CASE STUDY OF BRIDGE DESIGN COMPETITION

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ABSTRACT: Some proof that politics and culture bear direct influence on innovation in bridge design comes from post-World War II Germany, which has promoted structural innovations through bridge design competitions. The design competition is a realistic policy tool for encouraging engineers to design structures creatively. This paper presents a case study of one recent competition for a bridge in Ingolstadt, Germany, to demonstrate in detail the competition’s organization. The paper explains the conceptual design process for the winning bridge, and gives a simple structural explanation that illuminates the fitness of the early design process for conceiving structural innovations.

INTRODUCTION

Although competition in the American bidding process for bridge contracts is the business of builders and remains primarily economic, European countries such as Switzerland and Germany have elevated modern bridge design to an artistic level by making the design process itself competitive. The jury of a design competition evaluates the appearance of a bridge in addition to its performance, buildability, and cost. Not only do design competitions ensure a high level of engineering quality in bridges, but competitions have also consistently fostered innovation in structural design.

 Shortly after World War II, German cities such as Cologne and Düsseldorf sponsored design competitions to rebuild several destroyed bridges over the Rhine River. These competitions are most famous for having produced the cable-stayed bridges, which became symbolic of a new era of light-weight construction. This era has brought forth many innovations in structural design, and it proves that the engineer’s creativity need not limit itself to the rare quest to conquer epic heights and distances.

An example of such innovative design is the North Bridge over the Rhine in Düsseldorf, which opened to the public in 1957 and became the first significant cable-stayed span to be completed in Germany. Engineer Karl Schaechterle had cooperated with architect Friedrich Tamms to produce a structure that broke decisively from the heavy-looking, monumental aspirations of the Third Reich to become an elegant symbol for the reconstruction of a democratic city. Although the most economical design of a tied arch was 22% less expensive than the winning cable-stayed design, the jury preferred the cable-stayed bridge on the grounds of its striking appearance.

Fifty years later, while German emphasis has shifted from projects that express the hopes of reconstruction to projects that respect a city’s precious green space, design competitions continue to produce the best bridges. Recently the city of Ingolstadt, Germany, held an invited design competition for a new three lane bridge over the Danube River. Ingolstadt officials expected that a first-place competition design would cost more than a common bridge for the roughly 100-m span. This increased cost, however, would total only a small percentage of the entire project cost and would pay for itself by producing a bridge whose beauty and interest would gain renown beyond the city limits of Ingolstadt.

This paper describes both the Ingolstadt design competition and the development of the winning design by the office of Schlaich, Bergermann and Partners (SBP) of Stuttgart, Germany. Innovative technically, the new bridge was first designed “by hand” with recourse to engineering intuition and simple calculations. This conceptual design process and the resulting construction procedure are depicted in summary.

COMPETITION ORGANIZATION

The considerations for a third bridge over the Danube River in Ingolstadt, Germany, began more than 25 years ago, though the idea for a design competition did not surface as a realistic option until early 1993. The city of Ingolstadt announced the competition in July of 1993 and awarded prizes in December of that same year. The bridge engineers and the city of Ingolstadt expect to complete the bridge by 1998.

Central to the debates concerning this bridge is the fact that one of its approaches must traverse the existing Luitpold Park, visible on the right-hand side of Fig. 1. Ingolstadt decided to construct this third bridge over the Danube to reroute traffic onto a road circling the outskirts of the city and thereby preserve the town’s intimate, pedestrian atmosphere.

The design competition in Ingolstadt originated after officials had made a thorough investigation both of the site and of possible bridge designs. These investigations, made for all German bridge projects, must consider structural form, historic preservation, and urban planning.

After the Bavarian government had approved the design conditions in 1992, the city explored five different designs, including an S-curved concrete hollow-box bridge, a cable-stayed bridge, and an arch bridge. Originally the hollow box gained the greatest favor, but eventually it raised serious doubts about the city’s attempt to deal sensitively with the disturbance of Luitpold Park. Ingolstadt finally decided that a design competition would best solve this critical problem.

The city organized a competition in early 1993 under the direction of the Bavarian authorities and in accordance with the 1977 rules for design competitions. Ingolstadt officials invited only five competitors and engaged them in a preliminary design process, which included engineers, architects, and landscape architects. Furthermore, in the fall of 1993, before entries were due, designers and city officials discussed design concepts over the course of two colloquia. The city used the colloquia both to discuss privately, with the entrants, issues having to do directly with their designs and also to discuss general design issues among the group of competitors. This unusual procedure fostered a good understanding among the entrants and city officials.

