Conceptual Bridge Design beyond Signature Structures

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Abstract

The present paper outlines important aspects of the collaboration in interdisciplinary bridge design teams, using some of the authors’ recent successful projects as illustrative examples. It is emphasized that design competitions have significantly contributed to the fact that in Switzerland – contrary to international tendencies – hardly any sculptural, inefficient and excessively expensive bridges were built over the past decades, while aesthetic criteria and innovative approaches are appreciated even in the design of minor bridges and civil engineering structures.

Keywords: Bridges, bridge design, conceptual design, design competitions, signature structures.

1 Swiss Tradition of Bridge Design

Conceptual bridge design has a long-lasting tradition in Switzerland. Engineers like Robert Maillart, Alexandre Sarrasin and Christian Menn (Figures 1-3) significantly contributed to the evolution of today’s international state-of-art in bridge design and technology and to the recognition of the cultural value of modern engineering structures.

More than 30 years ago, Billington [1] introduced the terms efficiency, economy and elegance as common denominator of their approach to bridge design and promoted it as an ideal alternative to the countless anonymous, often ugly utility structures based on purely technical and economic criteria.

Figure 1. Salginatobelbrücke, R. Maillart, 1930 [2]

Figure 2. Pont du Gueuroz, A. Sarrasin, 1934 [2]
This type of holistic, integral approach to conceptual design, adding sustainability and innovation as additional design goals, is what the authors, presumably like many other structural engineers, are striving for when conceiving a new bridge.

2 International Trends in Conceptual Bridge Design

However, instead of following Billington’s approach, international bridge design unfortunately appears to have evolved in two different, opposite directions over the past decades.

On one hand, a trend to so-called signature bridges, conceived with the primary goal of producing new landmarks, is observed. Some of these bridges are indeed beautiful, efficient and reasonably economic structures, see for example Figure 4. Note that this bridge has been conceived by an eminent structural engineer, not an architect.

Many of these bridges, however, are essentially giant sculptures with complicated and inefficient structural configurations, typically sketched by renowned architects without much knowledge nor concern for construction methods, see for example Figure 5.

While these bridges may achieve the goal of attracting attention by looking beautiful or original to the general public – which, being a matter of taste, is at least debatable in many cases, see for example Figure 6 – their execution often requires enormous efforts, resulting in disproportionate costs and carbon footprints.

On the other hand, less important structures are ever more designed for minimum cost, completely neglecting their aesthetic and cultural importance – in spite of the fact that, considering their envisaged lifespan, these structures will inevitably leave a significant imprint on their environment.
3 Contemporary Swiss Bridge Design

Fortunately, these trends have had little impact in Switzerland. Hardly any sculptural, inefficient and excessively expensive bridges have been built here, and aesthetic criteria and innovative approaches are appreciated even in the design of minor bridges and civil engineering structures. Doubtlessly, this awareness is fostered by design competitions, which are regularly organized by public clients. In these competitions, the project entries are judged on a holistic set of criteria, and usually, structural engineers join forces with architects and other experts to form design teams.

4 Bridge Design Competitions

In the following, the authors are sharing their personal thoughts with respect to conceptual bridge design, based on their experience, particularly in design competitions. These ideas are certainly debatable and lack scientific rigour. Still, the authors hope to animate their colleagues to think critically about their role in conceptual bridge design, and stimulate the discussion.

4.1 Interdisciplinary Teams

Modern day bridge design encompasses classical engineering issues such as structural analysis, construction processes and economy, but many other aspects as well. Among these additional facets, there are many topics, such as geotechnics, hydrology, environmental protection, traffic engineering and, of course, aesthetics. The latter comprises the conformity with the surroundings, urbanistic aspects, shapes and proportions as well as other facets crucial for a good structural concept.

Structural engineers are not specifically trained for many of these aspects, and only few geniuses are capable of mastering all of them and design a splendid bridge as shown in Figure 4. Therefore, collaborations of structural engineers with architects (and specialized consultants for additional topics) have become common. While some years ago, many Swiss structural engineers felt embarrassed if clients asked for design teams including an architect to participate in design competitions, it has become normal today. Based on positive experiences with collaborations in competitions, many engineers are consulting nowadays with architects not only in design competitions, but also in normally tendered, challenging projects.

