The True Goals of Bridge Aesthetics

by
Frederick Gottemoeller, P.E., R.A.
Principal, Bridgescape LLC

Introduction

The public is taking a larger and rapidly growing interest in the appearance of their bridges, in other words, in Bridge Aesthetics. This interest stems from three things:

- Their dissatisfaction with the dreary, ordinary bridges provided by their transportation and public works agencies, made up of simple, standardized parts, girders, pier cap, columns, not particularly integrated with each other (Fig. 1),
- Their realization, from seeing attractive bridges in their travels here and abroad, that more attractive bridges are possible,
- The popularity of the Context Sensitive Design movement with its core value of creating transportation facilities better suited to their communities.

Figure 1. A bridge where absolutely no one paid any attention to appearance.

Transportation and public works agencies have responded to this interest by trying to improve the appearance of their bridges. Three different approaches have emerged:

- *Decorated Bridges*
- *Signature/Sculptural Bridges*
- *Structural Art*[1]

Unfortunately; the first two types are not based on sound engineering, and often lead to unnecessary and in some cases unreasonable cost, without necessarily leading to a better looking bridge. As a result the whole notion of improving bridge aesthetics gets a bad name. Only the third approach, structural art, arises out of engineering criteria and is the only one which leads to memorable bridges at a reasonable cost.

Decorated Bridges

The decorated bridge arises from the public's frequent reaction to the typical modern bridge. As a result of seeing too many bridges like Figure 1, many members of the public have come to believe that it is not possible to make a modern bridge look good. So, they have decided it is best to cover the bridge up so that it looks like something else, perhaps an old bridge previously at the site or nearby historic buildings. The most frequent response is to take an ordinary bridge and add some vaguely historical detail. This approach gains strength when an old bridge is being replaced; public can't imagine that a good-looking contemporary bridge is possible, so they want the new bridge built to look like the old bridge. A typical strategy is to festoon the bridge with "historic" light poles. It's almost as if people think that no one has designed a decent light fixture since the nineteenth century. It looks particularly bad when the bridge itself is clearly a modern form, such as a haunched box girder, because grafted-on historical detail fit doesn't fit the modern form.

And that is the basic problem with the decorated bridge: cost gets added, but the result is something that is neither historical nor contemporary; it is some weird mixture of the two. So, the bridge costs more but there is little or no improvement in its appearance.

[1] The term was originated by David P. Billington of Princeton University. His ideas have influenced much of the analysis herein.

Fig. 2. Adding historical detail to an ordinary bridge

This is a problem often faced by architects. Washington, D.C. is famous for trying to get new buildings to fit into the context of the historical buildings around it. A new office building was recently opened there with a distinctive modern appearance. Many criticized it for not "fitting in". But, here's what the architectural critic of the Washington Post, Benjamin Forgey, had to say about it: "This design is responsive to its environment. It is 'historically contextual' in that it celebrates its own historical period, our time, instead of pining after some long dead 19th century style." When these questions arise for bridges, the public should be offered a choice of a contemporary memorable bridge, a bridge of our time, rather than automatically settling for an ordinary bridge with historical decorations.

Signature/Sculptural Bridges

Then there are the locations where the public is already interested in a memorable contemporary bridge. It is typical for people who support such things to also believe that engineers can't be trusted to make an outstanding bridge, and so they need to bring in an architect or sculptor or someone like Santiago Calatrava, who is both, as well as being an engineer. Since such designers will not be bound by budgets or engineering logic, people begin to think they have to throw huge amounts of money at the bridge to get what they want. The Sundial pedestrian bridge in Redding, CA. cost $20 m. The contractor said it is not bridge but a piece of sculpture. The reason is that is even though Calatrava is also an engineer, he takes an anti-engineering approach to design. An engineering approach to design is to make the forces follow the simplest and most direct route to the ground. Calatrava's approach is to make forces go around corners, to take the most complicated and least direct route to the ground, and that inevitably adds cost.

