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ROBERT MAILLART: THE EVOLUTION OF REINFORCED CONCRETE BRIDGE FORMS

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ABSTRACT

Robert Maillart (1872-1940) was a Swiss structural engineer and bridge designer, a pioneer in developing many innovative bridge forms in reinforced concrete. This paper chronicles his bridge design work, struggling to establish a niche for reinforced concrete in the building industry, competing against the tradition of iron and stone construction. More importantly, he worked to liberate bridge building in this innovative material from the straightjacket imposed by the aesthetic ideals of his time. While many of his contemporaries supported the idea that reinforced concrete structures should simply mirror the characteristically heavy masonry designs of the past, Maillart believed that a structure's load carrying function is intrinsically derived from its form and material. The ability to cast bridge pieces monolithically, leading to an improved tensile load carrying ability, meant that a heavy masonry aesthetic would become obsolete, and would also prove inefficient if recreated with reinforced concrete. This led to Maillart's first major structural innovation – the reinforced concrete hollow box arch bridge – first used for the **Zuoz** (1901) and **Tavanasa** (1906) bridges, and subsequently refined throughout his career, with the **Salginatobel Bridge** (1929) standing as his crowning achievement. Maillart's aesthetic motivation to demonstrate the lightness that is possible in reinforced concrete structures then led to his most versatile bridge form – the deck-stiffened arch. The arch was initially paired with a straight deck, as seen in the **Schrähbach** (1924), **Valtschielbach** (1925) and **Töss** (1934) bridges, but the form was further developed to include a curved bridge deck, as seen in the **Ziggenbach** (1924), **Bolbach** (1932) and **Schwandsbach** (1933) bridges (Billington, 1997).

1. DESIGN APPROACH

Modern engineers perhaps take established bridge forms for granted, as these may seem to have effortlessly developed in the rapid progression of applied science throughout the 20th century. Yet at some point in time there must have been an individual or a group to champion a novel design, new material or construction technique. In examining the bridges built by Robert Maillart (1872-1940), this paper gives credit to one such pioneer in the field of structural engineering.

Born in Bern, Switzerland in 1872, it was the duality of the Swiss culture that would later manifest itself so clearly in Maillart's work. His upbringing was a synthesis of German rationality and French passion, later crystalized into engineering principals at the Federal Technical Institute of Zurich (Eidgenössische Technische Hochschule, ETH) (Billington, 1983). During his tenure at the institute he studied under Wilhelm Ritter (1847-1906), who instilled in him the idea that engineers are not simply the stewards of the technical aspect of construction but also hold responsibility for the aesthetic manifestation of a structure. Coupled with the teaching of graphic statics, an analysis technique that focuses on the visual representation of forces rather than the algebraic, this formed the basis for Maillart's career as a builder, designer and artist (Billington, 1997).

1.1 Critiques by Maillart's Contemporaries

To fully appreciate Maillart's accomplishments, it becomes necessary to address the contemporaneous engineering attitudes and the prevailing design culture against which he had to struggle to develop new structural forms. With reinforced concrete as a relatively novel material, Maillart faced opposition on both the technical and aesthetic fronts, manifested in the critique he received on many of his early design competition entries. Following the retirement of his mentor Wilhelm Ritter, contemporary researchers at ETH, such as Arthur Rohn (1878-1956) and Max Ritter (1884-1946, no relation to Wilhelm Ritter), felt that his design work was not based enough on complex mathematical theories (Billington, 2000). Meanwhile established designers such as Robert Moser (1838-1918) felt that proper reinforced concrete designs should mirror the aesthetic ideals of heavy stone bridges (Billington, 1997). Advocating for novel structural forms against prominent academic opponents, while eschewing the decorative approach to bridge design championed by his colleagues, would prove the major challenge of Maillart's career (Billington, 2000). Only by virtue of the cost savings that could be achieved with his lighter reinforced concrete designs was he able to carve out a niche in the conservative building industry of his time (Fürst, 1997).

