. 1.

[17] Greenough, Horatio. Form and Function: Remarks on Art by Horatio Greenough, (ed. by Harold Small) (Berkeley, CA: University of California Press), 1947, p. 15.

[18] "planning" similarly embraces the 'essential' framework. Planning needs function to organize the elements (or other needs and determinants) of the design.

[19] Semper's theory, by stating that "art originates from the interplay of practical purpose, material, tool and method of production" is based on 'beauty' as a product, or result not a sum or series. See Frankl, The Gothic, p. 589, for further discussion. The 'exception' to the rule alluded to, is caused by the confusion of the pre-constitutents of form and the constituents of form by most designs. Semper attempts to find the pre-constituents first which are "idea, energy, matter and means" and then finds the constituent form. See also

Theodore Brown, "Greenough, Paine, Emerson and the Organic Aesthetic" Journal of Aesthetics and Art Criticism, 1956.

[20] E. Baldwin-Smith, The Dome: A Study in the History of Ideas. (Princeton, New Jersey: Princeton University Press), 1971.

[21] Paul Frankl, The Gothic: Literary Sources and Interpretations through Eight Centuries. (Princeton, New Jersey: Princeton University Press) 1960.

[22] Martin Heidegger. A German philosopher has contributed many writings on the nature of technology. "Being and Time" (1927) aids in our understanding of man within the context of a 'temporal-historical' "horizon". "The Question Concerning Technology" (1953) and "Building, Dwelling, Thinking" (1964) lead to questioning (and a knowing search) that distinctly differentiates between philosophy and thinking. Heidegger's concept of "historicity" is grounded not in technology but man. Technology is the means for man to realize his possibilities.

[23] Louis Kahn saw "Order" as a "means of finding the human place in the world, the nature of our consciousness, and the relationship of our consciousness to nature." Although speaking metaphorically about 'Order', Kahn's "House-A house-home" framework gives the three distinct meanings. "House is the abstract characteristic of spaces good to live in. House is the form, in the mind of wonder, it should be there without shape or dimension. A house is a conditional interpretation of these spaces. This is design. ...Home is the house and its occupants. Home becomes different with each occupant." Louis Kahn as quoted by Vincent Scully, Jr., Louis T. Kahn, (New York: George Braziller), 1962. p. 115.

[24] Lao-tze realized that man's ability to understand existence was not absolute. See Witter Bynner, The Way of Life according to Laotzu: An American Version. (New York: Capricorn Books), 1944. pp. 25, 32.

Chapter Three: THE CASE STUDIES

Case 3.1: The Cismone Timber Truss Bridge

[1] Charles Whitney, Bridges: A Study in Their Art, Science, and Evolution. (New York: William Edwin Rudge, Publisher), 1929. p. 203.

[2] Robert Fletcher and J. P. Snow, "A History of the Development of Wooden Bridges," American Wooden Bridges. (New York: The American Society of Civil Engineers), ASCE Historical Publication No. 4, 1979, p. 36.

Case 3.2: The Essex-Merrimack River Bridge

[1] David Plowden, Bridges: The Spans of North America. (New York: The Viking Press,) 1974. p. 33.

[2] Ibid., p. 35.

[3] George B. Pease, "Timothy Palmer, Bridge-builder of the Eighteenth Century," Essex Institute Historical Collections, vol. LXXXIII, no. 2, April 1947, pp. 97.

[4] Theodore Cooper, "American Railroad Bridges", American Wooden Bridges. (New York:

The American Society of Civil Engineers), ASCE Historical Publication No. 4, 1979, p. 10.

[5] Pease, op. cit., p. 99.

[6] David Steinman and Sara R. Watson, Bridges and Their Builders (New York: G. P. Putnam's Sons), 1941. p. 120.

[7] Ibid., p. 121.

Case 3.3 The New Waterloo Bridge

[1] Melan principle was a theory of deflection. "Melan was an Austrian engineer who contributed significantly to the development of the reinforced-concrete arch." For further discussion see Joseph Gies, Bridges and Men. (New York: Doubleday & Co., Inc.,) 1963, p. 246.