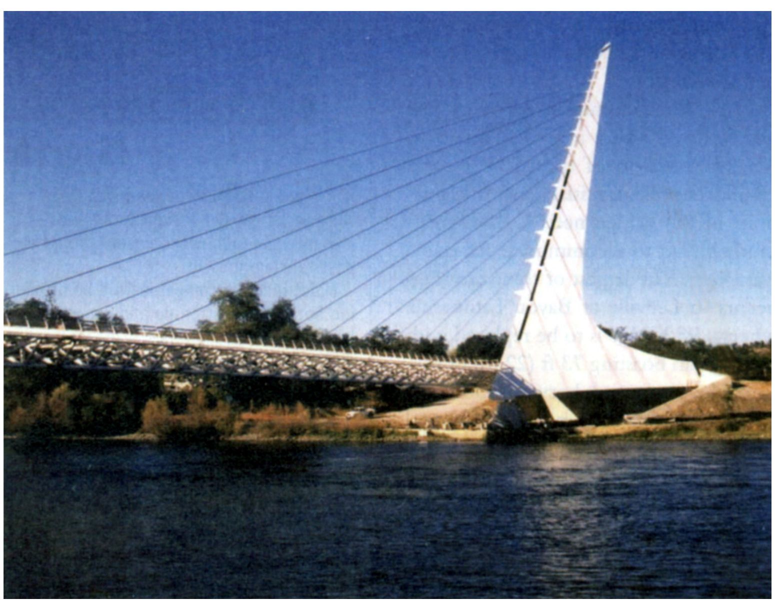

Fig. 3. The Sundial Bridge

Consider the problem of dealing with the horizontal forces of the stays at the top of the tower. Calatrava's answer is to turn the tower into a big cantilever, a large moment arm, producing a huge moment at its base (Fig. 4). Resisting this moment requires much material and complicated fabrication. Consider let's an engineer's approach to the same problem; if there is a cable pulling on one side of the tower, the simplest solution is to balance it with a cable on the other side pulling in the opposite direction (Fig. 5). There is then no moment at the base of the tower. The tower becomes much simpler and easier to erect. An example shown below, the Liberty Bridge in Greenville, SC (Fig. 13), uses this approach. In my opinion, it is as attractive if not more attractive than the Sundial Bridge, and it cost much less.

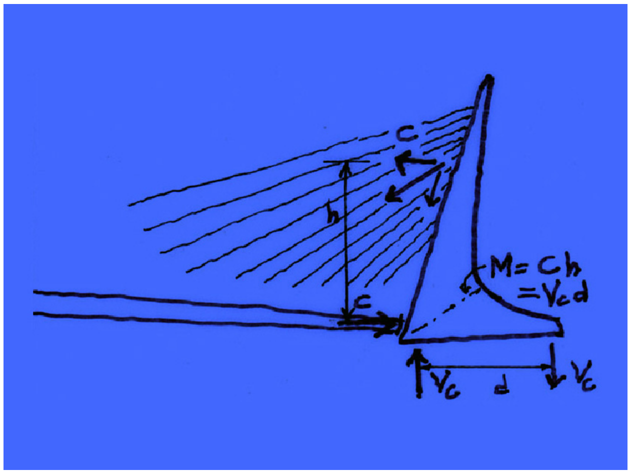

Fig. 4. Forces on the Redding Tower

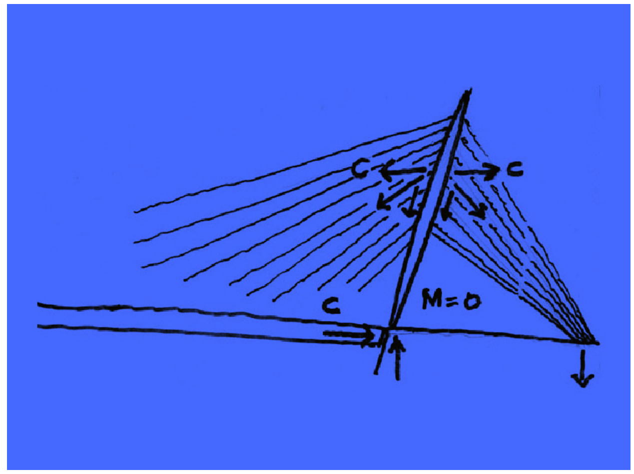

Fig. 5. Forces on an Alternative Tower

It may be acceptable to spend money on sculptural effect if it is private money, as it was in Redding. If a wealthy patron wants to buy a piece of sculpture the size of a pedestrian bridge and put it in a city park, it is hard to argue against it. But what if it's public money, and it is a bridge the size of the east span of the San Francisco Bay Bridge (Fig. 6). The bridge will connect Yerba Buena Island to Oakland, replacing an existing secion that does not meet modern earthquake standards.