1.2 Artist and Engineer

Maillart's design techniques and approaches to engineering, in contrast to those taught by his contemporaries at ETH, have in some ways been lost in the modern bridge design process. For example, his practice of conducting full-scale load tests on his completed bridges as a means to evaluate their safety and performance has been replaced with modern Finite Element (FE) software and rigorous mathematical analysis techniques (Billington, 1997). Yet even without advanced techniques Maillart's bridges, by virtue of their lightness and panoramic settings, are in many cases considered works of structural art. This, however, should not overshadow his excellence as an engineer; Maillart was known to submit detailed structural calculations for his design competition entries for all stages of construction.

Maillart's engineering ability was further displayed in his patent for flat slab construction with smoothly integrated capitals, removing the need for expensive extra joists and columns to support the slab (Fürst, 1997). Using graphic statics, he was also able to apply concrete trusses in the construction of the Magazzini Generali warehouse roof at Chiasso (Zastavani, 2008). Maillart was further able to translate his engineering talents into business success, running a successful company in Russia, designing mainly industrial buildings before the First World War (Billington, 1997). He was further known through numerous academic publications during his time, and is even credited with the development of the "shear center" theory, i.e. establishing the center of shear as a sectional property (Timoshenko, 1983). Before delving into a study of his specific bridge designs, all these accomplishments serve as a reminder that Maillart was much more than just an aesthetic visionary. He was a modern figure and a talented engineer, who showed that bridges could be pure expressions of the engineering ideals – cost and efficiency – while remaining works of art.

2. THE HOLLOW-BOX ARCH BRIDGE

In traditional masonry construction, the arch alone carries the whole weight of the bridge, with all other components of the bridge serving only as additional weight to be supported by the arch. As the stone arch is in itself a heavy component, either the span of the arch is decreased or its thickness increased for it to be able to support its own weight, often leading to massive and heavy looking bridges. Maillart realized that the use of concrete would necessitate both a structural and aesthetic departure from these masonry arch bridges. The nature of concrete and the ability to form and cast structural elements integrally with one another, allows bridge elements to work in conjunction to carry loads. The arch no longer needs to be designed as the sole load-bearing element; the longitudinal walls and deck would also be components of the structural system, effectively forming a stiff concrete box of varying depth along the length of the bridge. The thickness of the arch itself can be reduced, as it is no longer the sole structural component, resulting in a lighter overall structure capable of spanning greater distances. Material and scaffolding costs are also reduced by virtue of the weight reduction (Billington, 1997).

2.1 The Zuoz Bridge

The Zouz Bridge (1901), with a main span of 38m, was the first concrete hollow box structure ever built. It expressed Maillart's evolving view of concrete construction. Improving upon his first concrete arch bridge, which he had built at Stauffacher (1899), "the [Zouz] structure would have the virtues of stone but without its great weight" (Billington, 2003). The strength of the hollow-box section at the midway point between the crown and the hinge is similar to that of a 130-centimeter thick stone arch, but weighing only the equivalent of a 40-centimeter thick stone arch (Billington, 2003). With the arch, walls and deck of the Zuoz Bridge carrying the load together, Maillart began a new era in concrete bridge construction, proving that his novel arch form could be stronger, lighter and cheaper than a comparative masonry structure.

