Innovation and Aesthetics

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Throughout engineering history, innovation and aesthetics have been intertwined. The introduction of new materials inspires the creation of forms that exploit their structural capabilities. These forms generate new aesthetic responses and create new opportunities for aesthetic pleasure. Although the acceptance of new ideas and forms is often slow, new materials and thus innovations are constantly on the horizon. Eventually the public recognizes and appreciates the beauty of them. Thomas Telford proved this with his development and use of iron. Telford's breathtaking proposal for a cast iron bridge in London was denied, but by the mid-19th century his ideas were standard for major metropolitan areas. Today we look forward to a similar but, it is hoped, faster acceptance of the innovations made possible with high-performance steel, high-strength concrete, and composites of the two. Furthermore, with the new load and resistance factor design (LRFD) specifications, designers will have greater flexibility in creating more efficient and aesthetic structures. With today's methodology and experience, it is possible to provide engineering solutions to issues tailored to the specifics of the bridge at hand. The challenge for designers of these structures is to develop forms that exploit and display the inherent advantages of laciness and transparency while at the same time addressing modern criteria of simplicity and the expression of structural forces. The structures that result will evoke new aesthetic reactions. We will see then how long it will be this time before general public acceptance follows.

Throughout engineering history innovation and aesthetics have been intertwined. The introduction of new materials inspires an engineer to create forms that take full advantage of the structural capabilities of the new materials. These forms generate new aesthetic responses and create new opportunities for aesthetic pleasure. The most creative engineers recognize the aesthetic potential of new forms and exploit their characteristics for the same purposes that an artist would, to maximize their emotional and aesthetic impacts. Yet, because of the general public's reluctance to change, many new technologies do not immediately get the amount of use they merit, and often, innovations are left to emerge only slowly as practical solutions to modern problems. As they emerge, artists and art critics see them and adopt the aesthetic ideas into other areas of art. Then new forms become generally accepted.

The history of innovation in structural art is a series of these cycles. Each cycle begins with the acceptance and support of a standard method of bridge construction both by the public and, as the methodology is refined, by institutions such as the fine arts commissions and the academies of art and by critics of art and architecture. Then a new material or technique is introduced, and a particularly creative engineer with the vision to understand the opportunities presented creates a new type of structure. The new form is often unfamiliar and therefore seems to violate the accepted norm.

Consequently, the public and the art establishments resist the change, and its use is restricted to out-of-the-way places where the art establishment is not involved in the decision making and the economy of the structure is the overriding political concern.

Then the new technique begins to attract supporters. People experience a new type of aesthetic reaction and consequently recognize a new type of beauty in its form. As the more forward thinking critics see its virtues, the new technique is invited into the centers of major cities. In time its acceptance grows and the innovation becomes the new standard for design and, in many cases, an inspiration for other art forms.

New materials and thus innovations are constantly on the horizon. Today we look forward to high-performance steel, high-strength concrete, and composites of these materials. In addition, we can anticipate innovations in design encouraged by the change to load and resistance factor design (LRFD) specifications. Although we may not be able to predict the specifics of the bridges that these materials will produce or who will bring these new potentials to the fore, we can expect the cycle to continue. There will be a new type of structure, probably in an out-of-the-way place, greeted by anguished criticism from the art community. Then, over time, acceptance, widespread use, and perhaps even a spin-off into other realms of art will emerge. The speeding up of modern life and an increasing acceptance of modern materials and techniques have reduced the time for each cycle, but the basic cycle remains.

By taking a look at examples from the past and by thinking about the structural capabilities of the new materials in the light of this history, we can develop some ideas about how the introduction of these new materials will result again in new structural as well as aesthetic ideas.

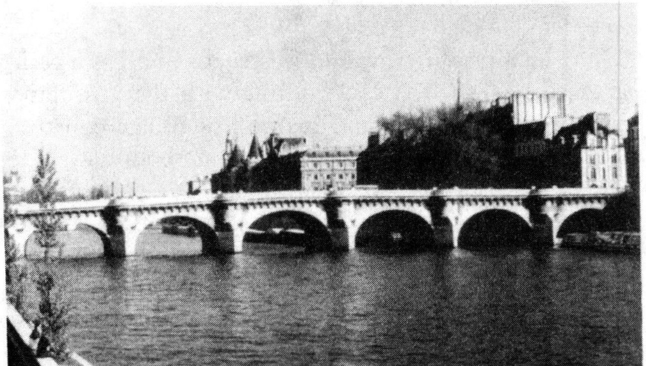

FIGURE 1 Pont Neuf, Paris, 1736.

EXAMPLES FROM THE PAST

Bridge engineering for many centuries was dominated by the semicircular stone Roman arch, and bridges built as much as 15 centuries apart looked remarkably similar. The Pont Neuf in Paris, built in 1736, has nearly the same elevation as bridges built in Rome more than 1,400 years earlier (Figure 1). In all of Europe, for centuries the "proper" way to build an important bridge was to build a monumental stone arch.