Fig. 6. Proposed East Span of the San Francisco Bay Bridge

It is a self-anchored suspension bridge, proposed for a location that met none of the engineering criteria for such a bridge, that was indeed the worst possible place to put a bridge of this type. The type was selected through a political process based solely on visual considerations. The notion was that San Francisco has two landmark suspension bridges, so Oakland should have one too.

Why is the design such a bad idea from an engineering point of view? The basic problem is foundation conditions: the site is underlain by hundreds of feet of bay mud (the light brown material in Fig. 7). That meant a conventional suspension bridge is not possible, because there is no way to build the conventional anchorage required for the suspension cables. A self-anchored suspension bridge solves that problem, because the cable forces are resisted by the deck structure. Unfortunately, with a self-anchored suspension bridge both deck and cables have to be in place before the bridge is self-supporting. The deck is usually built on

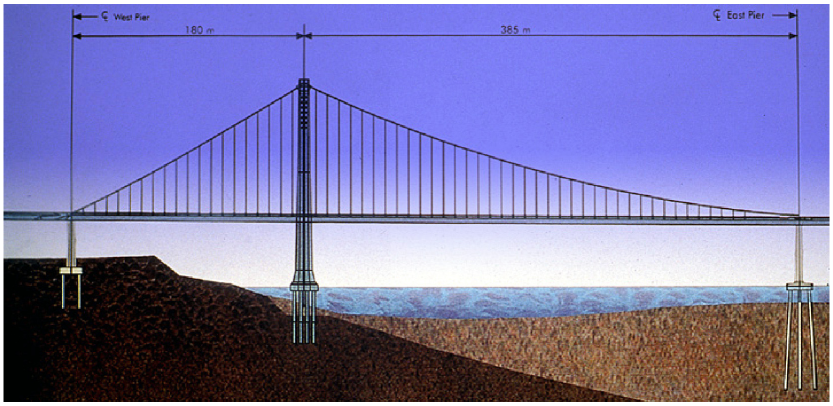

Fig. 7. Foundation Conditions

falsework, then the cables added. But, then the problem of the Bay mud comes up again, because that is all there is to support the falsework. So, the falsework becomes very expensive.

When CalTrans took bids on the bridge several months ago, the sole bid was $620 million over the $780 million estimate. At first, Governor Schwazneger pulled the plug on it and told the designers to find something more economical. Then, apparently for unrelated political reasons, he decided to let the bridge proceed. Now a frantic study is underway to find ways to reduce the cost.

Both of these bridges started from forms based on preconceived visual goals, not engineering criteria. Both cost a fortune, and both went through periods when it was doubted that they could be built at all.

Fig. 8. Maillart's Salginatobel Bridge

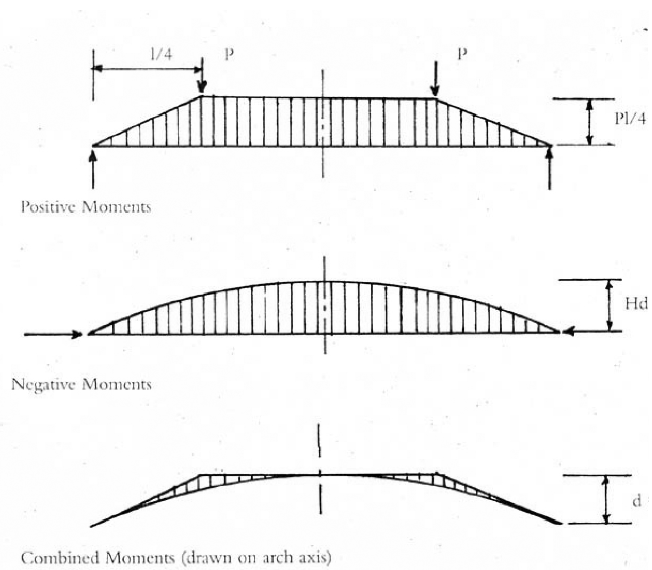

Fig. 9. Salginatobel's Moment Diagram

Structural Art

Structural art results when the form the bridge is based on engineering criteria, but with the understanding by the engineer that engineering criteria properly include more than efficiency and economy. Elegance must also be a criterion, considered equally with the other two. In other words, the engineer must also take responsibility for aesthetic quality.