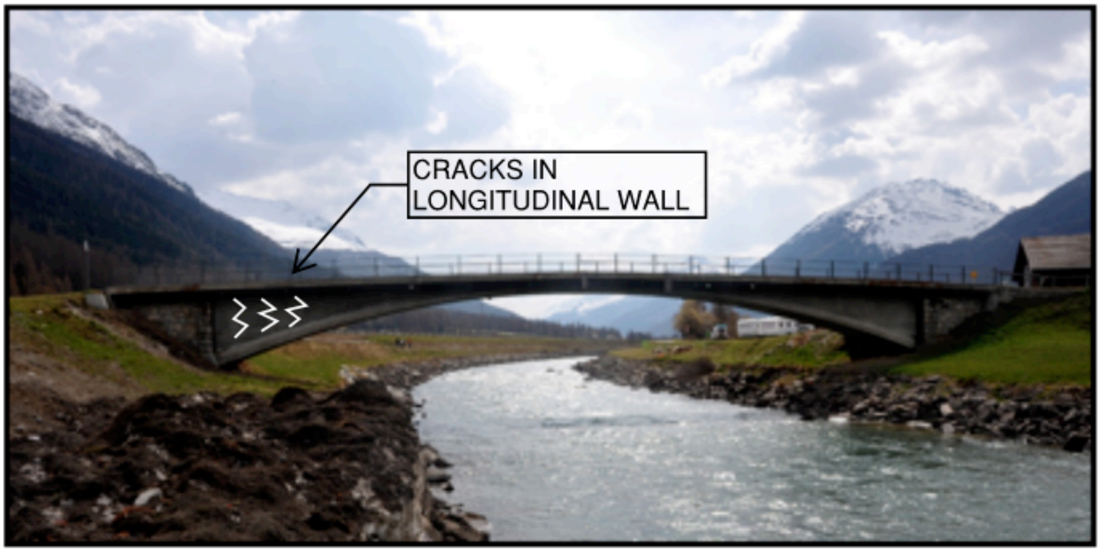

Figure 1. The Zuoz Bridge (1901) over the Inn River, Switzerland (Kleis, 2011).

2.2 The Tavanasa Bridge

The Tavanasa Bridge (1906) was another step forward in the improvement of the hollow-box arch form pioneered at Zuoz. This refinement of the form was inspired in 1903 when Maillart was asked to inspect cracks that had developed on the longitudinal walls near the abutments of his recently completed Zuoz Bridge. Interestingly, his report concluded that the cracks had no impact on the structural integrity of the bridge. The arch's internal forces, while distributed across the whole section (arch, walls and deck) at the crown, are in fact concentrated at the abutment hinges where the cracks occurred (Fig. 1). This meant that the longitudinal walls, at the location of the cracks, were in fact structurally useless. The use of longitudinal walls at the abutments was a feature that dated back to antiquity, where it had been a crucial structural component in the circular masonry bridges of the Romans, but was obsolete in modern bridges, simply been passed down to designers as a stylistic element (Billington, 2003).

Contrary to the prevailing architectural trends of his time, Maillart chose to design the Tavanasa Bridge without embellishment – simply mirroring the flow of forces documented at Zuoz. The structure was made even lighter than the Zuoz Bridge by removing the unnecessary longitudinal walls at the abutments, but was just as strong. Beyond the point of maximum moment, the arch section begins to taper towards the abutment hinge, further reducing the amount of material used. At the time of the bridge's completion, with a main span of 53m, it was the longest reinforced concrete bridge in Switzerland, and 3rd largest in the world (Billington, 1983).

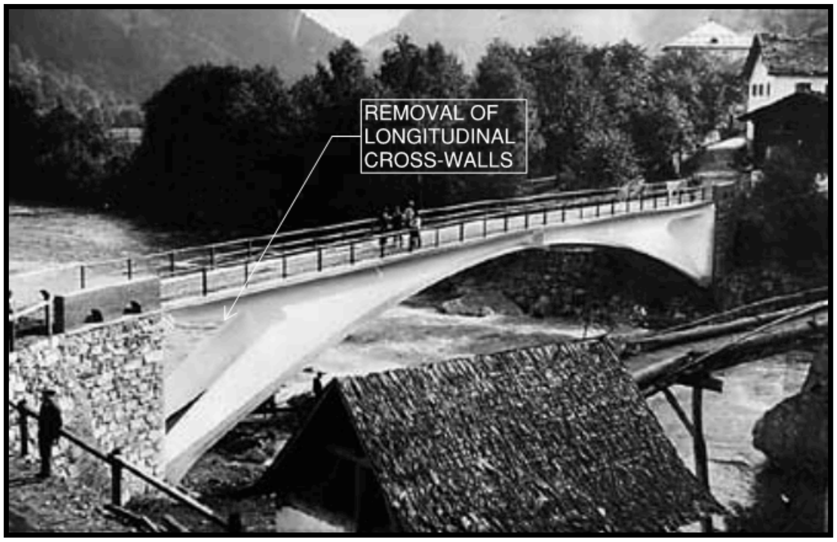

Figure 2. The Tavanasa Bridge (1906) over the Rhine, Switzerland (Kleis, 2011).

