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Bridge Aesthetics — Structural Art

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3.1 Introduction

In recent years it has become apparent that the real problems of bridge design include more than the structural or construction issues relating to the spanning of a gap. The public often expresses concern over the appearance of bridges, having recognized that a bridge's visual impact on its community is lasting and must receive serious consideration.

The public knows that civilization forms around civil works: for water, transportation, and shelter. The quality of public life depends, therefore, on the quality of such civil works as aqueducts, bridges, towers, terminals, and meeting halls: their efficiency of design, their economy of construction, and the visual appearance of their completed forms. At their best, these civil works function reliably, cost the public as little as possible, and, when sensitively designed, become works of art.

Thus, engineers all over the world are being forced to address the issues of aesthetics. Engineers cannot avoid aesthetic issues by taking care of the structural elements and leaving the visual quality to someone else. It is the shapes and sizes of the structural components themselves that dominate the appearance of the bridge, not the details, color, or surfaces. Since they control the shapes and sizes of the structural components, engineers must acknowledge the fact that they are ultimately responsible for the appearance of their structures. Engineers are used to dealing with issues of performance, efficiency, and cost. Now, they must also be prepared to deal with issues of appearance.

FIGURE 3.1 Thomas Telford's Craigellachie Bridge.

3.2 The Engineer's Aesthetic and Structural Art

"Aesthetics" is a mysterious subject to most engineers, not lending itself to the engineer's usual tools of analysis. It is a topic rarely taught in engineering schools. Many contemporary engineers are not aware that a long line of engineers have made aesthetics an explicit element in their work, beginning with the British engineer Thomas Telford. In 1812, Telford defined structural art as the personal expression of structure within the disciplines of efficiency and economy. Efficiency here meant reliable performance with minimum materials, and economy implied the construction with competitive costs and restricted maintenance expenses. Within these bounds, structural artists find the means to choose forms and details that express their own vision, as Telford did in his Craigellachie Bridge (Figure 3.1). The arch is shaped to be an efficient structural form in cast iron, while his diamond pattern of spandrel bars, at a location in the bridge where structural considerations permit many options, is clearly chosen with an eye to its appearance.

Those engineers who were most conscious of the centrality of aesthetics for structure have also been regarded as the best in a purely technical sense. Starting with Thomas Telford (1757–1834), we can identify Gustave Eiffel (1832–1923) and John Roebling (1806–1869) as the undisputed leaders in their fields during the 19th century. They designed the largest and most technically challenging structures, and they were leaders of their professions. Telford was the first president of the first formal engineering society, the Institution of Civil Engineers, and remained president for 14 years until his death. Eiffel directed his own design–construction–fabrication company and created the longest spanning arches and the highest tower; Roebling founded his large scale wire rope manufacturing organization while building the world's longest spanning bridges (Figure 3.2).

In reinforced concrete, Robert Maillart (1872–1940) was the major structural artist of the early 20th century. First in his 1905 Tavanasa Bridge, and later with the 1930 Salginatobel (Figure 3.3) and 1936 Vessy designs, he imagined a new form for three-hinged arches that included his own invention of the hollow box in reinforced concrete. The Swiss engineer Christian Menn (1927–) has demonstrated how a deep understanding of arches, prestressing, and cable-stayed forms can lead to structures worthy of exhibition in art museums. Especially noteworthy are the 1964 Reichenau Arch, the 1974 Felsenau prestressed cantilever, and the 1980 concrete cable-stayed Ganter Bridge. Meanwhile, German engineer

FIGURE 3.2 John Roebling's Brooklyn Bridge.

Jorg Schlaich has developed new ideas for light structures often using cables, characterized by a series of elegant footbridges in and around Stuttgart (Figure 3.4).

The engineers' aesthetic results from the conscious choice of form by engineers who seek the expression of structure. It is neither the unconscious result of the search for economy nor the product of supposedly optimizing calculations. Many of the best structural engineers have recognized the possibility for structural engineering to be an art form parallel to but independent of architecture. These people have, over the past two centuries, defined a new tradition, structural art, which we take here to be the ideal for an engineer's aesthetic.

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

In our own age the works of structural art provide evidence that the common life flourishes best when the goals of freedom and discipline are held in balance. The disciplines of structural art are efficiency and economy, and its freedom lies in the potential it offers the individual designer for the expression of a personal style motivated by the conscious aesthetic search for engineering elegance. These are the three leading ideals of structural art — efficiency, economy, and elegance.

FIGURE 3.3 Robert Maillert's Salginotobel Bridge.

FIGURE 3.4 One of Jorg Schlaich's footbridges.

3.3 The Three Dimensions of Structure

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

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

Technological objects visually dominate our industrial, urban landscape. They are among the most powerful symbols of the modern age. Structures and machines define our environment. The locomotive of the 19th century has given way to the automobile and airplane of the 20th. Large-scale complexes that include structures and machines become major public issues. Power plants, weapons systems, refineries, river works — all have come to symbolize the promises and problems of industrial civilization.