[2] Ernest Ransome, American engineer who developed continuous floor slab of reinforced concrete. See Sigfried Giedion, Space, Time and Architecture, The Growth of a New Tradition. (Cambridge: The Harvard University Press), 1954, p. 323.

[3] 'Rennie Masterpiece' refers to the first Waterloo Bridge built in a classical style in 1817 by John Rennie.

[4] Elizabeth Mock, The Architecture of Bridges. (New York: The Museum of Modern Art), 1949, p. 119.

[5] Sir Giles Gilbert Scott, in paper submitted to Journal of the Institution of Civil Engineers No. 7. 1942-43, June 1943, p. 159.

[6] Ibid., p. 146.

Case 3.4: Santa Trinita Bridge

[1] Sir Bannister Fletcher, A History of Architecture on the Comparative Method. Seventh Edition. (New York: Charles Scribner's Sons), 1963, p. 657.

[2] James S. Ackerman. The Architecture of Michelangelo, (Pelican Books), 1970, p. 52.

[3] Ibid., p. 42.

[4] H. J. Hopkins, A Span of Bridges: An Illustrated History, p. 41.

[5] Ibid., p. 42.

[6] Joseph Gies, Bridges and Men, New York: Doubleday & Co., Inc., 1963, p. 61.

Case 3.5: The Iron Bridge at Coalbrookdale

[1] "There is evidence of an iron arch, a footbridge of 22 m (72 ft) span in Kirklees Park near Leeds, reported in 1770, which was probably the first." John H. Stephens. Towers, Bridges and Other Structures, (New York: Sterling Publishing Co., Inc., 1976. p. 18.

[2] Rowland Mainstone, Developments in Structural Form. (Cambridge, MA: The MIT Press,) 1975, p. 106.

[3] Some references record the fact that the rib castings were poured directly from a blast furnace on site, others say nearby foundry.

See Gosta E. Sandstrom, *Man the Builder*, (New York: McGraw-Hill Book Company), p. 224.

[4] Neil Cossons and Barrie Trinder, *The Iron Bridge: Symbol of the Industrial Revolution*. (Wiltshire, England: Moonraker Press), 1979. p. 53.

Case 3.6: Risorgimento Bridge

[1] Pier Luigi Nervi, *Structures*. (trans. by Giuseppina and Mario Salvadori). (New York: Dodge Corporation), 1956, p. 15.

[2] Hopkins, op. cit., p. 248.

Case 3.7a: Ponte Vecchio

[1] Steinman, op. cit., p. 89.

[2] Hopkins, op. cit., p. 41.

[3] Gies, op. cit., p. 50.

[4] Hans Straub, *A History of Civil Engineering: An Outline from Ancient to Modern Times*, (trans. by E. Rockwell) (London: Leonard Hill, Limited, 1952), p. 50.

[5] Wilbur Watson and Sara Ruth Watson, *Bridges in History and Legend*. (Cleveland, Ohio: J. H. Jansen), 1937, p. 157.

Case 3.7b: Ponte Rialto

[1] Gies, op. cit., p. 50.

[2] S. B. Hamilton "Bridges", from *A History of Technology* (ed. by Charles Singer) Vol. 2, (Oxford Clarendon Press), 1956, p. 424.

[3] Gies, op. cit., p. 59.

Case 3.8

This case number was intentionally omitted to point out that there is no 'Essence' type bridge built during the "schism" period (1750-1880) that would adequately fit the definition.

Case 3.9: The Ruck-A-Chucky Bridge

[1] T. Y. Lin, H. K. Lu., and Charles Redfield, "The Design of the Ruck-A-Chucky Bridge", *Concrete International*. pp. 32-33.

[2] "flutter will not occur with wind velocity up to 120 mph, ...noting that the 100-year wind velocity at the site is only 90 mph. ...the long unsupported cables of various lengths tend to be excited by winds of relatively low velocity through the phenomenon of vortex shedding, but none of their frequencies is likely to excite important girder modes." Ibid., p. 36.