Iron and Steel

The modern history of engineering begins with the introduction of cast iron and wrought iron as structural materials in the late 7th century. The first structural artist to recognize the possibilities of these materials was Thomas Telford, the founder of the civil engineering profession. Telford realized that the material provided an opportunity for different forms and different methods of fabrication. His Craiglechie Bridge in Scotland puts most of the material into a flat, segmental arch and then connects the arch and the deck with a lightweight lattice of bars. This design, with its lightness, transparency, and relative horizontality, was immediately accepted for structural reasons and became the structural standard for metal bridges from that point forward (Figure 2).

Aesthetic acceptance took longer. People who were raised all their lives on the solid stone masonry of Roman arches were uncomfortable with the tracery of the Craiglechie Bridge. Consequently, Telford's breathtaking proposal for a cast iron bridge in London with a 600-ft span was denied (Figure 3). Telford and his metal bridges were relegated to the outer reaches of the British Isles. It was not until the mid-19th century that bridges of this form and material were built in major metropolitan areas.

FIGURE 2 Craiglechie Bridge over Spey River, Thomas Telford, Elgin, Scotland, 1814.

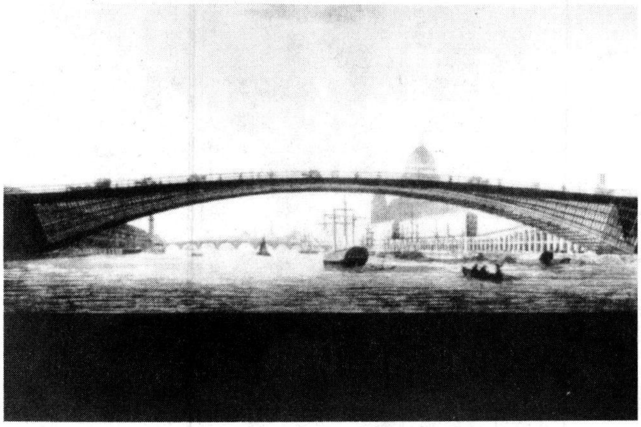

FIGURE 3 Telford's proposal for a cast iron London bridge, 1800.

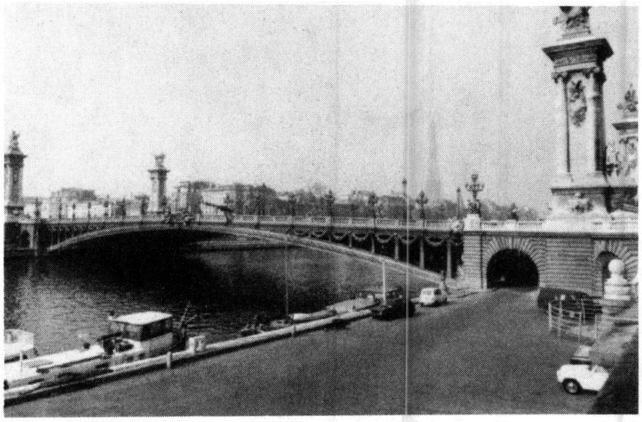

FIGURE 4 Pont Alexandre III, Paris, 1899.

The Pont Alexandre III in Paris (Figure 4), in contrast to the Pont Neuf (Figure 1) just a few meters downstream, shows how far the basic form eventually evolved. Here it is very decorated, but the flat arch and lightweight spandrel connections, as introduced by Telford, are easily discernible.

The next structural artist to come on the scene was Gustave Eiffel. His railroad bridges in southern France, which took advantage of the strength of the new material, steel, also introduced new shapes designed to more efficiently withstand or reduce the force of wind. The towers and arch rib of the Garabit Viaduct are widened at the bottom to provide a stronger base to resist horizontal wind forces. The bracing takes advantage of the strength of the material to reduce member thickness and thus reduce the area on which the wind is acting (Figure 5).

Eiffel's way of thinking found its ultimate expression in his famous Tower. The Tower, in spite of the initial grumbling of academic critics, found fast acceptance both with the public and with the art community [Figure 6 (*left*)]. It introduced a whole new way of seeing not only structure itself but space and time as well. The process of rising through the structure on the elevators and viewing the city from constantly changing angles through the lacework of structural members inspired a whole new approach to art. The Cubist movement, aimed at showing the same objects from multiple vantage points and at multiple points in time [Figure 6 (*right*)] grew out of this new way of seeing things.

At about the same time John Roebling applied his structural artistry to another new material, steel wire, developing new and improved structural forms. The Brooklyn Bridge represents the most complete and successful example of his vision [Figure 7 (*left*)]. Like the Eiffel Tower, this structure introduced new aesthetic themes and captured the imagination of the public and the art community. As one moves across the bridge one sees the city from various vantage points, often through the veil of the stays and suspenders, and with a constant sweep of the main cables and deck curves interacting with each other. Artists have fastened onto these images, and the bridge has been a theme of many paintings, photographs, sculptures, and even poetry [Figure 7 (*right*)].