The Golden Gate, the George Washington, and the Verrazano Bridges carry on the traditions set by the Brooklyn Bridge. The Chicago Hancock and Sears Towers, and the New York Woolworth, Empire State, and World Trade Center Towers all bring the promise of the Eiffel Tower into the utility of city office and apartment buildings. The Astrodome, the Kingdome, and the Superdome carry into the late 20th century the vision of huge permanently covered meeting spaces first dramatized by the 1851 Crystal Palace in London and the 1889 Gallery of Machines in Paris.

Nearly every American knows something about these immense 20th-century structures, and modern cities repeatedly publicize themselves by visual reference to these works. As Montgomery Schuyler, the first American critic of structures, wrote in the 19th century for the opening of the Brooklyn Bridge, "It so happens that the work which is likely to be our most durable monument, and to convey some knowledge of us to the most remote posterity, is a work of bare utility; not a shrine, not a fortress, not a palace but a bridge. This is in itself characteristic of our time."[1].

So it is that the third dimension of technology is symbolic, and it is, of course, this dimension that opens up the possibility for the new engineering to be structural art. Although there can be no measure for a symbolic dimension, we recognize a symbol by its elegance and its expressive power. Thus, the Sunshine Skyway (Figure 3.5) has become a symbol of both Florida's Tampa Bay area and the best of late-20th-century technology.

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

For the structural designer the scientific criterion is primary (as is the social criterion for the architect and the symbolic criterion for the sculptor). Yet the structural designer must balance the primary criterion with the other two. It is true that all structural art springs from the central ideal of artificial forms controlling natural forces. Structural forms will, however, never get built if they do not gain some social acceptance. The will of the designer is never enough. Finally, the designer must think aesthetically for structural form to become structural art. All of the leading artists of

FIGURE 3.5 The Sunshine Skyway.

structure thought about the appearance of their designs. These engineers consciously made aesthetic choices to arrive at their final designs. Their writings about aesthetics show that they did not base design only on the scientific and social criteria of efficiency and economy. Within those two constraints, they found the freedom to invent form. It was precisely the austere discipline of minimizing materials and costs that gave them the license to create new images that could be built and endure.

3.4 Structure and Architecture

The modern world tends to classify towers, stadiums, and even bridges as architecture, creating an important, but subtle, fallacy. Even the word is a problem, because *architect* comes from the Greek word meaning chief technician. But, beginning with the Industrial Revolution, structure has become an art form separate from architecture. The visible forms of the Eiffel Tower, Seattle's Kingdome, and the Brooklyn Bridge result directly from technological ideas and from the experience and imagination of individual structural engineers. Sometimes, the engineers have worked with architects just as with mechanical or electrical engineers, but the forms have come from structural engineering ideas.

Structural designers give form to objects that are of relatively large scale and of single use, and these designers see forms as the means of controlling the forces of nature to be resisted. Architectural designers, on the other hand, give form to objects that are of relatively small scale and of complex human use, and these designers see forms as the means of controlling the spaces to be used by people. The prototypical engineering form — the public bridge — requires no architect. The prototypical architectural form — the private house — requires no engineer. Structural engineers and architects learn from each other and sometimes collaborate fruitfully, especially when, as with tall buildings, large scale goes together with complex use. But the two types of designers act predominately in different spheres.

The works of structural art have sprung from the imagination of engineers who have, for the most part, come from a new type of school — the polytechnical school, unheard of prior to the late 18th century. Engineers organized new professional societies, worked with new materials, and stimulated political thinkers to devise new images of future society. Their schools developed curricula that decidedly cut whatever bond had previously existed between those who made architectural forms and those who began to make — out of industrialized metal and later from reinforced concrete — the new engineering forms by which we everywhere recognize the modern world. For these forms the ideas inherited from the masonry world of antiquity no longer applied; new ideas were essential in order to build with the new materials. But as these new ideas broke so radically with conventional taste, they were rejected by the cultural establishment.

This is, of course, a classic problem in the history of art: new forms often offend the academics. In this case, it was beaux arts against structural arts. The skeletal metal of the 19th century offended most architects and cultural leaders. New buildings and city bridges suffered from valiant attempts to cover up or contort their structure into some reflection of stone form. In the 20th century, the use of reinforced concrete led to similar attempts. Although some people were able to see the potential for lightness and energy, most architects tried gamely to make concrete look like stone or, later on, like the emerging abstractions of modern art. There was a deep sense that engineering alone was insufficient.

The conservative, plodding, hip-booted technicians might be, as the architect Le Corbusier said, "healthy and virile, active and useful, balanced and happy in their work, but only the architect, by his arrangement of forms, realizes an order which is pure creation of his spirit ... it is then that we experience the sense of beauty." The belief that the happy engineer, like the noble savage, gives us useful things but only the architect can make them into art is one that ignores the centrality of aesthetics to the structural artist. In towers, bridges, free-spanning roofs, and many types of industrial buildings, aesthetic considerations provide important criteria for the engineer's design. The best of such engineering works are examples of structural art, made by engineers, and they have appeared with enough frequency to justify the identification of structural art as a mature tradition with a unique character. One of the most recent manifestations is Christian Menn's Sunniberg Bridge (Figure 3.6).