The classic example of structural art is Robert Maillart's Salginatobel Bridge in Switzerland (Fig. 8). We know it is art because the artists themselves have said it is, at a show in 1949 at New York's Museum of Modern Art. David Billington's analytical drawing of the moment diagram (Fig. 9) makes it clear how the forces on it influenced the form of the bridge.

A more recent Swiss bridge by Christian Menn, the Sunniberg Bridge (Figure 10) near the international ski resort of Klosters, Switzerland, is another excellent example of structural art. The bridge is clearly visible from Klosters. It is 526 m long, and the longest span is 140 m. The deck is 9 m wide curb to curb and carries two lanes. The tallest pier rises about 62 m from the valley floor to the deck. The pylons rise an additional 15 m above the deck, giving a pylon height to span ratio of 1:10 versus the 1:4 usually found in cable stayed bridges. Edge girders are about 1.07 m deep, giving a depth-to-span ration of about 1:136. These departures from the usual proportions of a cable-stayed bridge were specifically directed toward an explicit design intention/vision. The citizens of Klosters asked that the bridge be thin

Figure 10. Menn's Sunniberg Bridge

Figure 11. Pylon Shape

Fig. 12. Menn's Sunniberg Pier

and transparent in order to have as little visual impact on their valley as possible. In my conversations with Menn he has been quite clear that he began from that point. The selection of the basic elements, the thin deck and the low pylons, all stemmed from that request.

If Menn had sized the pylons as in a typical cable stayed bridge they would have projected 35 m above the deck. The tallest pylon would have been 97 m high. This would have brought the pylon tops roughly level with the windows of Klosters, which lies at the head of the valley. The short pylons stay well below this level. When viewed from most locations in Klosters they are hidden by intervening vegetation.

This solution of the aesthetic problem created some structural challenges. With a pylon height to span ratio of 1:10 the forces in the cables increased significantly. Pylons for typical cable stayed are relatively thin and therefore flexible. Unbalanced cable loadings under unbalanced live loads combined with thin pylons would have created significant pylon deflections and therefore significant girder deflections. In response Menn made the pylon thicker at the top to stiffen it against longitudinal deflections (Figure 11).

The pylon is rigidly connected to the deck and can thus also add stiffness to the deck. Because the bridge is curved the bridge deck can respond to temperature changes by expanding and contracting radially, carrying the piers along with it. This eliminates the need for expansion joints at the abutments. With no need for expansion joints the deck can be anchored at its ends. The deck can thus stabilize the pylon/piers longitudinally against deflection due to unbalanced live loads and laterally against wind and other transverse loads. The additional axial forces due to the low cable angles and the longitudinal stabilization of the towers puts relatively large axial forces into the deck and its edge girders, which were thickened near the pylons, where the axial forces are the greatest, to guard against buckling.

The pier/pylon must respond to a number of forces. The longitudinal restraint created by the deck and the footings creates longitudinal moments which decrease to a minimum at about one-third pier height and then slightly increase again as the pier nears the ground. Menn shaped the pier to respond to these moments. In the longitudinal direction the piers are

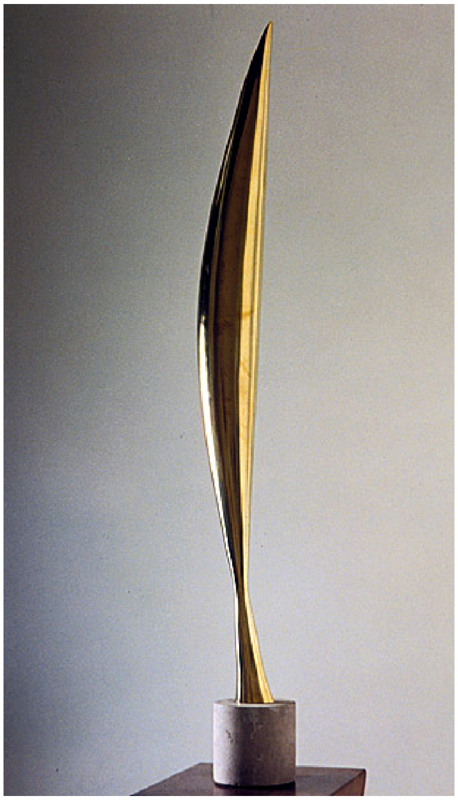

Fig. 13. Brancusi's Bird in Space

thinnest at a point about one-third of their height above ground and flare outward above and below that (Figure 12).