Concrete

The introduction of reinforced concrete in the late 19th century presented additional opportunities. The master in this medium was the Swiss engineer Robert Maillart. He began with the forms of stone masonry very much in mind. However, as he began to understand the tensile capabilities of the material, he began to carve away the areas of structure that were not necessary to support

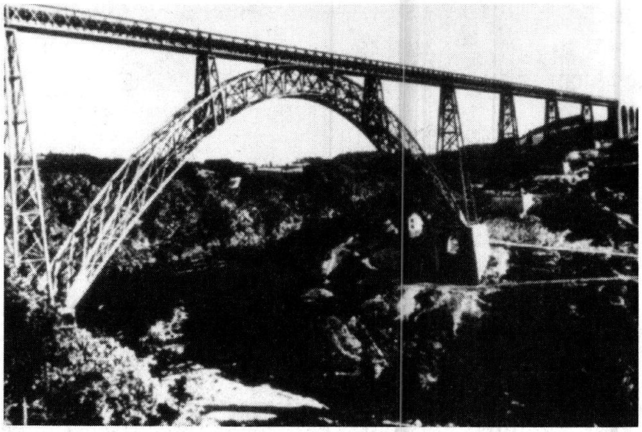

FIGURE 5 Garabit Viaduct over Truyère River, Gustave Eiffel, St. Flour, France, 1884.

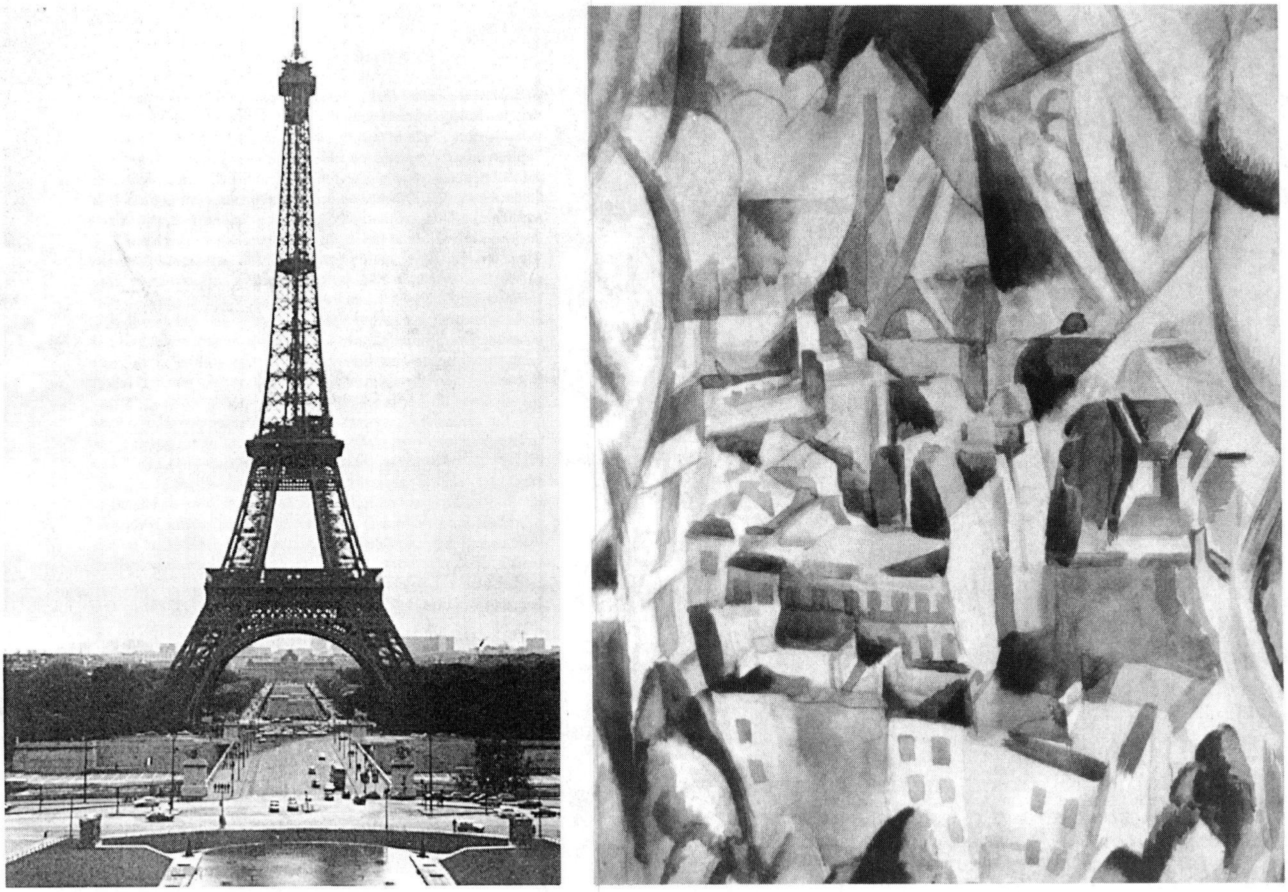

FIGURE 6 *Left,* **Eiffel Tower, Gustave Eiffel, Paris, 1899.** ***Right,*** **Cubist painting of Eiffel Tower.**

the load, until he had created very thin arch structures and three-hinged arches. Both represented new, dynamic forms of the arch bridge. His most famous structure, the Salginatobel Bridge in Switzerland, has become an icon of modern art (Figure 8).