3.5 Application to Everyday Design

Many of today's engineers see themselves as a type of applied scientist, analyzing preexisting structural forms that have been established by others. Seeing oneself as an applied scientist is an unfortunate state of mind for a design engineer. It eliminates the imaginative half of the design process and forfeits the opportunity for the integration of form and structural requirements that can result in structural art. Design must start with the selection of a structural form. It is a decision that can be made well only by the engineer because it must be based on a knowledge of structural forms and how they control forces and movements.

In the case of most everyday bridges the selection of form is based largely on precedents and standards established by the bridge-building agency. For example, the form of a highway overpass may be predetermined by the client agency to be a welded plate girder bridge because that is what the agency prefers or what local steel fabricators are used to or even because the steel industry is a dominant political force in the state. In other cases, the form may be established by an architect or urban designer for reasons outside structural requirements. Thus the form is set without any serious consideration of whether or not that is in fact the best form for that particular site.

Creative form determination consists not of applying free visual imagination alone nor in applying rigorous scientific analysis alone, but of applying both together, at the same time. The art starts with a vision of what might be. The development of that vision is the key. Many engineers call the development of the vision conceptual engineering. It is the most important part of design. It is the stage at which all plausible forms are examined. The examination must include, to a rough level of precision, the whole range of considerations; performance, cost, and appearance. All that follows, including the aesthetic impression the bridge makes, will depend on the quality of the form selected. This stage is often ignored or foreclosed, based on precedents, standards, preconceived ideas or prior experience that may or may not apply.

FIGURE 3.6 Christian Menn's Sunniberg Bridge.

The reasons often given for shortchanging this stage include, "Everybody knows that [steel plate girders, precast concrete girders, cast-in-place concrete] are the most economical structure for this location," or "We always build [steel plate girders, precast concrete girders, cast-in-place concrete] in this state," or "Let's use the same design as we did for [any bridge] last year."

At this point someone will protest that other considerations (costs, the preferences of the local contracting industry, etc.) will indeed differentiate and determine the form. Too often these reasons are based on unexamined assumptions, such as, "The local contracting industry will not adjust to a different form," or "Cost differentials from [a past project] still apply," or "The client will never consider a different idea." Or the belief is based on a misleading analysis of costs which relies too much on assumed unit costs. Or that belief may be simply habit — either the engineer's or the client's — often expressed in the phrase, "We've always done it that way." Accepting these assumptions and beliefs places an unfortunate and unnecessary limitation on the quality of the resulting bridge for, by definition, improvements must come from the realm of ideas not tried before.

As Captain James B. Eads put it in the preliminary report on his great bridge over the Mississippi River at St. Louis:

> Must we admit that because a thing has never been done, it never can be, when our knowledge and judgment assure us that it is entirely practicable?[2].

FIGURE 3.7 MD 18 over U.S. 50.

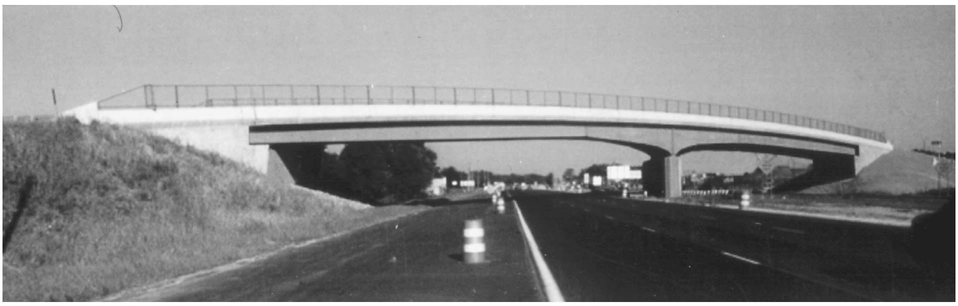

FIGURE 3.8 Another possibility for MD 18 over U.S. 50.

The engineer's first job is to question all such determinations, assumptions and beliefs. From that questioning will come the open mind that is necessary to develop a vision of what each structure can be at its best.

Unless such questioning is the starting point it is unlikely that the most promising ideas will ever appear. No design will occur. Instead, there will be a premature assumption of the bridge form, and the engineer will move immediately into the analysis of the assumed form. That is why so many engineers mistake analysis for design. Design is more correctly the selection of the form in the first place, which most engineers have not been permitted to do. Design is by far the more important of the two activities.

Engineers also focus on analysis in the belief that the form (shape and dimensions) will be determined by the forces as calculated in the analysis. But, in fact, there are a large number of forms that can be shown by the analysis to work equally well. It is the engineer's option to choose among them, and in so doing to determine the forces by means of the form, not the other way around.

Take the simple example of a two-span continuous girder bridge, using an existing structure, MD 18 over U.S. 50 (Figure 3.7). Here the engineer has a wide range of possibilities such as a girder with parallel flanges, or with various haunches having a wide range of proportions (Figure 3.8). The moments will depend on the stiffness at each point, which in turn will depend on the presence or absence of a haunch and its shape (Figure 3.9). The engineer's choice of shape and dimensions will determine the moments at each point along the girder. The forces will follow the choice of form. Within limits, the engineer can direct the forces.