2.3 The Salginatobel Bridge

The Salginatobel Bridge (1929) is a masterpiece in Maillart's exploration of the three hinged hollow-box reinforced concrete form. Spanning 90m, this would become his most famous structure, named an International Historic Civil Engineering Landmark in 1991 (Billington, 1997). The Tavanasa Bridge, having been destroyed in 1927 by an avalanche, is thought to have inspired him to revisit this early bridge when submitting his preliminary design for the Salgina crossing. Through an iterative process, Maillart once again made use of graphic statics to adjust the geometry and profile of the arch to arrive at the most efficient shape possible for this specific application, one where bending moments are reduced throughout the arch (Fivet, 2010). Striving for improved structural efficiency led to immediate cost savings by virtue of the reduction in materials, but also reduced tensile cracking of the concrete leading to an improved durability of the bridge, which went without requiring repairs for 45 years after its completion (Figi, 2000). Visually, the choice to integrate the approach spans with the main structure, rather than leave heavy stone abutments, as was the case with the Tavanasa Bridge, also shows an aesthetic maturity in Maillart's design of the Salginatobel Bridge.

Figure 3. The Salginatobel Bridge (1929) over the Salgina Brook in Schiers, Switzerland (Kleis, 2011).

3. THE DECK-STIFFENED ARCH BRIDGE

In the early 1920s, after almost two decades of building experience, Maillart once again redefined what was considered structurally possible in reinforced concrete bridge design. As with the hollow-box form, where the deck and arch acted integrally through the connection imposed by the longitudinal cross wall, the deck-stiffened arch concept also built upon a mutually reinforcing interaction between the bridge components. Yet for the deck-stiffened concrete arch, Maillart strived to create a structural system that solely emphasized the interaction between the deck and the arch. The whole deck section, including the parapet walls, would act as a stiff beam, which when integrated with the rest of the structure would reduce the bending forces in the arch, allowing it to be much thinner and lighter (Billington, 2000). Further, while a hollow-box bridge by definition must be designed with longitudinal cross-walls for the deck-arch connection, Maillart realized that for a deck-stiffened arch the connection could be equally achieved with transverse cross-walls. The material and weight reduction in removing the longitudinal cross-walls led to cost savings, while viewing the bridge in profile would visually emphasize the lightness of the structure (Billington, 1973).

3.1 The Schrähbach Bridge

The first deck-stiffened arch bridges designed by Maillart were the Fienglibach (1923) and Schrähbach (1924) bridges, both commissioned by the hydroelectric power plant above the Wägital Valley in Switzerland (Billington, 1973). The structural efficiency that was achieved from stiffening the arch using the deck and parapets is evident in a reduction of the required arch thickness. For example, the unstiffened traditional arch at Stauffacher spanning 39.6m required a 72cm thick arch at the crown, while the deck-stiffened arches spanning 39.7m at Fienglibach, and 28.8m at Schrähbach, were designed with arches only 25cm and 18cm thick respectively (Lewsi, 2001). However, the thinness of the Schrähbach arch was obscured when decorative non-structural horizontal cross-walls were added soon after construction. Their function was solely to mirror the aesthetic trends in bridge design at the time.

Figure 4. The Schrähbach Bridge (1924) in the Wägital Valley, Switzerland (Kleis, 2011).