The next great innovation in technique was prestressed concrete. The economic and structural capabilities of this material encouraged the move away from arch forms to girder forms. The girder form is most efficient when its depth changes to reflect the concentration of forces at the supports. The result is a haunched girder. These have been built as both cast-in-place and precast bridges. The masters of this form, such as John Muller and Christian Menn, have found ways to refine the materials into structures of outstanding grace (Figure 9).

The combination of higher-strength concrete and higher-strength steel strand has made possible the stayed girder concept. These new structures have been refined into very attractive bridges that, as in the past, have captured the public's imagination. The Tampa Skyway Bridge is now the accepted standard in the popular imagination for a "signature bridge," and communities all over the country are asking for one like it, whether or not the situation lends itself to this type of structure.

Menn has further refined the use of concrete and high-strength steel strand into a structure that follows a horizontal curve. His Ganter Bridge in Sweden encases the stays in concrete to allow them to follow the curvature of the roadway (Figure 10). It has taken its place alongside the Salginatobel Bridge as an icon of 20th century technology and structural art.

All of the aforementioned designers and designs have a number of things in common. None of these engineers were pursuing art for art's sake when they developed their works. None depended on the addition of unneeded decorative materials for their effects. All were built under the pressure of economy and efficient use of resources and had to respond to the fabrication techniques and materials available. All continue to withstand their assigned loads many years after their completion. Finally, by expressing in the form of the structure the forces on it and the materials it was made of, the engineers found ways to produce bridges that are works of art.

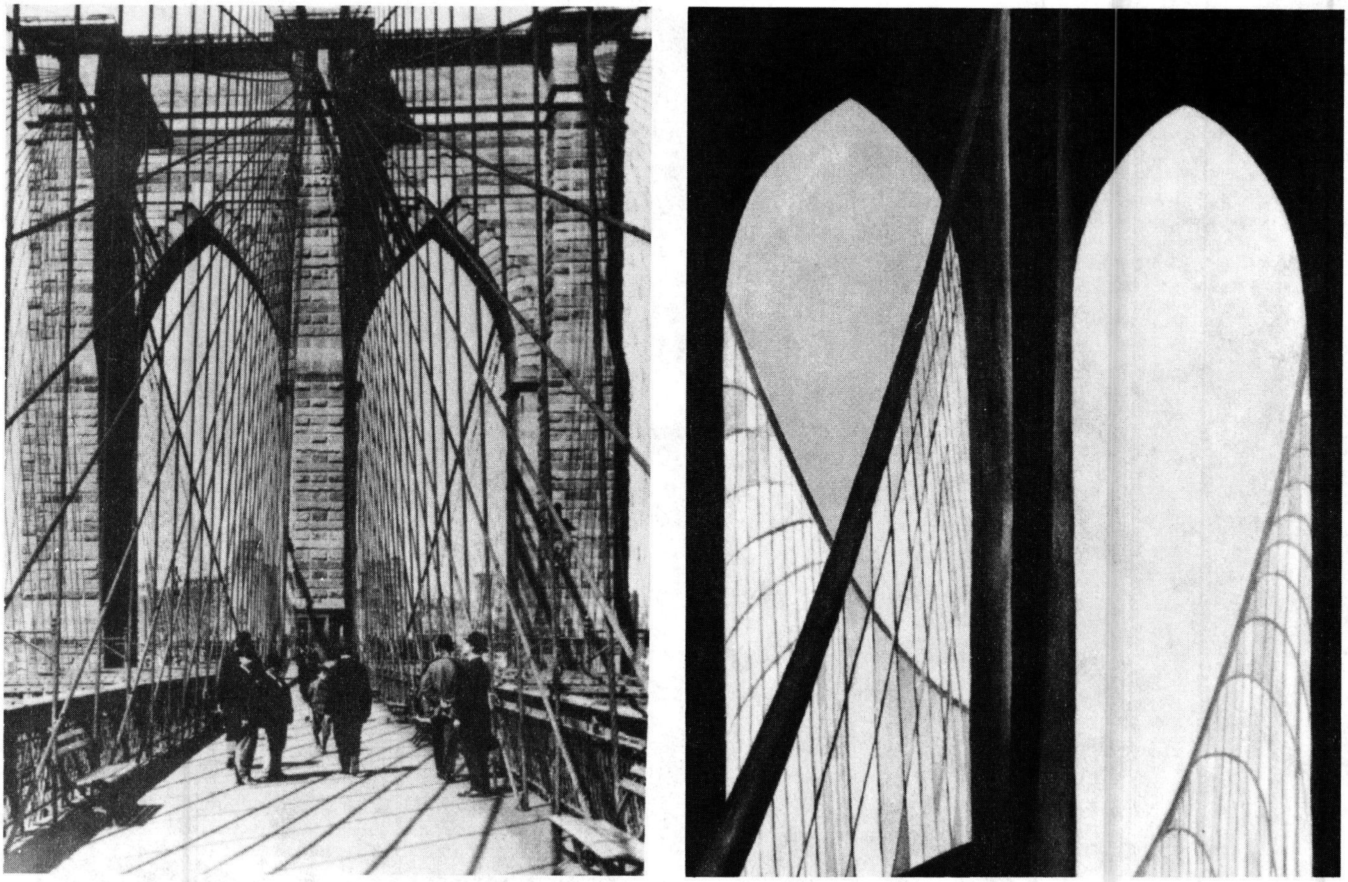

FIGURE 7 *Left*, **Brooklyn Bridge, John Roebling, New York, 1886.** ***Right*, Brooklyn Bridge in art, Georgia O'Keeffe.**

FIGURE 8 Salginatobel Bridge, Robert Maillart, Switzerland, 1930.