Let's examine which form the engineer should choose. Allcan support the required load. Depending on the specifics of the local contracting industry, many of them will be essentially equal in cost. All would perform equally well and all are comparable in cost, leaving the engineer a decision that can only be made on aesthetic grounds. Why not pick the one the engineer believes looks best?

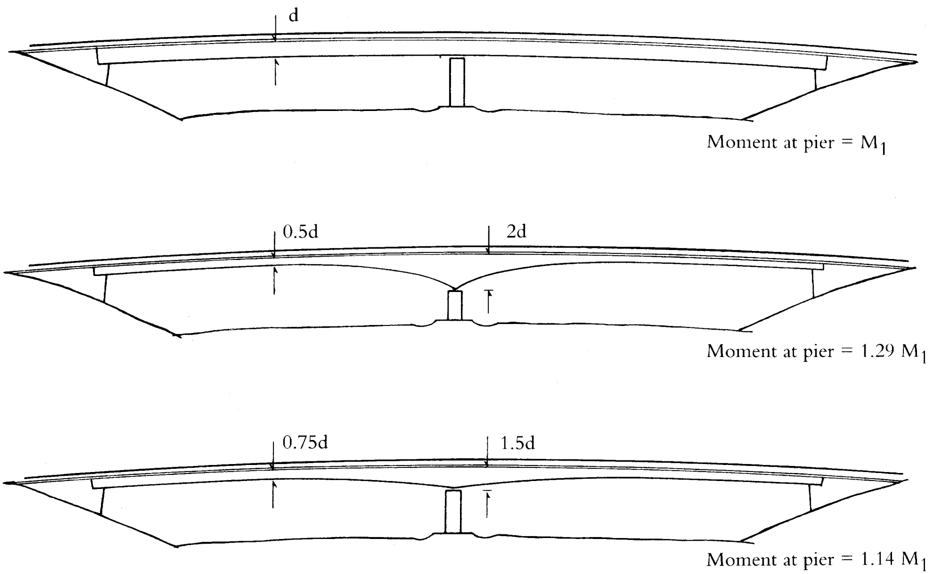

FIGURE 3.9 Forces determined by the engineer's choice of form.

That, in a nutshell, is the process that all of the great engineers have followed. Maillart's work, as one example, shows that the engineer cannot choose form as freely as a sculptor, but the engineer is not restricted to the discovery of preexisting forms as the scientist is. The engineer invents form, and Maillart's career shows that such invention has both a visual and a scientific basis. When either is denied, engineering design ceases. For Maillart, the dimensions were not to be determined by the calculations, and even the results of the calculations could be changed (by adjusting the form) because a designer rather than an analyst is at work. Analysis and calculation are the servants of design. Design, analysis, and must work together. In the words of Spanish engineer Eduardo Torroja,

> The imagination alone cannot reach such [elegant] designs unaided by reason, nor can a process of deduction, advancing by successive cycles of refinement, be so logical and determinate as to lead inevitably to them.[3]

The engineering challenge is not just to find the least costly solution. The engineering challenge is to bring forth elegance from utility: We should not be content with bridges that only move vehicles and people. They should move our spirits as well.

3.6 The Role of Case Studies in Bridge Design

Bridge design, even of highway overpasses, often involves standard problems but always in different situations. Case studies can help in the design of these standard problems by showing models and points of comparison for a large number of bridges without implying that each such bridge be mere imitation.

The primary goals of a case study are to look carefully at all major aspects of the completed bridge, to understand the reasons for each design decision, and to discuss alternatives, all to the end of improving future designs. Such cases help to define more general ideas or principles. Case studies are well recognized by engineers when designing for acceptable performance and low cost; they can be useful when considering appearance as well.

A common organization of these studies will help identify standard problems and make comparisons easier. First comes an overall evaluation of the bridge as a justification for studying it. Is it a good example that can be better? Is it a model of near perfection? Is it a bad example to be avoided?, Second comes a description of the complete bridge, which is divided into parts roughly coinciding with easily identifiable costs and including modifications to each part as suggested improvements. In this major description section there is an order to the parts that implies a priority for the structural engineer: concept and form of the entire structure, superstructure, supports, deck, color, and landscaping.

1. The *concept and form* of the completed bridge goes together with a summary of the bridge performance history (including maintenance) and of its construction cost, usually given per square meter of bridge. Required clearances, foundation conditions, hydraulic requirements, traffic issues, and other general requirements would be covered here.
2. The *superstructure* here includes primarily the main horizontal spanning members such as continuous girders, arches, trusses, etc. In continuous steel girder bridges, the cost is primarily identified with the fabricated steel cost. Modification in design by haunching, changing span lengths, or making girders continuous with columns would be discussed including their influence on cost.
3. The *pier supports* are most frequently columns or frames either in the median or outside the shoulders, or at both places in highway overpasses. These are normally highly visible elements and can have many possible forms. Different designs for the relationship among steel girder, bearings, and columns can make major improvements in appearance without detriment to cost or performance.
4. The *abutment supports* are also highly visible parts of the bridge, which include bearings, cantilever walls, cheek walls, and wing walls.
5. The *deck* includes the concrete slab or orthotropic steel deck, overhangs, railings, parapets, and provisions for drainage, all of which have an influence on performance as well as on the appearance either when seen in profile or from beneath the bridge.
6. The *color* is especially significant for steel structures that are painted, and *texture* can be important for concrete surfaces of piers, abutments, and deck.
7. The *landscaping/guardrail* includes plantings and other features that can have important visual consequences to the design.