3.2 The Valtschielbach Bridge

The Valtschielbach Bridge (1925) displays a further step in Maillart's understanding of the complex interaction between bridge and deck, serving as testament to the potential of the deck-stiffened arch forms first used in his Wägital bridges. The main span of 43.2m, larger than Maillart's previous deck-stiffened bridges, has an arch thickness of merely 23cm at the crown (Lewsi, 2001). Furthermore, with no additional cross-walls added, the intended visual impact of the bridge remained unaltered, unlike the modifications to his previous bridges of the same form. When viewed in profile, the combination of the deep ravine and the lightness of the arch leave a striking impression, although the bridge is somewhat aesthetically discontinuous in the abrupt curve of the road as it meets the Romanesque approaches.

Figure 5. The Valtschielbach Bridge (1925) in Donath, Switzerland (Kleis, 2011).

3.3 The Töss Bridge

The Töss footbridge (1934) would mark Maillart's final bridge in the deck-stiffened form, resembling more a sculpture than a work of engineering (Billington, 2003). The design of the bridge went through three separate iterations, showing the care Maillart took at this point in his career to balance both the structural performance and aesthetic impact of his bridges. In the first iteration, the bridge spanning 38m was designed with a 90cm thick deck stiffener coupled with a 10cm thick arch, with both components merging at the crown leaving only three transverse cross-walls on either side. In the second iteration, the deck thickness was reduced to 40cm while the arch was increased to a thickness to 14cm (Billington, 1997). Additionally, the length of merged deck and arch was reduced, adding an additional cross-wall on either side of the crown to compensate. Although the first iteration of the bridge was structurally sound, Maillart felt that the thick deck section with respect to the thin arch would create a visual discontinuity in the bridge. This could be amended at no extra cost by thickening the arch slightly with material offset from reducing the deck depth.

In the third and final iteration, a slight counter-curvature was added to either end of the bridge in order to more seamlessly integrate it with the riverbanks (Billington, 1997). When compared to the footbridge over the Töss built by P.E. Soutter in 1931, which was both heavier and 50% more expensive, it becomes evident that Maillart's artistic interventions do not necessarily conflict with cost. With the Töss Bridge, Maillart showed that both aesthetics and economy could be balanced by modifying the structural form to properly suit the application (Billington, 2003).

Figure 6. The Töss footbridge (1934) in Winterthur, Switzerland (Kleis, 2011).

3. THE CURVED DECK-STIFFENED ARCH BRIDGE

Designing bridges in mountainous regions has always proved a challenge for engineers by forcing them to deal with unpredictable soil conditions during design and precarious conditions during construction. While three-pinned arch bridges could be used to counter soil movement and properly constructed false work could ensure safety at the work sight, there were few effective ways to integrate the tight winding roads of the mountain passes with traditional straight bridges. In 1924, as an already established engineer with numerous bridges over the valleys and rivers in his native Switzerland, Maillart was no stranger to these difficulties. With his curved deck-stiffened arch form, he would once again step to the forefront of his profession by elegantly solving the problem of how to combine curved roads with bridges.

Straight bridges have always been simpler to design, so when a crossing with curved approach roads was necessary the straight bridge was simply designed to meet the roadway at an angle. This was done for the Valtschielbach Bridge, where the discontinuity between the approach road and the arch is evident when viewed in plan. While a structurally suitable solution, this technique results in a change in curvature between the road and the bridge, a safety hazard for vehicles driving at night or in poor weather conditions. Furthermore, in railway bridges this angle would have to be minimized to allow the track to continue smoothly. With the development of the straight deck-stiffened arch, Maillart saw the potential to further refine this form to integrate a smoothly curving deck with the arch. This would result in an elegant structural solution that could achieve visual continuity in both profile and plan views, while resolving the safety concerns.