At the second colloquium on October 8, 1993, each entrant gave a private 15-min presentation to the jury, who then took 30-min to discuss the proposal with its representative. In addition, Ingolstadt provided each design office with the plans already proposed by the two offices previously involved with

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the project: (1) Preliminary documents produced by the office of Obermeyer; and (2) a design proposal submitted by the office of Mayr and Ludescher. The second colloquium also established that the jury would have the final say in ranking the bridges.

All plans were due on November 9, 1993, and models on November 16, 1993. The competition regulations laid out the official judgment criteria for the jury as follows:

- Form and integration into the environment
- Construction, materials
- Function of the different traffic axes
- Economy, maintainability

A prejury committee then compiled a report to aid the jury in comparing the five designs and to provide the jury with ready documentation on the original criteria. This report laid out the issues in two sections, one for the structure and the other for traffic.

1. Structure
   - Dimensions
   - Structural system
   - Superstructure
   - Supports in the river (if any)
   - Foundations
   - Further clarification
   - Method of construction

2. Traffic
   - Average bridge width
   - Connection to South Ring Road
   - Entrance to the Danube Rowing Club
   - Connection with the castle area (to the south)
   - Width of combined foot/bike path
   - Connections for foot/bike path

The report then gave each competition structure a two-page description including a diagrammatic representation of the structure. The jury used these summaries as working papers while they studied the plans and models submitted by each design office. On November 26, 1993, the jury met to discuss the designs and award prizes.

The first- and third-place designs shown in Fig. 2 attempted to integrate the bridge system with the park and city environ-

ment and, therefore, produced the most interesting jury comments. In his first place design, Jörg Schlaich radically separated pedestrian from automobile traffic by means of a slender deck supported on steel cables. The foot and bike paths rest on smaller cables lying on either side of the main cables, leading pedestrians along the contour of the hanging cables while automobiles travel across the flatter deck. Schlaich also substituted the bridge's S-curve plan with a straight crossing, skewed 20°; such a basic move, he argued, would allow for a more economic structure. Since Schlaich's design rose higher above the river than the city's original proposal, it met the approaches 4-m off the ground, where the roadway would continue through the park, elevated on a solid wall covered in natural stone.

Although each design office had attended to the sensitive site with remarkable imagination, Schlaich's proposal for an especially light and transparent bridge won the jury over. Ending the jury's report are some general words on the design to which they awarded first prize (see Figs. 3 and 4).

The costs of such a bridge will be higher than a conventional bridge, but will remain within an acceptable range. This project seems capable of adding to the number of meaningful structures in Ingolstadt and of being so recognized far beyond the boundaries of the city. (Hines 1995)

Prizes were awarded as follows:

- First prize of DM 30,000 was awarded to the firm of Schlaich, Bergermann and Partners for a bridge form consisting of a deck supported on underslung cables.
- Second prize of DM 18,000 was awarded to the firm of Martinka and Grad for a bridge form that was cable-stayed with main supports at center of river.
- Third prize of DM 12,000 was awarded to the firm of Mayr and Ludescher for a bridge form that was cable-stayed with pylons off to either side.
- Honorable mention went to the firm of Dietrich and Kneidl for a bridge form that was cable-stayed with V-shaped pylons on either end of span.
- Honorable mention also went to the firm of Obermeyer for a bridge form consisting of a concrete deck with two four-pronged supports in the river.

Each entrant received an additional honorarium of DM
FIG. 2. Diagrammatic Representation of First- through Third-Place Bridge Designs: (a) First Prize (Plan: Straight); (b) Second Prize (Plan: Straight); (c) Third Prize (Plan: S-Form) (City of Ingolstadt, Prefatory Report; Dimensions in Meters)

FIG. 3. Elevation View of First-Place Design (SBP)

FIG. 4. Perspective Line Drawing of First-Place Design (SBP)

20,000. The awards cost the city a total of DM 160,000; roughly 1.1% of the final cost of the bridge and 0.3% of the total project cost. [For conversion to dollars, assume $1 = DM 1.654, which was the 1993 annual average, or $1 = DM 1.622, which was the 1994 annual average exchange rate according to the Economist Intelligence Unit, Country Profile for Germany (1996–1997) Simon Tilford, ed.]