The order of these parts is significant because it focuses attention on the engineering design. The performance of a weak structural concept cannot be saved by good deck details. An ugly form cannot be salvaged by color or landscaping. The first four parts are structural, the fifth is in part structural, whereas the last two, while essential for the bridge engineer to consider, involve primarily nonstructural ideas.

Third, the case study can give a critique of the concept and form by comparison with other similar bridges or bridge designs for similar conditions, including those with very different forms, as a stimulus to design imagination.

Fourth and finally, the case should conclude with some discussion of the relationship of this study to a theory of bridge design. Clearly, any such study must be based upon a set of ideas about design which often implicitly bias the writer who should make these ideas explicit. This conclusion should show how the present study illustrates a theory and even at times forces a modification of it. General ideas form only out of specific examples.

3.7 Case Study in Colorado: Buckley Road over I-76

Colorado's Buckley Road over I-76 (Figure 3.10) offers the application of an innovative form to prestressed concrete girders in order to achieve longer than normal spans, with a visually unique result. It is therefore a worthy subject for a case study.

FIGURE 3.10 Buckley Road over I-76.

3.7.1 Description of the Bridge

In *concept* this is a three-span continuous beam bridge with a 47° skew made of precast prestressed girders set onto cast-in-place concrete piers and abutments.

The *superstructure* consists of seven girders spaced approximately 3 m apart and each made up of five precast prestressed concrete segments (Figure 3.11). The main span is approximately 56 m and each side span is approximately 50 m. Segments one and five are 37.8 m long and behave essentially as simply supported beams between the abutments and the cantilever segments two and four. These latter cantilever 12 m into the side spans and 15 m into the main span. Segment three is 25.6 m long and behaves approximately as a simply supported beam within the main span. There are 0.15 m spacings between segments for closure pours. The cantilever segments have a linear haunch of 0.6 m from the girder depth of 1.8 m for the other three segments, which are Colorado BT72 girders.

The two *piers* each consist of a pier cap beam 1.2 m wide by 1.8 m deep and 28 m long supported by three walls each 1.2 m wide, about 7.6 m high, and 6 m long at their tops tapering to 3 m long at the footings. The cap beam extends about 1.5 m beyond the centerline of the exterior girder or about 1.1 m beyond the edge of that girder's bottom flange. The pier next to the railroad has a crash wall built into the three tapered walls.

The *abutments* are shallow concrete beams 0.9 m wide supported on piles and carrying the precast girders. The *deck* is a series of precast pretensioned concrete panels made composite with the precast girders. Bounded by Jersey barriers, the deck is 20.4 m in width and overhangs the exterior girders by 0.96 m or slightly over half the depth of the unhaunched girder segments.

3.7.2 Critique of the Bridge

The *concept* of a fully precast superstructure, a three-span continuous beam, and cast-in-place piers has led to an economical structure and fits well the site conditions of crossing both I-76 and the double-track railroad. Other reasonable concepts include a two-span bridge and a three-span bridge with the cantilever segments two and four cast in place with the piers (as illustrated by the Stewart

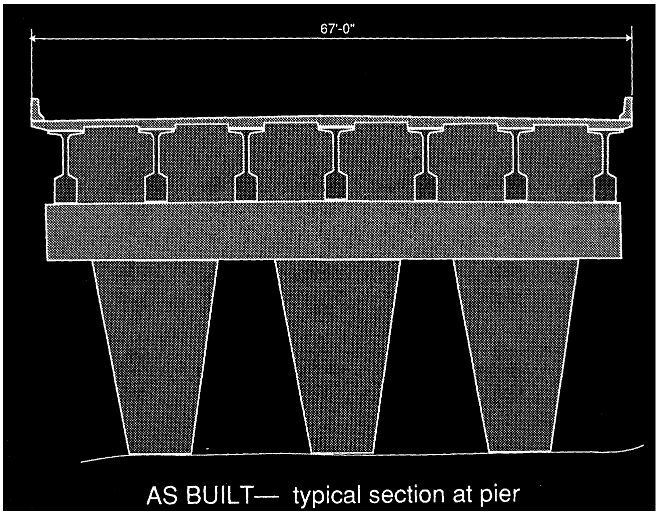

FIGURE 3.11 Typical section of Buckley Road as built.

Park Bridge in Oregon). This critique will confine itself to the present concept, but a comparison of this bridge and the Oregon one will follow. In each case, the ideas of structural art will form the basis for a critique.