Expectations for the Future

What kind of innovations are on the horizon for bridges? With the potential of high-performance steel, high-strength concrete, and composites of the two, coupled with the flexibility of the LRFD specifications, many possibilities exist.

High-Performance Steel

High-performance steels are steels with improved ductility and weldability. They will make field welding more practical and will reduce concerns about fatigue and fracture-critical fabrication. Consequently, designers may once again become interested in truss and tied-arch bridges. However, as these forms regain popularity, they will be subject to aesthetic review. Previously, with their intricate and apparently weighty systems, trusses

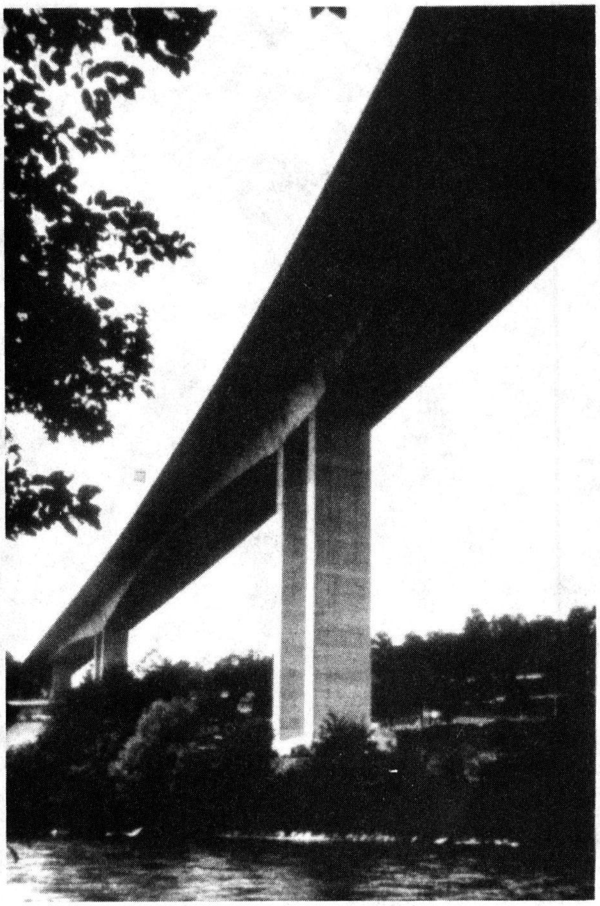

FIGURE 9 Felsenau Bridge, Christian Menn, Bern, Switzerland, 1974.

FIGURE 10 Ganter Bridge, Christian Menn, Switzerland, 1980.

had earned the reputation of being the ugly ducklings of the bridge world. Now, with the use of high-performance steels, there is a lacy quality with truss bridges that can be very attractive (Figure 11).

The key to success with truss bridges is to arrange the members in some easily recognizable pattern so that the eye can read the pattern and understand the logic involved. Although the equilateral triangles of the recently built Wando River Bridge provide one successful example of this approach (Figure 12), the fanned members of the famous Firth of Forth Bridge provide a unique pattern of their own (Figure 13). When they are seen in elevation, it appears that they are all arranged to intersect at two points in space, the compression members at a point below the bridge and the tension members at a point above the bridge. The tension members are laced steel structures and almost disappear at a distance. The compression members are tubular and have the appearance of solidity consistent with their function in the structure.

High-strength steel has allowed for innovations in the design of arched bridges as well as in the design of truss bridges. By using higher-strength steel and new steel building techniques, the appearance of arches could be improved. The Swiss engineer Santiago Calatrava has produced a striking proposal for an arched bridge in which tubular steel members reflect the light, lacy appearance of trussed structures (Figure 14).

Tubular members have inherent advantages for compression members because of their stiffness. They can also be more attractive because their stiffness allows for the use of thinner members, thus reducing the visible surface area and making them easier to understand than wide flange members. Finally, they offer less wind resistance than rectangular members.

Although in the past it has been difficult to calculate the stresses at the intersections of tubular members and to fabricate these intersections, computerized design can now facilitate both of these issues. In addition, the experience gained in the fabrication of drilling platforms with tubular members for the oil industry should be transferrable to bridge construction as well. Therefore, the improved weldability of high-performance steel in combination with improved welding techniques and