Schlaich's bridge structure was estimated on July 28, 1994, to cost DM 10,985,000. Additional costs, such as lighting, paving, and noise protection raised the final contract price for the bridge to DM 15,114,497.72, authorized by Ingolstadt mayor, Peter Schnell on September 12, 1994.

Looking at the total project cost of DM 55,107,000 for the new bridge, roads, and landscaping, it becomes clear that the cost of a design competition is a negligible sum compared to this larger cost. The competition, whose cost totaled close to
350,000 DM, accounted for 2.3% of the bridge cost and 0.64% of the total project cost.

Although this is such a low percentage of the total costs, the first place bridge design will cost roughly 15% more than the original hollow-box proposal, whereas the total project will cost an additional 12%—a difference that is small in comparison with the North Bridge competition mentioned earlier. Much of this added cost stems from the fact that a hollow-box span would be easier to prefabricate, whereas the winning design, or any other from the competition, must be thought out and produced from scratch.

**DESIGN PROCESS**

The designers did not immediately come to the idea of a deck supported on underslung cables. Rather this solution evolved from an intensive study of the interaction between the structure and its environment and between the structure and the people of Ingolstadt. From the beginning, the bridge was conceived not simply to connect two sides of a river, but as the symbolic extension of the shore on either side. While the spirit of such a process is central to architectural practice, it is unfortunately rare in engineering design.

The design team of Schlaich, Ackermann and Kluska, an engineer, an architect and a landscape architect, set forth as its initial design criteria the following:

1. A light and elegant span that does not disturb the Danube river.
2. Separation of the pedestrian and bicycle pathway from the roadway.
3. Heavy abutments on either shore, which call to mind the many stone and masonry walls within the medieval city of Ingolstadt. Furthermore, such abutments give expression to the fact that a lighter bridge over the river places greater axial load demand on the supports. A shallow arch produces immense horizontal forces, and a low profile cable produces comparable tensile forces.
4. An asymmetrical bridge to express the transition from a park to a main road.

The following abridged description of original sketches drawn by Jörg and Michael Schlaich is based on an interview with Michael Schlaich, the bridge's chief engineer. With an admitted sacrifice in clarity, these sketches have been preserved as the authors' photocopies of the original sketches on trace. These sketches reveal some key moments in the search for a form that separates the pedestrian pathway from the main bridge deck.

Figs. 5 and 6 give an idea of how the bridge would become the superposition of three curves: (1) the structural arch; (2) the pedestrian walkway; and (3) the roadway. The sections in Fig. 6 show the variation of the walkway with regard to the structural arch at the quarter span versus the midspan of the bridge. This arch design is similar in form and span to Robert Maillart's Salginatobel and Rossgraben bridges.

Fig. 7 shows the asymmetrical support cast in the form of half an arch. While potentially the most graceful of any of the asymmetrical designs, the designers became wary of this sketch on the grounds of its structural and visual ambiguity.

In Fig. 7 we find also the first traces of dimensions—the
depth of the shallow arch made by the road deck is 3 m, the width of the supports at the base as well as the depth of the deck at the left abutment are 2 m. These specific dimensions remained guidelines throughout the design process, since the designers thought that a higher arch would disturb visually both the park and the city.

The sketch in Fig. 8 considers a cable-stayed bridge of modest proportions and shows an attempt to reconcile the towers with the town by shaping them stylistically. Solid towers maintain the medieval city feeling produced by the stone abutments. Although the design has completely changed from arch to cable, the same motivations are evident—vertical separation of pedestrians and cars and a light, transparent span between two solid, traditional fixtures. The Brooklyn Bridge, designed by John Roebling in the late 1800s, is the very model of such a design philosophy with its slender deck cradled between two monumental stone towers. Roebling also made a point of separating the foot traffic from the automobiles, raising the pedestrian part of his bridge high above the center of the road.

In the Fig. 8 sketch, the designers set the deck above the main cable at the center span. Such a decision makes little change in the behavior of the main cable, but it does put the connections between the deck and main cable into compression and reduces the height of the towers, integrating them more modestly into the surrounding landscape.

The sketches in Fig. 9 show the designers’ closing efforts to combine the compressive and tensile systems into a hybrid structure. The main spans are inverted suspension systems, where steel cables carry the tension produced by the weight of a concrete deck. After arriving at this form, the designers faced the decision of whether to leave the supports standing straight up or to rake them inward. As illustrated in the following section the decision to rake the supports was more than sculptural and constitutes the major innovation in the structure.