The *superstructure* represents an unusual use of a precast bulb T girder whose bulb is extended vertically to create a haunch at the two interior supports. The profile view expresses the increased forces at the interior supports and the construction photos (with temporary walkway) show the lightness achieved by an overhang that is about the same dimension as the girder depth.

The *haunches* would be more effective visually were they deeper and the segments one, three, and five correspondingly shallower. For example, with the Colorado C68 girder, the depth would decrease to 1.7 m and a haunch of 2.6 m would more strikingly express the flow of forces. At the same time, the girder spacing would be reduced to 2.9 m to permit an overhang of 1.4 m.

Another solution would be to retain the Colorado BT72 girders, increase the haunch to 3 m, and reduce the number of girders from seven to six, thus again increasing the overhang. If the six girders were spaced 3.35 m on centers, then the overhang would be 1.7 m or nearly the depth of the BT72 girders.

The *pier*s are visually prominent and look heavy. They also have a formal shaping which does not clearly express the structure. Specifically, the horizontal lines of the hammerhead beam separate it from the supporting walls and the 1.8-m depth of that beam is far greater than needed to carry the girder loads over the 2.4-m span between the wide supporting walls below. Since these piers are relatively short compared with the long spans of the girders, their massive appearance is accentuated by the lack of structural expression. It is clear from beneath the bridge that the 6-m-wide walls can easily be made to support all the girders directly without any hammerhead beam (Figure 3.12). The walls will therefore be higher and, if carefully shaped, will form a striking integration with the deck girders. The cast-in-place diaphragm can then be structurally integrated with the walls and the girders to form a cross frame for live loads.

The *abutments* can be improved by eliminating the wall that hides the girder ends and bearings. Along with the lighter-looking girders, this structural expression at the abutments will increase the already striking appearance of the bridge profile.

The *deck* overhang, by being increased, lends lightness to the girders. Otherwise, the system used is good and avoids the staining that can arise when metal slab forms are left in place.

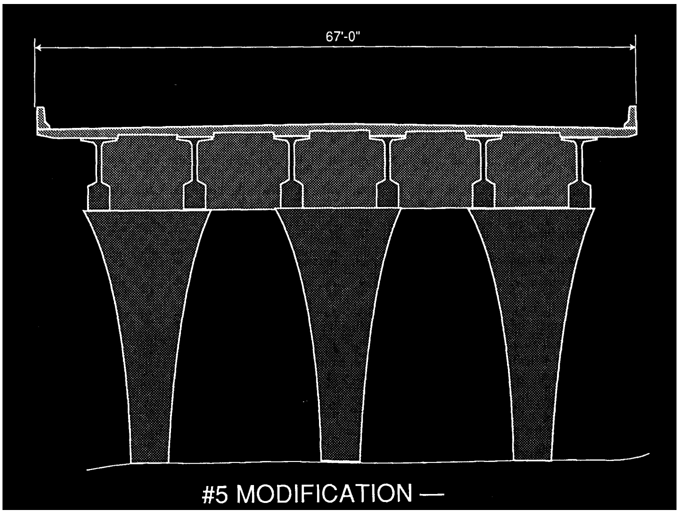

FIGURE 3.12 Possible modification to Buckley Road.

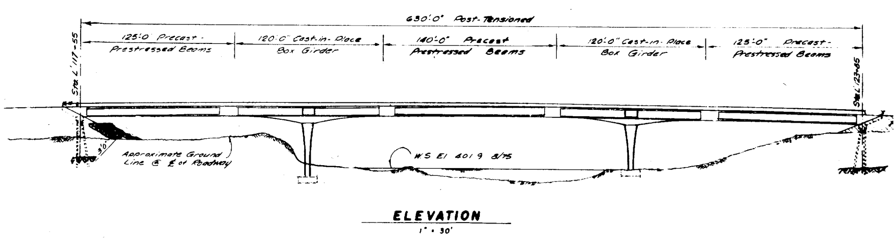

FIGURE 3.13 Elevation of Louis Pierce's Stewart Park Bridge.

3.7.3 The Stewart Park Bridge

The *concept* for this 1978 bridge (Figure 3.13) designed by Louis Pierce is the same as for Buckley Road except for the cantilever segments two and four which are cast-in-place prestressed concrete hollow boxes. Because the spans (56.4, 79.2, 56.4 m) are longer than those for Buckley Road, segments one, three, and five are each made of two separate precast pieces.

The *superstructure* and the *piers* are thus integrated into one form rather than separated into two forms as at Buckley Road. The boxes are haunched from the 2.4 m of the constant section segments to 3.65 m at the two interior supports for a ratio of 1.55. But the boxes are 2.4 m deep along their exterior faces and haunch laterally to 3.65 m over a distance of 2.5 m. Just as at Buckley Road, the *deck* overhang is too short, about 0.8 m for a girder depth of 2.4 m.

The shape of the two piers are walls 7.6 m wide, 2.3 m thick at the top, tapering to 5.8 m wide and 1.4 m thick at the base. The total height is 12.7 m above the footing but only about 7.6 m above the ground line. This shaping of piers, having about the same height as those of Buckley Road, gives an impression of lightness missing from the latter structure (Figure 3.14).