In the transverse direction additional moments are created in the pier/pylons by the lateral restraint of the deck and by the eccentricities between the points at which the cables attach to the deck and the pylons caused by the curvature of the bridge. The piers could not just be made solid. Some flexibility is required to allow them to move laterally as the deck expands and contracts. So Menn used a vertical vierendeel truss. The horizontal struts of the truss also stiffen the pier legs against buckling. The pylons are flared at the top to keep the cable stays clear of the curved roadway edges. Menn smoothly continues this flare into the pier legs below the deck, bringing the pier legs together so that they are half as far apart at the bottom as they are at the top, further reducing the forces in the pier legs caused by the lateral restraint of the deck. The pier legs themselves are hat-shaped in plan, giving them maximum stiffness against local buckling with a minimum of material, and creating a deep shadow line up the pier leg that make it look even thinner than it is.

But, it is not enough to get the structural elements right. Menn also turned his attention the details of its appearance. He refined the exact shape of the leg and the exact curve of the flare to get the most graceful appearance. In that endeavor he was seeking to tap the aesthetic pleasure that can be created by an attractive shape. The sculptor Constantin Brancusi also sought to tap the appeal of pure shape in pieces like his *Bird in Space* (Figure 13). The difference is that the engineer's shape must start from the requirements of his or her structure.

The result is an elegantly shaped transparent pier that allows views in all directions. In the overall view the thin deck seems to float above the trees, cradled by the towers. There are no embellishments, unless you call the pattern of construction joints on the piers an embellishment. All of the features that create the aesthetic impression arise from the shapes and sizes of the structural members themselves. And the shapes and sizes of the structural members arise from engineering considerations. A viewer can understand how the bridge works by studying the shapes of all the major elements.

Menn states the goal of Structural Art clearly in his book *Precast Bridges*:

> *"The visual expression of efficient structural function is a fundamental criterion of elegance in bridge design."*[i]

The cost of the Sunniberg bridge was 20m Swiss Francs in 1998. It was about 15% greater than that of the cheapest of the other bridge designs proposed for the site. The increase amounted to about 0.5%of the cost of the entire Klosters Bypass project. The canton engineer and the people of Klosters apparently thought that this additional money was well spent. Not only did it preserve one of their major assets, their scenic appeal, but it added another, "a magnificent monument to their tradition of bridge engineering"[ii].

Banzinger Bacchetta Partner of Chur, Switzerland did the detailed design for the Sunniberg Bridge, Switzerland based on Menn's conceptual design. More details of the analysis and design can be found in an article by Chelsea Honigman and David P. Billingon in the May/June 2003 issue of the Journal of Bridge Engineering.[iii] More on Menn's overall approach to bridge design and his other works can be found in *The Art of Bridge Design, A Swiss Legacy*.[14]

The search for structural art may be summarized as follows: Use the structural members themselves, shaped in response to engineering considerations, to both illustrate how they are functioning and create a memorable aesthetic impact. Success depends in part on the shapes as required by the forces involved. But through his or her choice of structural type and relative sizes, the engineer can steer those forces where he or she wants them to go, to develop a shape that meets his or her aesthetic vision. Once the basic shapes are determined by engineering considerations, the exact curve of the flare, the exact proportions of the cross struts and other features can be refined to achieve visual elegance.

Potential New Examples of Structural Art

Not many engineers get a chance to build a bridge near an international ski resort. But many engineers are asked to build a visually prominent bridge in an important location. A number of recent bridges demonstrate that their designers were well aware of their opportunity as well as their responsibility. All of the bridges bear indications of the search for structural art. Only time will tell whether posterity will judge that they have succeeded.