Fig. 10 shows the final competition design. Note the picture of the suspension bridge at the top right-hand corner and the calculation for the horizontal force \( H \) in the midspan of a uniformly loaded hanging cable

\[
H = \frac{q^2}{8d} = \frac{(200 \text{ kN/m})(68 \text{ m})^2}{8(3 \text{ m})} = 38,533 \text{ kN} = 8,659 \text{ kips}
\]
STRUCTURAL INNOVATION IN INGOLSTADT BRIDGE

Something familiar exists in almost all new ideas. One can often trace the lineage of an innovation in bridge design back to ancestors that predate the innovation by a century. Such was certainly the case with the cable-stayed bridges that emerged after World War II. Such bridges had been discussed, but not perfected, early in the nineteenth century. With the design evolution of the Ingolstadt Bridge in mind, some mention of historical precedents for the bridge’s form, followed by a simple structural explanation of the bridge, will bring to light in specific terms the nature of the bridge’s innovation.

While Schlaich’s office used a three-dimensional finite-element model to analyze details of the bridge’s construction, this model became necessary only in the final design stages, after the production of preliminary construction documents. For the competition and for seven months afterwards, the engineers used only hand calculations, physical models, and a two-dimensional computer model to develop the design. For this reason it is appropriate to feature the bridge’s conceptual design as the key to its innovative qualities.

As Fig. 11 demonstrates, the Ingolstadt Bridge can be viewed as a suspension bridge whose deck rests on top of the cables combined with an arch, which has been split apart at the center. This form stems from the moment diagram for a uniformly loaded simple beam, which has the same shape as a hanging cable under uniform load. Nineteenth-century structures such as the railroad viaduct at Biesenbach, Germany (see Fig. 12) or the Karstlenbach Bridge in Amsteg, Switzerland, built in 1882 and stiffened in 1908 (see Fig. 13), appear similar but also much heavier with their bellied trusses for a simple span. In the 1970s the firm of T. Y. Lin designed the Costa Rican Rio Colorado Bridge with a deck supported on cables hung below, encased in concrete (“Inverted” 1972). T. Y. Lin’s design went a step beyond earlier parabolic trusses to create an inverted suspension bridge.

Fig. 14 shows how the office of Schlaich, Bergemann and Partners had experimented with this form in previous designs.

FIG. 11. Ingolstadt as Hybrid Design of Tension and Compression Structures (Hines 1995)

FIG. 12. Railroad Viaduct at Biesenbach (Hines 1995)
As Jörg Schlaich mentioned in one interview, Swiss engineer Christian Menn has also researched extensively the structural implications of supporting light-weight decks on top of underslung cables to span longer distances. In several of the precedents mentioned, however, the sag at the midspan often appears too deep to be counted among the finer examples of aesthetic bridge design. For this reason and because the bridge would not rise more than a few meters above the river, the problem in Ingolstadt hinged on engineering as low a depth-to-span ratio for the hanging cables as possible.

The Ingolstadt Bridge is a hybrid structure that combines, as described by the bridge's chief engineer Michael Schlaich, a tension cable and a raked frame (see Fig. 15). These two structural systems perform explicitly separate functions. The two systems also reflect the two main visual ideas that generated the bridge form.

First, the compression in the "arch" and the tension in the cable both require substantial supports and anchorages. Second, the cables span the river on a level that continuously differs from that of the deck, creating a pedestrian path that remains separate from the road across the river.

Different expressions of these two visual ideas showed up throughout the design process, illustrated by sketches from the offices of Schlaich and Ackermann made during the design development. At first, the designers primarily explored the idea of an inverted suspension bridge. The raked frame later became both a visually pleasing and technically efficient way of putting the bridge deck into compression and prestressing it against local bending.

**SIMPLIFIED STRUCTURAL DESCRIPTION**

A five-phase chronology explains the engineers' recommended approach to the construction of the Ingolstadt Bridge. Each phase is pictured in Fig. 16.

1. Erect the supports with temporary hinges, held in place by temporary cables attached at the support wings and the anchorages.
2. Hang the eight main cables, tying them into the anchorage and clamping them on the support wings.
3. Preload the main cables in the center span and posttension the side span portions of the cables, to keep the supports in equilibrium. Set up scaffolding on the cables.
and attach the steel supports for the deck to the cables, thus avoiding falsework in the river.