3.7.4 Summary

The Buckley Road bridge represents a good design. A similar concept can be improved in future designs by relatively small changes in the superstructure through stronger haunching and wider deck overhangs and by major changes in the pier form. The use of cast-in-place cantilever sections offers increased possibilities for elegant forms and closer integration of superstructure with piers.

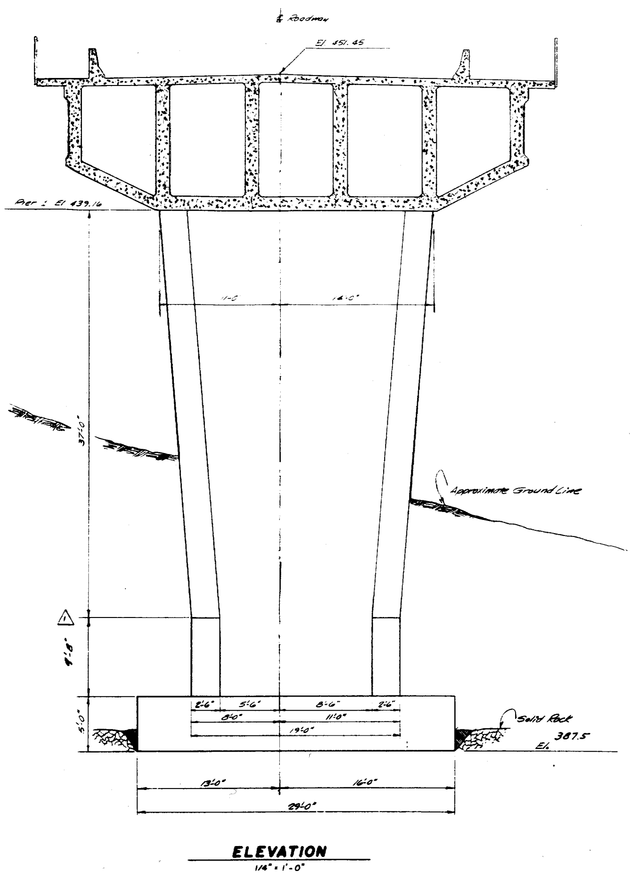

FIGURE 3.14 Typical section of Stewart Park Bridge at pier.

This case study gives an example of how a good bridge can provide an excellent basis for further study and improvement.

3.8 Achieving Structural Art in Modern Society: Computer Analysis and Design Competitions

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

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

The form controls the forces and the more clearly that designers can visualize those forces the surer they are of their forms. The great early and mid-20th-century structural artists such as Robert Maillart and Pier Luigi Nervi have all written forcefully against the urge to complicate analysis. We see the same arguments put forth by the best designers in the late 20th century. When the form is well chosen, its analysis becomes astoundingly simple. The computer, of course, has become more and more useful as a time saver for routine calculations that come after the design is set. It is also increasingly valuable in aiding the designer through computer graphics. But like any machine, although it can reduce human labor, it cannot substitute for human creativity.

Turning to the social dimension, a leading idea that has come out of structural art is the effectiveness of public design competitions. Design quality arises from the stimulus of competing designs for the same project rather than from complex regulations imposed upon a single designer. The progress of modern bridge design illustrates the benefit and meaning of alternative designs. Many alternative designs have been prepared pursuant to design competitions, which bring the public into the process in a positive way. It is not enough for the public merely to protest the building of ugly, expensive designs. A positive activity is essential, and that can only come about when the public sees the alternative designs that are possible for a project. Thus, governments can ensure better designs by relinquishing some of their control over who designs and on what forms are chosen, and by giving some of this control to an informed jury which includes representatives of the lay public.

Although there is little tradition in the United States for design competitions in bridges, such a tradition is firmly rooted elsewhere, with results that are both politically and aesthetically spectacular. Switzerland has the longest and most intensive tradition of bridge design competitions, and it is no coincidence that, by nearly common consent, the two greatest bridge designers of the first half of the 20th century were Swiss: Robert Maillart (1872–1940), who designed in concrete, and Othmar Amman (1879–1966), designer of the George Washington and Verrazano Bridges, who designed in steel. That Switzerland, one sixth the size of Colorado, and with fewer people than New York City, could achieve such world prominence is due to the centrality of economics and aesthetics for both their engineering teachers and their practicing designers, a centrality which is encouraged by design competitions.

Maillart's concrete arches in Switzerland were often the least expensive proposals in design competitions, and they were later to provide the main focus for the first art museum exhibition ever devoted exclusively to the work of one engineer: the New York City Museum of Modern Art's 1947 exhibition on Maillart's structures. Amman has been similarly honored. His centennial was celebrated by symposia both in Boston and in New York and by an exhibition held in Switzerland. Both Maillart and Amman wrote articulately on the appearance as well as on the economy of bridges. They are prime examples of structural artists.

This Swiss bridge tradition continues today with a large number of striking new bridges in concrete that follow Maillart in principle if not in imitative detail. The most impressive post-World War II works are those of Christian Menn, whose long-span arches and cantilevers extend the new technique of prestressing to its limits, as Maillart's three-hinged and deck-stiffened arches did earlier with reinforced concrete.