Liberty Bridge, Greenville, SC

Fig. 14. Liberty Bridge and Botanical Garden

This pedestrian bridge connects the two halves of Greenville's downtown above the falls of the Reedy River and a public botanical garden (Fig. 14). The approach to the tower design was illustrated previously in Figure 4. The bridge is curved in plan. It is about 400' long with a 200' main span. The suspension cable and suspenders are all on one side, and the towers are tied back by cables to ground anchors. The torsion in the deck is resisted by a circumferential cable below the deck acting through the frames of the steel stiffening truss (Fig. 15). It is a three dimensional pretensioned cable network, and is very stable.

Fig. 15. Liberty Bridge Structural

Thanks to its thin deck and spidery suspension system, the new bridge appears to float through the treetops. At the same time, the twin towers and suspension cable are visible from vantage points around the city, calling attention and drawing visitors to the public botanical garden, falls, and river. The bridge itself is an aerial amphitheatre, allowing visitors to enjoy the whole scene, something particularly appreciated by the elderly and handicapped, who have no other way to enjoy the garden and falls. In the 12 months since its opening it has become a valued landmark of downtown Greenville.

Schlaich Bergerman und Partners of Stuttgart, Germany, developed the design in a joint venture, Rosales Gottemoeller & Associates, which served as architectural/urban design consultant. The author was the engineer of record. The bridge rreceived the Arthur G. Hayden Award at the 2005 Pittsburgh International Bridge Conference.

95th Street Bridge, Redmond, WA

In size this is a relatively modest bridge but it occupies an important spot in Redmond. The designer used Y-shaped piers to reduce the span while giving the bridge a memorable shape. The same approach was carried into the railing which uses compatible, contemporary shapes to provide interest for pedestrians and nearby observers. Apparently, the designer felt he could engage people in the bridge without resorting to 19th century coach lamps.

Fig. 16. 95th Street Bridge

Fig. 17. Pier and Railing Detail

Puente de la Barqueta, Seville, Spain

The Puente de la Barqueta (Fig. 18) is one of three major bridges built as part of the infrastructure for Seville's 1993 Worlds Fair. It carries four lanes of traffic and two sidewalks over a span of about 550 feet. The unique tied arch design is innovative and sophisticated both structurally and visually. The single rib arch keeps the perimeter free of suspenders, giving bridge users unobstructed views up and down the river. It also appears light and graceful, carrying its load with a minimum of carefully shaped materials. The arch rib is a box section made of welded steel plates, with indentations that both stiffen the plates and create shadow lines that minimize the apparent thickness of the rib members. The details at the piers (Fig. 19) show how the forces are resolved into the tie and the piers. The bridge exudes grace and strength with calm dignity, in marked contrast to the visual histrionics of Calatrava's Alamillo Bridge nearby. In the author's opinion, this bridge will withstand the test of time, both as a structure and a work of structural art, better than its nearby neighbor. The bridge was designed by Juan J. Arenas.

Fig. 18. Puente de la Barqueta

Fig. 19. Tie Details at the Piers

Woodrow Wilson Bridge, Washington, D.C.

The Woodrow Wilson Memorial Bridge is the only Potomac River crossing in the southern half of the Washington, DC, metropolitan area. It carries the Capital Beltway, I-495, and the main north/south interstate route on the East Coast, I-95, across the river. Built originally with six lanes to carry 75,000 vehicles per day, it now carries 175,000 vehicles per day and is expected to carry 300,000 vehicles per day by 2020. The bridge includes a moveable span to accommodate ocean-going shipping to Alexandria and the District of Columbia. The bridge is visible from the White House and many other locations in Washington, and is considered part of the city's monumental core. The replacement of the bridge raised many concerns on the part of both community groups and review agencies about the visual and urban design effects of the replacement bridge.

The Federal Highway Administration, Maryland, and Virginia agreed to select the design for the bridge via a design competition. The competition used an approach similar to Maryland's successful 1988 design competition for the prize-winning U.S. Naval Academy Bridge in Annapolis. The design created by the Parsons Transportation Group (PTG) was declared the winner. The author was the urban design and aesthetic advisor to the PTG competition team.

One of the major criteria of the competition was that the bridge use arches or have an archlike appearance. Unfortunately, the foundation conditions at the site have very poor bearing capacities. The usual method of building a string of arches in these conditions is to carry the horizontal reactions from pier to pier until they reach the abutments. However, in this case, the moveable span interrupts the string at the navigation channel, where the foundation conditions are the worst. Building the structure as a string of true arches would have required the construction of sizable and expensive foundations at the moveable span.