[3] Elbasani and Dubin, as quoted in "First Award: Architectural Design, The Ruck-A-Chucky Bridge," *Progressive Architecture*, January 1979. p. 69.

Case 3.10: Pont du Gard

[1] Steinman, op. cit., p. 37.

[2] Hopkins, op. cit., p. 20.

[3] For discussion of the quality of stone, good enough to allow spans to be achieved without

the voussoir arch, see Mainstone, op. cit., pp. 95-104, 241. Also Hopkins, op. cit., p. 18-9.

Case 3.11 Prince Albert Royal Bridge

[1] David Billington, Structures and the Urban Environment, Lecture Notes CE262. Princeton University, Civil Engineering Department (unpublished), 1978. p. 23.

[2] Ibid., p. 23.

[3] Hopkins, op. cit., p. 135.

[4] Billington, op. cit., p. 25.

[5] Straub, op. cit., pp. 203-206.

Case 3.12

[1] Le Corbusier, When the Cathedrals Were White. Reynal and Hitchcock, 1947. (Also quoted in "The 'George' at 50." The Port Authority of NY & NJ. News Release, 9/24/81. p. 6)

[2] Gustav Lindenthal, a bridge engineer with whom Ammann worked, "had the conviction that the common method of bridge-building whereby the structure is designed by an engineer, and afterward, if at all, an architect is invoked to give it such form and comliness as may still be practicable, was a radically wrong method." See Architectural Record, (March 1909) p. 154. Lindenthal promoted the idea that the "artistic and scientific" construction were intended to be joined and nurtured from the design's conception.

[3] ______, "Original Bridge Construction" The Bergen News and The Sun Bulletin, Souvenir Edition, October 24, 1981. p. 10.

[4] O. H. Ammann, as quoted by Michael J. Celizic, "One man's dream crystallizes in a span of steel", The Sunday Record: A Special Edition, October 18, 1981. p. A-1.

[5] from "Facts on George Washington Bridge" The Port Authority of NY & NJ. (unpublished notes).

[6] List of vehicles in the cavalcade were incredible. See The Port Authortiy of NY & NJ for more information. "George Washington Bridge: 50th Anniversary Celebration Program. Fort Lee, New Jersey. Saturday, October 24, 1981."

[7] Children's book was inspired by the George Washington Bridge. The Little Red Lighthouse and the Great Gray Bridge by Hildegard Hoyt Swift.

Case 3.13 Pont Neuf

[1] as referenced by Whitney, op. cit., p. 139.

[2] Steinman, op. cit., p. 86.

[3] See Sparrow's comment about 'motive-powers'. "Can anyone explain why the feminine joy of going to market has ever been most adventurous in narrow streets, or in short streets of medium width?" Walter Shaw Sparrow and Frank Brangwyn, A Book of Bridges (London and New York: John Lane Company), 1915, p. 210.

[4] Fra Giocondo, Italian architect.

[5] Steinman, op. cit., p. 89.

[6] Ibid., pp. 87-89.

[7] R. Randal Phillips "The Bridges of Paris" Architectural Review, Vol. 23, p. 13.

[8] Gies, op. cit., p. 62.

[9] Steinman, op. cit., p. 89.

[10] Whitney, op. cit., p. 149.

Case 3.14 The Firth of Forth Bridge

[1] Charles Fowler, The Ideals of Engineering Architecture. (Chicago: Gilette Publishing Co.), 1929. p. 152.

[2] Sandstrom, op. cit., p. 227.

[3] Mainstone, op. cit., p. 247.

[4] Sandstrom, op. cit., p. 228.

[5] Mainstone, op. cit., p. 247.

[6] Ibid., p. 248.

[7] Tay bridge disaster, 1879. "All 13 main spans of the Tay railroad bridge collapsed, presumably because of aerostatic instability. See Michael Overman, Roads, Bridges and Tunnels, (New York: Doubleday Science Series) 1968, p. 15.