It is crucial for a successful collaboration that all the team members share a high level of professional skills, mutual respect and open-mindedness, particularly regarding ideas of other team members. In addition, they must have a true interest and basic competences in the other disciplines involved, such that all the team members can share ideas using a common vocabulary.

4.2 Conceptual Design Process

Conceptual bridge design is far from being a linear process. Rather, it is interdisciplinary, highly interactive and iterative. To foster creativity, the collaboration should be non-hierarchical, except for organizing the team (deadlines, deliverables).

While aesthetical criteria may dominate the structural concept of an urban small span footbridge, structural engineering aspects, including construction methods and economic considerations, must dictate the concept of large-span bridges. Otherwise, as mentioned above, disproportionate costs and carbon footprints will be the consequence.

Independently of the importance of structural or aesthetical criteria, engineers and architects should develop the structural concept, integrating all relevant criteria, in a dialogue. Neither should the engineer develop the concept and the architect refine it, nor the architect rely on the engineer just to check the feasibility of his idea. Just as it is impossible to obtain a good cake if the ingredients are baked separately, it is unlikely to obtain a good structural concept if the team members develop their ideas separately and assemble them a posteriori. Instead, the design team should take on the role of pre-modern master-builders, reuniting the tasks of architect and engineer.

The authors are convinced that a good structural concept – as a result of an integral, holistic design approach - is characterized by the fact that neither the concept as a whole, nor parts of it, can be credited to one of the team members - just like it is impossible to attribute the taste of a perfect soup to one of its ingredients.
### 4.3 Role of Structural Engineers

Mastering the technical challenges in bridge design and construction has become ordinary today, and the age of great structural engineering protagonists and bridge designers may be over. However, designing a bridge in order to satisfy all technical requirements such as safety, serviceability and durability still requires a high level of education, professional skills and experience, as well as a lot of hard work. Moreover, structural engineers carry most of the responsibility in bridge projects and assume the risks that come with construction. Therefore, independently of the significance of the different aspects in the design, a structural engineer—or a structural engineering firm—should generally adopt the role of the author of the project. Efforts are required in order to achieve that the public recognize the leading role of structural engineers in bridge design, rather than talking about the “architect” of the bridge.

There are of course bad examples of collaborations, where either the engineer made a sculptural or ornamental concept of the architect feasible, or the architect decorated an ill-conceived structure. However, these cases must not be taken as reasons to discredit collaborations in interdisciplinary design teams in general. Rather it is up to us engineers to take on an active role in the design process and discuss on a par with the architects and other team members.

### 4.4 Competition Juries

The jury members take on a key role in design competitions, as they evaluate the entries and select the best project. To a certain extent, the winning project will always reflect the attitude of the jury. It seems evident that the cumulated competences of all jury members should be at least equal to those of the participants and cover all the aspects involved in a project, even if the jury may be assisted by experts pre-examining the entries. Unfortunately, this is not always the case.

It does of course make a huge difference if the jury is dominated by politicians or sponsors with the idée fixe of building a landmark bridge, or rather by highly skilled and experienced engineers and architects as well as far-sighted representatives of the client, conscious of spending tax money. Fortunately, the latter applies to most bridge design competitions in Switzerland, which is why bridge design here has profited a lot from them.

### 5 Examples

In the following, three of the authors’ recent successful projects, all located in alpine surroundings, are presented, focusing on the development of their quite contrasting structural concepts.

#### 5.1 Inn Bridge Vulpera

The Inn Bridge Vulpera [5], opened to the traffic in 2010, connects the villages Scuol and Tarasp (Canton Grisons). It spans the Inn gorge at a height of about 70 m with a slope of 7.5%. Anticipating that the design and the construction of the bridge were going to be both technically as well as aesthetically challenging, the client decided to organize a design competition in 2005, stating clearly that an economical solution was sought.

The structural concept of the winning project is the result of an intensive evaluation of the topographical, environmental and geological issues at the project site. The new bridge is visible from many locations and has a great impact on its surroundings. Therefore, the design team opted for a prominent and elegant structure, without overpowering the spectacular alpine landscape. Rather than an arched bridge (that would have fitted well geometrically, although its bases would have been hidden by the forest), a concept minimizing horizontal foundation forces was favored because the solid rock suitable for bridge foundations is found only at considerable depth, and above it, the left valley slope is unstable. Finally, due to the steep valley slopes complicating site access, the structural concept aimed at building this bridge with the least amount of access points.