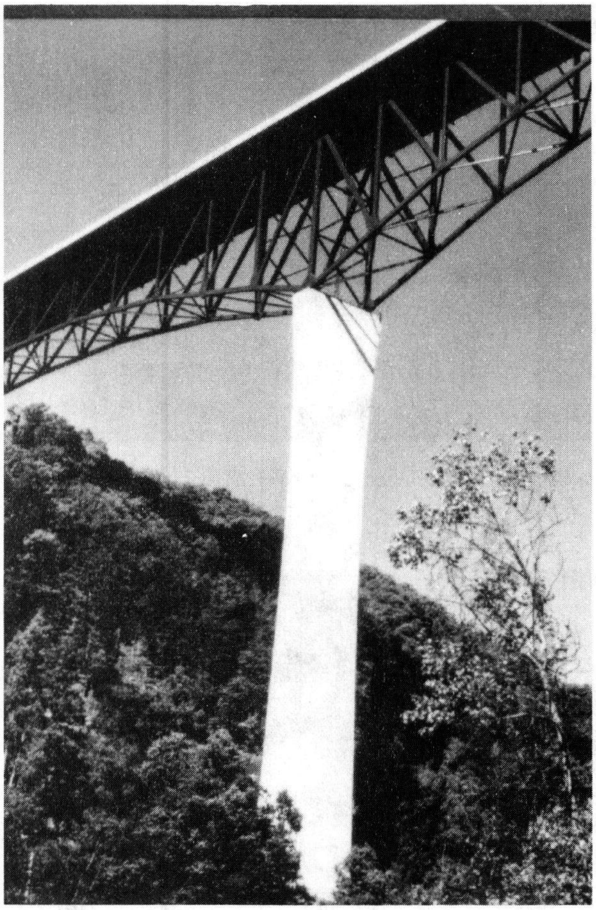

FIGURE 11 Glade Creek Bridge, West Virginia.

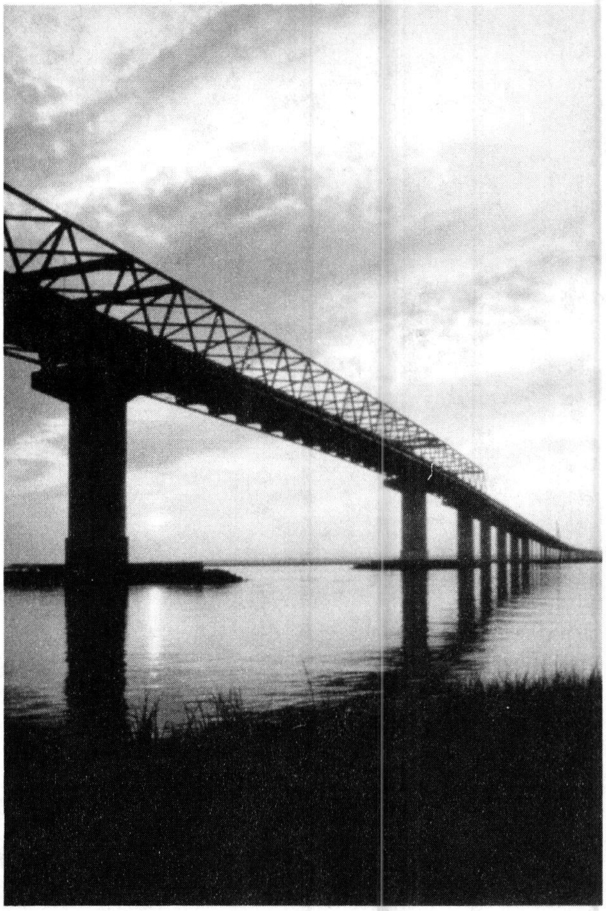

FIGURE 12 Wando River Bridge, South Carolina.

computer-driven machinery makes the use of tubular steel members more feasible.

Tied-arch bridges should also make a comeback with high-performance steels because it makes the fracture-critical tie less of a concern. The I-255 bridge over the Mississippi River illustrates the slenderness that can be achieved with this familiar but now rarely used structural type (Figure 15). If there is a return to these types of structures, it is hoped that they will be built with similar grace.

Finally, the new weldability of high-performance steel may make it more economical to design steel structures as thin and light and continuous as many contemporary concrete structures. The key is to be able to economically fabricate structures with integral cross girders.

The typical problem with steel girders is the need to support and brace every single girder, which requires a heavy concrete pier cap as well as a plethora of understructure bracing. As one attendee at a public hearing put it, "Looking under a steel bridge is like sticking your head under an old car." Integral cross girders, as

FIGURE 13 Firth of Forth Rail Bridge showing varying angles of the diagonals.