3.1 Ziggenbach Bridge

The Ziggenbach Bridge (1924) was the third bridge design commissioned for the Wägital hydroelectric plant (Billington, 1997). Maillart implemented his straight deck-stiffened arch for the two larger bridges, but decided to further experiment with the deck-stiffened arch form by adding a curved deck for the more modest 20m span of the Ziggenbach Bridge. This first attempt at a curved bridge is rather crude, with the deck not smoothly curved but polygonal in plan to allow for the 25m radius of curvature. In contrast, the arch is straight in plan with a constant width of 4.6m and a thickness of 26cm at the crown, merged with the deck for the central 10.82m of the bridge (Laffranchi, 1997). As with all of Maillart's concepts, the first attempt would simply serve as a trial, to be refined and perfected in subsequent attempts. The importance of this bridge lies not in its technical merit, but rather in how it illustrated Maillart's thought process as he continued to develop the curved deck-stiffened arch concept.

Figure 7. The Ziggenbach Bridge (1923) in the Wägital Valley, Switzerland (Kleis, 2011).

3.2 The Bolbach Bridge

The Bolbach Bridge (1932) could have been designed with a straight deck, but Maillart chose to use this opportunity as another small-scale experiment in refining the use of a curved deck to avoid kinks in the roadway approaches (Billington, 1997). The bridge spans only 14.4m with an arch thickness of 16cm at the crown, and has a smoothly curved deck along a tight 15m radius of curvature (Laffranchi, 1997). The outer edge of the arch is straight and tangential to the deck, while the inner edge of the arch follows the curvature of deck. The combination of a sharper curve and thinner arch that follows the curvature of the deck grants the Bolbach an aesthetic impact that would act as the inspiration for one of Maillart's final works of art.

Figure 8. The Bolbach Bridge (1932) in Habkern, Switzerland (Kleis, 2011).

3.3 The Schwandsbach Bridge

The Schwandsbach Bridge (1933) marked the culmination of the curved deck-stiffened arch form Maillart had been developing throughout his career. The arch spanning a substantial 37.4m, with a 20cm thickness at the crown, follows the curvature of the curved deck on the concave side and splays out at the abutments on the convex (Laffranchi, 1997). The deck is joined to the arch with trapezoidal cross-walls that run the width of the arch at the bottom and the width of the deck at the top, adding stability to the curved bridge. This emphasizes the flow of forces throughout the bridge, while highlighting its slender form when viewed in profile (Billington, 2003). The bridge is also designed without any heavy stone abutments or Romanesque arches at the approaches, marking a complete departure from the influence of an aesthetic rooted in stone construction. To further emphasize the separate structural components, the arch is only joined to the deck over the central 2.8m of the span (Laffranchi, 1997). With the Schwandsbach Bridge, Maillart was able to capture the technical excellence of his previous deck-stiffened arch bridges. He was able to modify the form to suit the constraints of a curved road while still creating a structurally efficient and cost sensitive work of structural art.

Figure 9. The Schwandsbach Bridge (1933) in Hinterfultigen, Switzerland (Kleis, 2011).

4. CONCLUSIONS

It was the combination of structural creativity and aesthetic vision that led to the construction of the bridges documented in this paper. Maillart's ability to conceptualize the overall flow of forces led him to experiment with bold new forms not bound by the heavy masonry ideals of his time. He was able to envision how reinforced concrete, and the ability to cast structural components monolithically, would allow the separate components in a bridge to act together. This led first to the hollow box bridge form and later to the straight and curved deck-stiffened arch bridge forms documented throughout this paper.

While it is clear that not every bridge built by Maillart is a masterpiece, it is the evolution and the visible progress in his ideals that is exemplary. He was always critical of his work, continually refining his designs to improve both their structural efficiency and aesthetic impact. For each structural form discussed in this paper, three showcased bridges are meant to illustrate this progression, starting with a concept that is later refined to a masterpiece. For example, it is likely that the first concrete hollow box bridge at Zuoz would have been enough to establish Maillart's place in engineering history, yet he continued to develop the form leading to the masterpiece of the Salginatobel Bridge. Likewise, his deck-stiffened arches were innovative at their inception, but were further refined in the Töss and Schwandsbach bridges. Maillart's holistic approach to bridge design – the combination of structural efficiency, economy and visual impact – was the inspiration for his work. He showed that an engineer should never consider these criteria mutually exclusive, and to balance them properly is to create works of structural art.

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