Based on these considerations, a conventional, yet carefully designed and detailed concrete box girder bridge was proposed. The variable depth girder has only two piers (other girder bridges proposed in the competition had three or more), corresponding to the site accesses, and is constructed using the balanced cantilever method. The superstructure is monolithically connected to the piers and has expansion joints and longitudinally movable bearings at the abutments, such that the required pier stiffness during construction can also be used in the final structure. Therefore, the abutments, located in...
the steep, partly unstable valley slopes, merely have to resist horizontal forces caused by friction of the bearings.

Figure 7. Inn Bridge Vulpera, 2010

The pier locations were determined taking into consideration the structural and aesthetic constraints. Criteria included: a well balanced span layout, similar pier heights and no additional pier on the Tarasp side. The total length of the bridge is 236 m, with spans of 59+104+73 m.

The shape of the superstructure and the piers, as well as the envisaged construction sequence, were developed foremost by considering the structural performance and optimized with regard to their appearance and the construction process (polyhedral, relatively simple geometries allowing for a repeated use of the same formwork with minimal adjustments). In this way, an elegant structure could be built without negative impact on construction cost. For example, while the bottom slab of the box girder has a constant width, its side faces become visible due to the inclined webs of the variable depth girder, showing the continually increasing depth of the bottom slab and emphasizing the flow of the forces without complicating the formwork. The dimensions of the pier sections correspond with the bending moments in the longitudinal and transverse directions, with a waist located in the area of minimal forces.

Figure 8. Inn Bridge Vulpera, 2010

Piers and abutments are founded on caissons in the stable rock. For the pier on the unstable left valley slope, an excavation of 18 m depth was required, using the bottom 4.7 m – the part lying in the solid rock - as caisson foundation with 10 m diameter. On top of this caisson foundation there is a cylindrical, hollow shaft including movable rings, separated by compressible joint material, which can adjust to the slow horizontal deformations of the deep unstable layers for an anticipated period without intervention of at least 100 years. Above the movable rings, a stiff hollow shaft of approximately 8 m height resists the pressure from the faster creeping slope on the surface. The shaft and the movable rings were built top-down such that they could already be used for stabilizing the excavation during construction.

5.2 New Versam Gorge Bridge

The new Versam Gorge Bridge [6] near Versam (Canton Grisons) is located close to the existing bridge built in 1897, one of the very few arched steel-truss bridges remaining in Switzerland. In addition, it is located in a dramatic landscape close proximity to the Rhine Gorge, which is in the federal inventory of national importance. Hence, the design was established in agreement with the Swiss nature conservation and heritage agencies.

Due to the relatively good rock quality, the site was attractive for statically efficient arch-type solutions. In order to avoid ingratiating similarities with the existing slender, almost transparent bridge, the design team opted for a large, generous and forceful looking strut frame structure, with a span of 80 m between the strut supports.
The shapes of the superstructure and the piers were developed in view of the internal force flow and optimized with respect to the appearance and construction process. The cross-sections are variable, with the greatest dimensions in the transition zone between the superstructure and the substructure. The pier shape tapering towards the bottom, resulting in a compact pier base, was chosen to fit in with the topographic conditions (dip of the slope strongly skewed to the bridge axis) as well as geotechnical considerations.

The rough terrain with steep valley slopes and the limited site access (falsework could only be delivered in small pieces due to the narrow access roads including low-profile tunnels) demanded a clear assessment of the construction process in order to guarantee a cost-effective solution.

In order to minimize horizontal reaction forces in the steep slopes, the 112 m long bridge rests on pot bearings moving that are movable longitudinally at both abutments. However, in order to achieve a high durability in the forested and shady, moist environment, no expansion joints were provided. The small pavement cracks that must be expected in this semi-integral solution with the given movement length were accepted by the client.

### 5.3 Replacement of Steinbach Viaduct

The Steinbach Viaduct [7] crosses the Sihlsee Reservoir (Canton Schwyz) with a length of about 440 m. The old, narrow bridge was no longer adequate to cope with today’s requirements and involved high maintenance costs, particularly due to excessive settlements and the high number of expansion joints. Therefore, a two-stage design competition was launched in 2006 in order to find the best possible solution for its replacement.