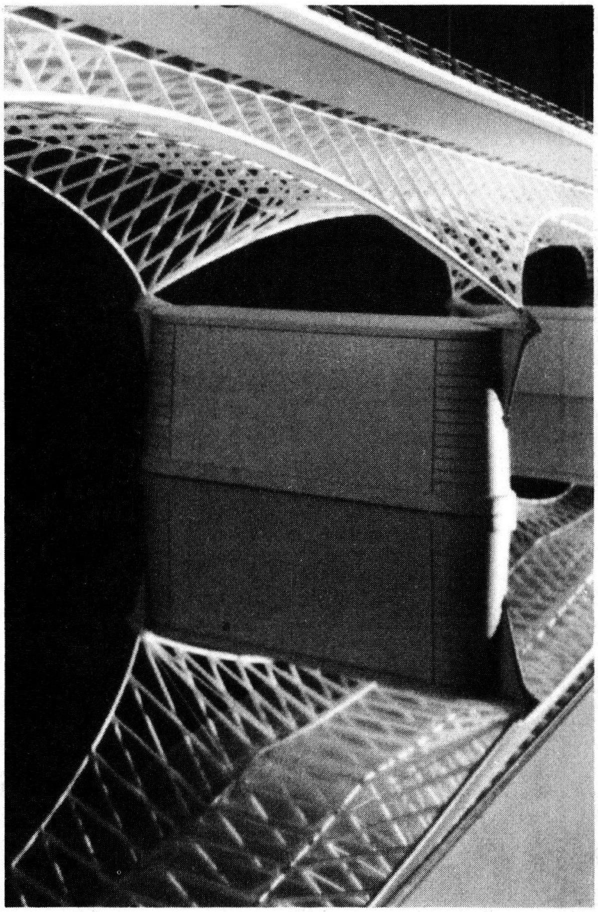

FIGURE 14 Proposed truss arch for Basel, Santiago Calatrava.

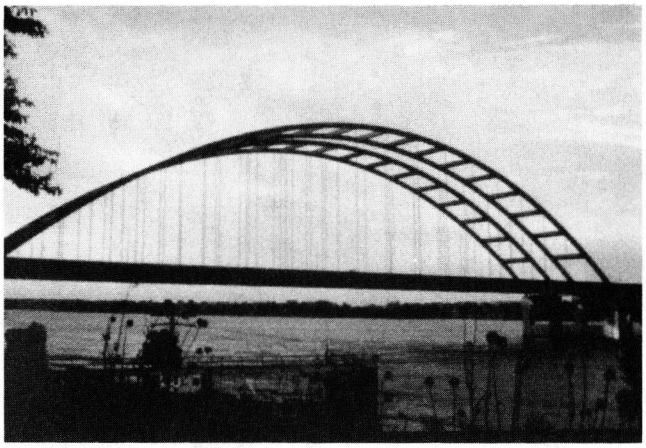

FIGURE 15 I-255 tied arch over Mississippi River.

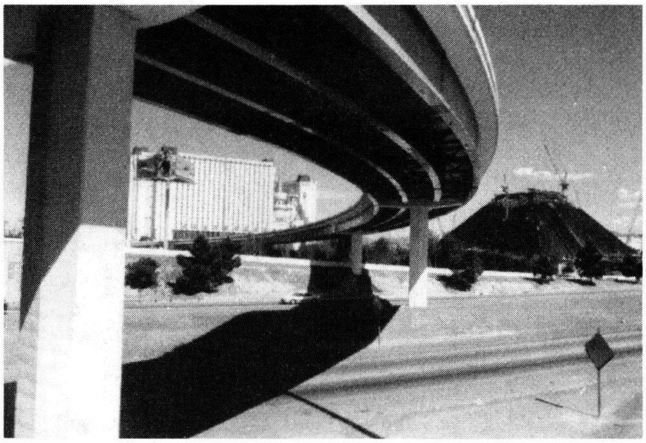

FIGURE 16 I-15 Tropical Boulevard overpass, Las Vegas.

in the I-15 Tropical Boulevard flyover in Las Vegas (Figure 16), eliminate the heavy pier cap, simplify the main lines of the structure, and allow it to directly reflect the lines of movement of the ramps overhead. The goal is the same kind of clean lines and simple structure that have been available in concrete structures.

High-Strength Concrete

Simultaneously with high-performance steel, innovations are appearing in the area of concrete strength and in techniques for joining precast concrete members.

The ability to achieve higher concrete stresses will result in thinner cast-in-place and precast members with higher levels of prestressing. Ontario has built hundreds of excellent post-tensioned concrete structures, but the designs have been limited by the strength of the available concrete. The development of reliable higher-strength concrete would allow continued development of such thin continuous concrete structures (Figure 17).

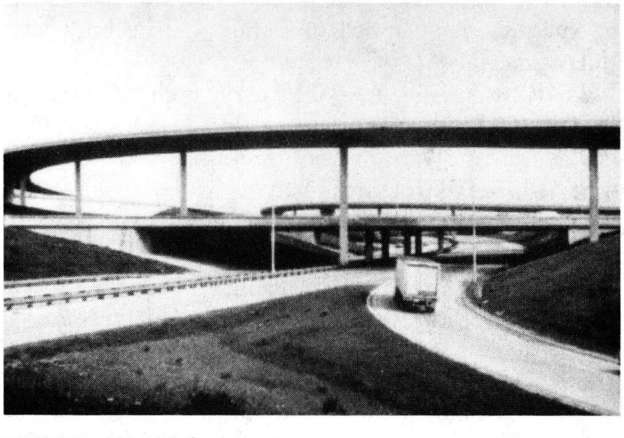

FIGURE 17 Highway 404 ramp, Toronto.

Furthermore, the development of higher-strength concretes should allow for longer spans and more economical construction of cable-stayed bridges. The integrity of these bridges depends on the balancing of compressive strength and weight within the deck, and therefore depends on the concrete composition of the deck. The advantages of higher-strength concrete in bridge decks are not limited to cable-stayed bridges alone. The same concerns that governed the development of cable-stayed bridges now govern the development of new types of suspension bridges, such as this self-anchored single-cable design from Japan (Figure 18).