[8] Gies, op. cit., p. 217.

Case 3.15 The Salginatobel Bridge
The Schwandbach Bridge

[1] Billington, op. cit., p. 105.

[2] Ibid., p. 109.

[3] Nervi would agree with Ritter when he recounts the story of the German structural engineers who strongly denounced the stability of the Risorgimento Bridge in Rome, through calculations. As in Nervi, op. cit., p. 15. See also Billington, op. cit., p. 109.

[4] David Billington, Robert Maillart's Bridges: The Art of Engineering, (Princeton, New Jersey: Princeton University Press), 1979, p. 107.

[5] Ibid., p. 88.

[6] David Billington, "Meaning in Maillart" Via, Publication of the Graduate School of Fine Arts, University of Pennsylvania, Vol. 2, 1973. Structures Implicit and Explicit (edited by James Bryan and Rolb Sauer). p. 39.

[7] Billington, Robert Maillart: The Art of Engineering, op. cit., p. 81.

[8] Ibid., p. 92.

[9] Robert Maillart as quoted by Max Bill, Robert Maillart, (Zurich: Les Editions d'Architecture SA), 1949, p. 15.

[10] Billington, Robert Maillart: The Art of Engineering, op. cit., p. 94.

[11] Billington, Structures and the Urban Environment, op. cit., p. 86.

[12] David Billington, Civil Engineering: History, Heritage and the Humanities: Background papers for the Second National Conference on

Civil Engineering (edited by John F. Abel), Oct. 4, 1972, (Princeton University, Princeton, New Jersey) p. 47.

Case 3.16 Pul-I-Khaju Bridge

[1] Mainstone, op. cit., p. 239.

[2] "There are three fundamental ways by which man shapes his environment. Natural order is developed by those closest to nature: the nomad and the villager. Geometric order relates to the system of man's most ancient cities as a unity within a unity. Harmonic order creates multiplicity within unity, geometric shapes linked in natural patterns within the framework of a superconscious geometry." Lalek Bakhtiar, and Nader Ardalan, *The Sense of Unity*. (Chicago and London: The University of Chicago Press,) 1973, p. 79.

[3] Ibid., p. 89.

[4] Sparrow, op. cit., p. 284.

[5] Bakhtiar, op. cit., p. 105.

Case 3.17

This case number was intentionally omitted as there was no 'Essence' type bridge that would satisfy the definition of the engineer's framework during the "schism".

Case 3.18 The Brooklyn Bridge

[1] Lewis Mumford, The Brown Decades: *A Study of the Arts in America, 1865-1895*. (New York: Dover Publications, Inc.), 1931, p. 27.

[2] Alan Trachtenberg, *Brooklyn Bridge* (New York: Oxford University Press), 1965. Introduction.

[3] "The Brown Decades" "The commonest axiom of history is that every generation revolts against its fathers and makes friends with its grandfathers. This reason alone might perhaps account for the fact that the generation which struggled or flourished after the Civil War now has a claim upon our interest." Mumford, op. cit., p. 1.

[4] Ibid., p. 27.

[5] David McCullough, *The Great Bridge*. (Avon Publishers), 1972. p. 26.

[6] Ibid., p. 27.

[7] Today the air may not be as 'pure', but Roebling's intention is to be commended. Ibid., p. 32.

[8] Ibid., p. 32.

[9] Mumford, op. cit., p. 45.

[10] Billington, *Structures and the Urban Environment*, p. 58.

[11] Billington, *Via* op. cit., p. 29.

[12] John Tauranac, *Essential New York: A Guide to the History and Architecture of Manhattan's Important Buildings, Parks, and Bridges*, (New York: Holt, Rinehart and Winston,) 1979. pp. 53-55.

[13] Mumford, op. cit., p. 46.

[14] Trachtenberg, op. cit., "Prologue".

[15] Ibid. "Prologue".

Chapter Four: CONCLUSIONS

[1] Whitehead, Alfred North, The Function of Reason (1861-1947). The Louis Clark Vanxaum Foundation Lectures, Princeton University Press, 1929, p. 34.