The competition team came up with the answer to these interlocking and seemingly contradictory requirements: to build the bridge as a series of V-shaped piers supporting continuous haunched steel girders (Figure 20). With this system, the lateral forces on the piers are reduced to primarily the wind and seismic loads that would be present in any case. There are no arch forces. The arms of the V are curved, and visually interact with the soffits of the haunched girders to form a continuously curved line that emulates a series of arches. The V-pier requires a tension tie at the top, but the tie is placed between adjacent girders, so it is

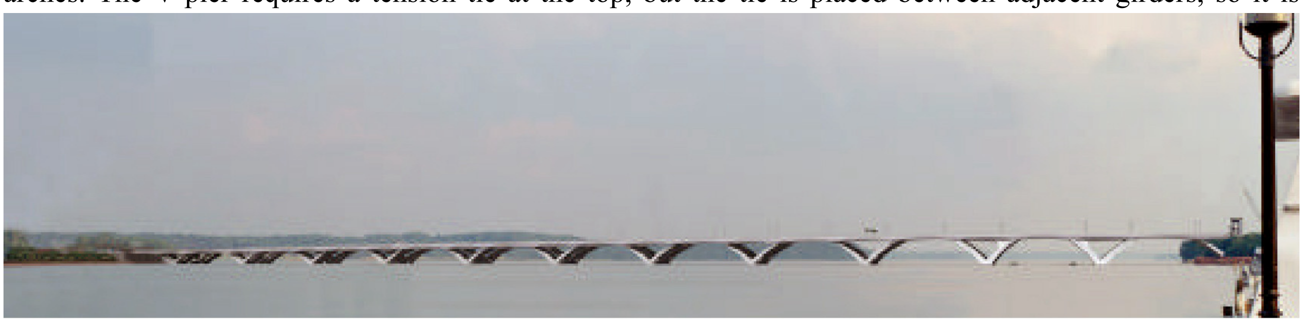

Figure 20. Woodrow Wilson Bridge

visible only from directly below. The V-shaped pier is adapted at the moveable spans to house a double-leaf bascule bridge. The result is that the moveable span is very similar in appearance to the approach spans. To pull the whole bridge together into one integrated theme, the railings, light poles, and sign structures were all conceived with a consistent family of contemporary shapes.

The jury's comments focused on its open appearance created by the large spans (up to 400') made possible by the V piers, and the way the moveable spans blend into the balance of the structures. The graceful curves of the V-piers were also recognized. One jury member likened them to the hands of Neptune reaching upward from below the water to support the structure. Also recognized were the relatively simple foundations, ease of construction, and relative economy the V-piers offer. The bridge was among the least costly of the seven designs submitted in the competition. It is expected that the eastbound bridge will be complete and open to traffic in 2006; anticipated completion of the entire bridge is in 2008.

Conclusion

This paper has tried to make three points:

- **Aesthetic Quality will not be gained by Decorating Bridges with Historical Add Ons**

This approach leads to a visual dead end: bridges that are neither historic nor attractive.

- **Aesthetic Quality will not be gained by Grasping for Sculptural Form Regardless of Cost.**

Jettisoning the criterion of economy does not automatically lead to a memorable form that will stand the test of time, but it does led to an inappropriate use of resources.

- **Aesthetic Quality will be gained by the Perfection of Engineered Form**

By pursuing equally the engineering criteria of effectiveness, economy and elegance designers can create Structural Art.

The French author Antoine St.Exupery described engineering perfection like this:

> *Perfection is finally achieved not when there is nothing left to add, but when there is nothing left to take away. It as if that line which the human eye will follow with effortless delight were a line that had not been invented, but simply discovered, had in the beginning been hidden by nature and in the end been discovered by the engineer.*

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[i] Menn, Christian, 1990. *Prestressed Concrete Bridges,* 2nd edition, ed. and trans. P. Gauvreau. Berlin.
[ii] Billington, D.P., 2003*, The Art of Bridge Design: A Swiss Legacy,* Princeton University Art Museum, Princeton, New Jersey., p. 192
[iii] Honigmann, C. and Billington, D.P., 2003, Conceptual Design for the Sunniberg Bridge, *Journal of Bridge Engineering*, American Society of Civil Engineers, Volume 8/ Number 3, Reston, Virginia