One of the main goals in the development of precast concrete construction is to enable engineers to design longer spans. However, joining precast segments at the piers, the point of maximum moment, has proven difficult and expensive. In order to provide full live load continuity engineers and designers must continue to develop new techniques. Experience in Kentucky and Colorado shows that the joining of continuous precast beams at their inflection points simplifies the process somewhat and allows significantly longer spans for the same depth of member (Figure 19). Methods under development at the University of Nebraska with expansive concrete also show promise for gaining full live load participation in precast concrete members.

LRFD Specification

Another area that may result in some change is due to the move to LRFD specifications. Recently, design has been dominated by guidelines about girder spacing, bracing spacing, and other parameters that came out of the current AASHTO specifications. In many cases these requirements aided designers with problems that are difficult to calculate without computers.

The new specifications permit more flexibility, provided that the designer is able to demonstrate the effects of his or her design. With today's methodology and recent experience with bridges of various types, it is now possible to provide engineering solutions to issues that are tailored to the specifics of the bridge at hand. These solutions in turn have the potential to significantly improve bridge appearance.

For example, wider girder spacing requires more robust girder sections that, taking into account the stiffness provided by the slab itself, make bracing less necessary. This will result in a cleaner underside and make girder bridges more attractive for areas where there is pedestrian traffic underneath. Wider girder spacing also allows additional overhang, which in turn provides a major improvement in the appearance of girder structures. Larger overhangs create larger shadow lines, breaking the bridge up into three horizontal stripes: light, dark, and light. The stripes make the bridge appear thinner than it actually is.

Recent experience with steel box girders shows a similar result. Steel box girders are inherently more at-

FIGURE 18 Hokko Bridge, Japan.

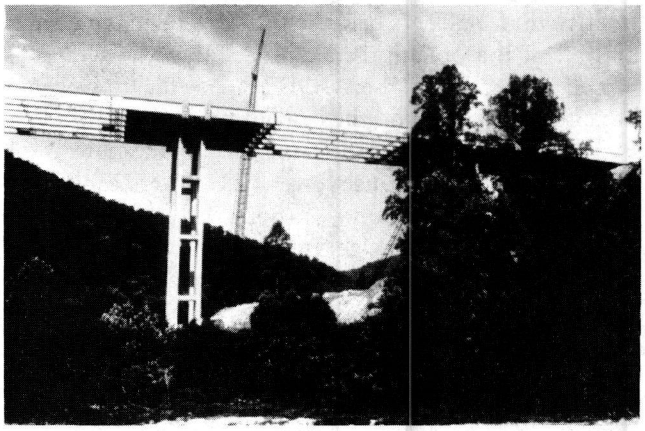

FIGURE 19 Shelby Creek Bridge, Kentucky.

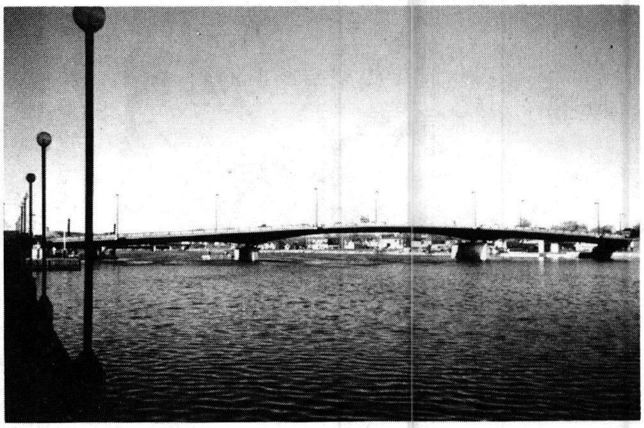

FIGURE 20 Dundas Street over Trent River, Trenton, Ontario.

tractive than I-girders because they can be made thinner and all of the bracing is enclosed. However, when designed according to the AASHTO specifications many boxes are required and the bridges become costlier than I-girder bridges. Given the flexibility of the new specifications, bridges that use fewer box girders can be developed. This saves money in both the fabrication and construction of the bridge. In addition, with fewer box girders the deck overhang is again increased, leading to an apparently thinner and more attractive structure (Figure 20).

CONCLUSION

Some of the improvements described here represent a continuation of the development of contemporary innovations in, for example, girder bridges. We may expect that those changes will be greeted with approval and appreciation. However, other changes, particularly those that have to do with truss bridges, represent a return to structural types that some believed had been left behind because of their supposedly poor appearance. With these structures we may expect to see a recurrence of the cycle: new method, disapproval, grudging acceptance, and eventually, accepted practice.

The challenge for the designers of these structures will be to develop structures that exploit and display the inherent advantages of laciness and transparency in their forms while at the same time addressing modern criteria of simplicity and the expression of structural forces.

Beyond these ideas, the new materials offer the potential for structural forms as yet unimagined. We may see again new and exciting structural forms in our midst. We should attempt to welcome these innovations, seek to understand their aesthetic implications, and avoid the historical cycle of adamant disapproval, grudging adoption, and final acceptance.