Design competitions stimulated these engineers and also educated the general public. To be effective, uch competitions must be accepted by political authorities, judged by engineers and informed lay members whose opinions will be debated in the public press, and controlled by carefully drawn rules.

It is false images of engineering that keep us from insisting on following our normal instinct for open competition. The American politics of public works falsely compares the engineering designer either with a medical doctor or with a building contractor.

Supporters of the first comparison argue that you would never hold a competition to decide who will repair your heart; rather, you would choose professionals on the basis of reputation and then leave them alone to do the skilled work for which they are trained. However, there is a key difference between hearts and bridges. For most people, there is only one heart which will do the job. Picking a "best" heart is not a consideration. On the other hand, for a given bridge site, there are many bridge designs that will solve the problem. The more minds that are put to the problem, the more likely that an outstanding design will emerge. After all, the ultimate goal is to pick the best bridge, not the best bridge designer.

Furthermore, developing the engineer's imagination creates a valuable asset for society. That imagination needs more chances to exercise than there are chances to build, and it is stimulated by competition. However, frustrating it may be to lose a competition, the activity is healthy and maturing, especially when even the losers are compensated financially for their time, as they often are in Switzerland.

For proponents of the second false comparison, design competitions are to be run just as building competitions in which the lowest bid for design cost gets the design contract. In American public structures, design and construction are legally distinct activities. The cost of design is normally 5% or less of the cost of construction. Therefore, a brilliant engineer might spend more preparing a design which, as can often happen, will cost the owners substantially less overall. By the same token, an engineer who cuts the design fee to get the job may have to make a more conservative design which could easily cost the owner more in overall costs. Hence, large amounts of potential savings to the public are lost by a foolish policy of saving a little during the first stage of a project.

In one type of Swiss design competition, a small number of designers are invited to compete, some of their costs are covered, and they get additional prize funds in the order recommended by the jury. The winner usually gets the commission for the detailed design. Only several such competitions a year are needed to stimulate the entire profession and to show the general public the numerous possibilities available as good solutions to any one problem. This method of design award opens up the political process to local people far more than does the cumbersome and largely negative one of protest, legal action, and negation of building that so dominates public action in late-20th-century America.

The state of Maryland is leading the way in the United States. In 1988, Maryland held a design competition for a new structure over the Severn River adjoining the U.S. Naval Academy in Annapolis. The competition was patterned on the Swiss practice. The results of the competition resolved an acrimonious community controversy. The winning structure, by Thomas Jenkins (Figure 3.15), was recognized by the American Institute of Steel Construction as the outstanding medium-span structure constructed in 1995–96. In 1998, Maryland, together with the state of Virginia, the District of Columbia, and the Federal Highway Administration, conducted a competition to select the design of the new Woodrow Wilson Bridge over the Potomac River at Washington, D.C. The winning design (Figure 3.16) was prepared by a team led by the Parsons Transportation Group.

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

FIGURE 3.15 Thomas Jenkins's U.S. Naval Academy Bridge over the Severn River.

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

3.9 The Engineer's Goal

The ideal bridge is structurally straightforward and elegant. It should provide safe passage and visual delight for drivers, pedestrians, and people living or working nearby. Society holds engineers responsible for the quality of their work, including its appearance. For the same reason engineers would not build a bridge that is unsafe, they should not build one that is ugly. Bridge designers must consider visual quality as fundamental a criterion in their work as performance, cost, and safety.

There are no fast rules or generic formulas conducive to outstanding visual quality in bridge design. Each bridge is unique and should be studied individually, always taking into consideration all the issues, constraints, and opportunities of its particular setting or environment. Nevertheless, by observing other bridges, using case studies and design guidelines, engineers can learn what makes bridges visually outstanding and develop their abilities to make their own bridges attractive. They can achieve outstanding visual quality in bridge design while maintaining structural integrity and meeting their budgets.

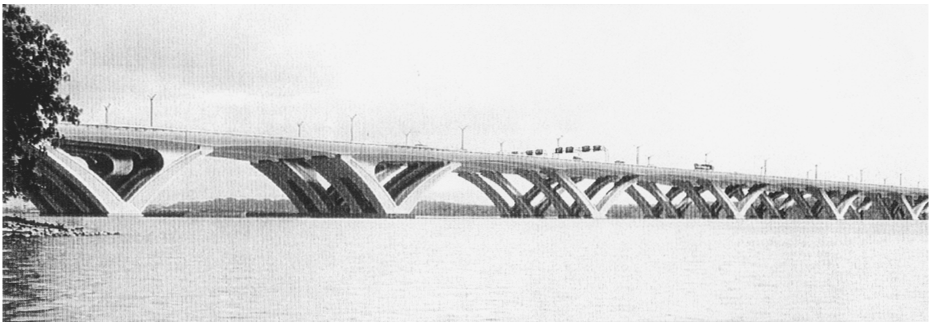

FIGURE 3.16 The competition-winning design for the new Woodrow Wilson Bridge over the Potomac River at Washington, D.C.

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