4. Pour the concrete deck and simultaneously let water out of the barrels to maintain a constant vertical load on the cables. Then relax the side-span portions of the cables, putting the deck into compression, and replace the temporary cables with cables that cover the entire span. These cables will serve as supports for the footpath.

5. Preload the side-span portions of the cables. Set up the steel supports and the cross beams for these deck supports. Pour the concrete for the side-span decks. Finish the necessary preparations for the road deck and pedestrian pathway. Pour concrete to fix the hinge at the base of each support. Install noise protection, lighting, and all other necessary fixtures.

The following description assumes that the support hinges do not eventually become fixed as indicated in Phase 5 of the construction description. In the actual design, these hinges are fixed to carry extra stresses induced at the support because of its 20° skew. This skew introduces out-of-plane lateral forces from the spans into the supports and shuts out the option for permanent hinges at the supports. The values for the forces presented next are the results of a structural analysis based on simple, statically determinate calculations (Hines 1995).

During Phase 1, the temporary cables experience a tensile force of around 20,000 kN as they tie back the supports that are inclined toward the river (see Fig. 17). Once the supports are securely fastened by the temporary cables, the eight main cables can be laid, completing Phase 2.

In Phase 3, water barrels are hung on the main-span cables, bringing them to their fully deflected position under a tensile force of 38,100 kN (see Fig. 18). The added vertical load on the supports puts the temporary, side-span cables into an additional 9,300 kN of tension.
tors in the design of successful public works. This does not mean, however, that cheaper is always better. The issue of economy in construction pertains both to the economy of materials and the economy of labor. Historically, engineers who were forced to minimize material costs, when these costs were high in proportion to the cost of labor, designed their bridges creatively to fit a given site. On the other hand, when it has been acceptable to use more materials than necessary to save on labor, through standardization and overly simple structural systems for instance, engineers have found little opportunity to explore original design ideas. Jörg Schlaich points out that Germany built beautiful bridges in the 1960s when labor costs were still low and material costs were high. Schlaich mentions that this general condition gave rise to the innovation and widespread use of prestressed concrete, especially in the “poorer lands of Germany and France after the war, while America was much wealthier and didn’t suffer the same necessity to conserve materials.” Looking beyond those post-war years, Schlaich critiques Germany for having forgotten the good stewardship that it had treasured before it grew rich.

With prosperity, it is sad, the wages and the standard of living rose in the 1970s. Gas and concrete became cheaper. So we began to pour out our materials wastefully and convinced the average citizen that such a thing was acceptable.

The economics behind standardized solutions to most bridging problems can easily waste materials to save labor costs if it goes unchecked by the knowledge that skilled labor will always be necessary to carry out high-quality designs appropriate to their location.

Just as architects consider the visual impact that their work has on the environment, so must engineers consider carefully the aesthetic value of their work. Although not exclusively capable of handling such issues, architects have valuable experience in thinking this way and can serve structural design- ers who wish to hear critiques of the visual and social aspects of a project. Nevertheless, in the tradition of structural art, the architect has always served as a better critic than a creator of form. It is the engineer who best understands the austere discipline of structural design, and therefore the engineer who can best work creatively within the bounds of this discipline.

In the Ingolstadt example, the architects and the engineers began by discussing the problem over simple sketches. The engineers would then propose a basic form, which both they and the architects addressed critically. This close cooperation was characterized by architect Peter Ackermann as a powerful tool in creating the bridge design because it abandoned concern for what exactly the architect or the engineer contributed to the design. Also, the Ingolstadt authorities strongly recommended in their competition regulations that the engineers collaborate with an architect as well as consult with a landscape architect. This reinforced the design competition’s emphasis not only on the bridge itself but also on its integration into Ingolstadt and Luitpold Park.

Finally, although great public works have been produced without design competitions, cases abound where competitions have pushed engineers to exceed the norms of current practice, resulting in some of history’s most important structures. Most often such a structure is both an imaginative and appropriate solution to a specific design problem. For each design problem, this balance between creativity and restraint can be determined well if it is the product of an intense dialogue between designers and a jury who are competent to judge the scientific, social, and symbolic consequences of the design.

CONCLUSIONS

Three major political-cultural issues come to the forefront in this discussion: (1) Economy of materials versus economy of labor; (2) cooperation between architects and engineers; and (3) the bridge design competition as public policy.

Economy has always been one of the greatest deciding fac-
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APPENDIX. REFERENCES