ILLUSTRATIONS

Chapter One: INTRODUCTION

Fig. 1. Author. Pedestrian bridge connecting sportsfield with main campus at University of Pennsylvania, Philadelphia. Steel-truss design by Peter McCleary. University of Pennsylvania Graduate School of Fine Arts, 1980. Fig. 2. "Bridge to Unite France to Italy," by Henri Labrouste, from The Architecture of the Ecole Des Beaux-Arts edited by Drexler. Fig. 3, 4, 5, 13, 14, from Whitney, Bridges: A Study in Their Art, Science and Evolution. Fig. 6, 8, 10. from Mock, The Architecture of Bridges. Fig. 9, 15, from Stephens, John H. Towers, Bridges and other Structures., New York: Sterling Publishing Co., Inc., 1976. Fig. 11. from Portfolio Magazine. January/February 1982, "In Detail: Joseph Stella and New York Interpreted", p. 41. Fig. 12. Stoltenberg, Art in the Built Environment.

Chapter Two: DEFINITIONS

Fig. 16, 18, 26, 27. from Mock, The Architecture of Bridges. Fig. 17, 20, 30, from Stephens. Fig. 19. from Watson, Bridge Architecture. Fig. 21. from Plowden, Bridges: The Spans of North America. Fig. 22. Author. Echo Bridge over Charles River, Newton, Mass. Asymmetrical design. (one 129' span and two smaller ones on one side.) Built by Boston Water Company 1876, carries conduit. Fig. 23 from Sturgis' Dictionary of Architecture, Vol. 1. Fig. 24, 29. from Whitney, Bridge Architecture. Fig. 25. from Sheehy, The Rediscovery of Ireland's Past. Fig. 28. from Commonwealth of Massachusetts, Department of Public Works. Temporary Bridge prefabricated steel panel truss, Gloucester, Mass.

Chapter Three: THE CASE STUDIES

Fig. 31, 32, from Giangiorgio Zorzi, Le Chiese e i ponti di Andrea Palladio. Neri Pozza Editore, 1967. Fig. 33 from Committee on the History and Heritage of American Civil Engineering. Fig. 34, 81 from Plowden, Bridges: the Spans of North America, Fig. 35, 36, 45, 57, 70, 71, 72, 73, 74. from Mock, The Architecture of Bridges. Fig. 37, 39. from Journal of the Institution of Civil Engineers No. 7., June 1943. "The New Waterloo Bridge" Fig. 38, 41, 42, 69. from Fowler, Ideals of Engineering Architecture. Fig. 40, 48, 50, 55, 64, 65, 68, 78, from Watson, Bridge Architecture. Fig. 43, 44, 46. from Cossons, The Iron Bridge: Symbol of the Industrial Revolution. Fig. 47. Nervi, Structures. Fig. 49, 51. from Gies, Bridges and Men. Fig. 52, 53, 54. from Progressive Architecture. January 1979. Fig. 56, 58. from Hopkins, A Span of Bridges. Fig. 59. from New York Port Authority. Fig. 60, 61, 62. from Embury, "The Aesthetics of Bridge Design" Pencil Points. Fig. 63. from Billington, (unpublished) Lecture Notes. Fig. 66, 67. from Whitney, Bridges: A Study in Their Art, Science, and Evolution, Fig, 75, 76. from Ardalan and Bakhtiar, The Sense of Unity: The Sufi Tradition in Persian Architecture, Fig. 77 from Leacroft, The Buildings of Early Islam. Fig. 79. from Annals of the New York Academy of Science. Long-Span Bridges: O. H. Ammann Centennial Conference, (edited by Edward Cohen and Blair Berdsall.) Vol. 352. Fig. 80. from Stussi, Othmar H. Ammann, Birkhauser Berlag Basel, 1974.

Chapter Four: CONCLUSION

Fig. 82. Author. The Golden Gate Bridge in the mist, viewed from San Francisco side.

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Chapter One: INTRODUCTION

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