The task of replacing the existing bridge proved to be very challenging. The choice of the structural concept was primarily influenced by the fact that the bridge had to be built without influencing the level of the reservoir, with water level fluctuations of up to 8 m, while temporary dams in the lake were inadmissible for environmental protection reasons. Furthermore, in view of the low load bearing capacity of the subsoil (soft lacustrine sediments up to 100 m depth) and its sensitivity to settlements, the choice of the foundation system was essential. Finally, the largely visible crossing over the lake, with the new, 13 m wide deck only just above the waterline at high reservoir levels, and its location in a recreational area posed high demands on the appearance.

The design team decided to opt for an unpretentious bridge fitting harmoniously into the dominant surrounding landscape, being as light as possible, but without affecting its robustness and durability. The proposed design, winning the design competition in 2007, is a multi-span continuous prestressed concrete bridge with a constant, lightweight open cross-section. The total length of the bridge is 441.0 m, with spans of 21.0 + 14·28.5 + 21.0 m. In order to achieve a high durability and minimum maintenance, all piers are monolithically connected to the bridge deck, with only two expansion joints, located at the abutments (as compared to 6 expansion joints and 20 hinged connections in the existing bridge).
The length of the normal span as well as the shapes of the deck and the piers were developed from the static requirements and optimised with regard to aesthetic considerations as well as the construction procedure. For example, in order to facilitate an optimal use of a launching-girder without intermediate supports, the cross-section of the deck is constant, without diaphragms nor transverse frames, the pier geometry allows for a direct support of the launching girder, and the normal span is relatively short. The latter also enables a very slender superstructure, to give the impression of an unpretentious, elegant strip over the water even at high water levels.

The height of the piers above the lake bottom varies between 8 and 12 m, and their appearance changes greatly with the changing water level. Hence, finding a pier geometry with proportions appropriate with full as well as empty reservoir – and satisfying the constraints of the envisaged erection procedure - was particularly challenging. In their uppermost part, the external geometry of all piers is identical, enabling the use of the same formwork. However, in order to ensure a reference of the piers to the water level, the horizontal connection joining the pier arms is located at the same elevation on each pier, which was achieved using a variable horizontal stop-end shuttering on the inside of the pier formwork. The abutments are designed to always remain above the water line, facilitating the ecological connectivity above the water level even when the reservoir is full.

The choice of the foundation concept, particularly regarding its construction, was crucial for the cost-effectiveness of the project. Piers and abutments are founded on prefabricated spun concrete piles Ø45 cm up to 36 m long, dimensioned based on the results of in-situ static load tests carried out one year before construction of the bridge. The 16 piles of each pier are connected by a massive pile cap, which ensures the load transfer and is only slightly embedded in the ground in order to minimise the impact on the lake bottom.
The foundations and the piers were built entirely using pontoons. First, the piles were driven. Then, a sheet-pile caisson was installed, followed by underwater excavation and the pouring of an underwater steel fibre reinforced concrete base. Next, the sheet-pile caisson was pumped out, using the piles and the underwater concrete in order to ensure safety against uplift. Now, the pile cap and the pier could be constructed in dry conditions and finally, the sheet-pile caisson was flooded and the sheet-piles removed. These works were carried out simultaneously on several piers in the sense of a line construction site, in order to achieve the required construction speed corresponding to the superstructure.

The latter was built span by span in a 3-week-cycle in two construction seasons, starting each year from the abutments. During the winter break in between, the launching-girder was moved from the middle of the lake to the second abutment such that, before pouring the closure span, the two half-bridges could be pressed apart. In this manner, the creep and shrinkage deformations of the 441 m long deck and the corresponding imposed deformations of the monolithically connected piers could be partly compensated.

6 Conclusions

As already stated, the view of the authors regarding the collaboration in interdisciplinary design teams may lack generality and scientific rigour, and the same applies to the examples presented above. Still, some conclusions can be drawn.

First of all, the projects presented, all of them with structural concepts developed by interdisciplinary design teams following the proposed holistic approach, were successful. They convinced the clients and the competition juries, respectively, and – more importantly – all of them passed the litmus test of construction without negative surprises, neither technically nor aesthetically, nor economically. Hence, they demonstrate that the proposed holistic approach is particularly suited for technically and aesthetically challenging projects.

Furthermore, the examples demonstrate that if the construction process is considered as integrating part of the design concept, aesthetic and economic demands can be simultaneously satisfied. Finally, it is evident that – at least if economic criteria are relevant - structural engineers must take on an active role in conceptual bridge design, in spite of the fact that nowadays, almost any structure (even giant sculptures) can be calculated and built.

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8 References