PERFORMANCE AND REPAIR OF THE STRUCTURES OF ROBERT MAILLART

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Abstract

This paper discusses the rehabilitation of four Swiss bridges designed by Robert Maillart (1872-1940), well known for his technical innovations and his elegant designs. The bridges served for from 45-66 years before rehabilitation and are currently in service after from 68 to 97 years old.

Introduction

Robert Maillart created in Switzerland a series of concrete structures viewed today as great works of structural art. Nearly all his major works are still serving their intended purpose and all are older than 56 years. Many stand in harsh weather conditions and most have been at least partially rehabilitated. This paper will present a series of these works, discuss their original design, describe rehabilitation means, and comment on their present condition.

The original design ideas of Maillart account for the permanence of these bridges in the sense of their low stresses and high quality; but some of his details have led to difficulties over time. The lessons learned from these great works provide for the designer today considerable insight into the nature of reinforced concrete just as they did for Maillart during his own career in design.

Table 1. Maillart Bridge Rehabilitations

Crossing and Location	Year Built	Year Rehabilitated	Bridge Type	Major Repairs
Inn River Zuoz	1901	1967	Three-hinged hollow-box arch	Deck replaced new cover
Aare River Aarburg	1912	1968	Hinge-less arch	Deck replaced new supports
Muota River Ibach	1913	1977	Hollow-box, cantilever beam	Fixed arch new cover
Salgina above Schiers	1930	1975	Three-hinged, hollow-box arch	Deck replaced, new hinge

Here we discuss four bridges (Table 1), each of which required significant rehabilitation--Zuoz (1901), Aarburg (1912), Muota (1913) and Salginatobel (1930). The loose foundations at Zuoz had allowed the arch to spread 4 cm at each abutment by 1967. The Aarburg Bridge of 1912 exhibited cracking early in its life due to inadequate detailing between the deck and vertical supports. The walkway on one side of the Muota Bridge had forced traffic loads to run slightly off center from the bridge's longitudinal axis, causing mostly longitudinal cracking. The cracks in the Salginatobel Bridge became most serious not on the arch, but in the deck which required both additional reinforcement and a new concrete overlay. In each bridge, some concrete had crumbled due to carbonation. This, in addition to structural cracks, had exposed reinforcing bars which in turn had popped off portions of cover as they rusted and expanded.

The Zuoz Bridge

Completed in 1901, the 38.25 m long Inn River Bridge at Zuoz (Figure 1) was the first concrete hollow-box ever built. It was

Maillart's first innovation. Cracks in the spandrel walls near the abutments led Maillart to cut out those walls in his 1905 Tavanasa Bridge, the first masterpiece of reinforced concrete design in the 20th century. The Fr. 85,000 renovation of Maillart's Zuoz Bridge centered around the fact that the bridge was an important piece of history and worth preserving. In addition to the arch having sunk and spread 4 cm horizontally on either side, the Zuoz deck and overhangs had suffered significant weathering, with much of the concrete cover having fallen off. The Zuoz Bridge hollow-box, reinforced concrete design still exhibited substantial reserve strength under asymmetric live loads in 1967.[1] Nevertheless, concern that the arch foundations might spread even further led the engineers to anchor them with four 50 ton rock anchors at either end.

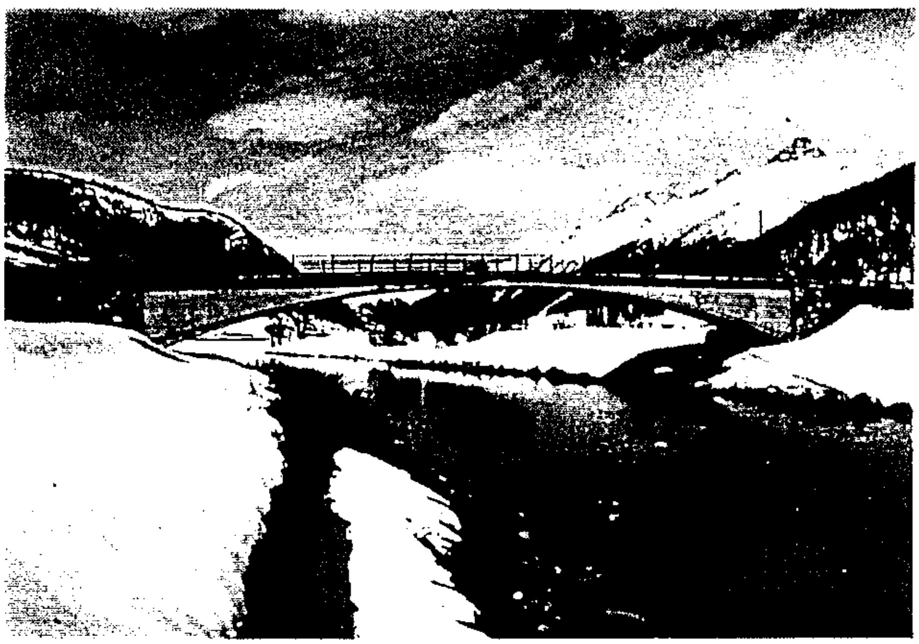

Figure 1: Inn River Bridge at Zuoz, 1901
(Fanzun, C., July 1967)

The deck was replaced entirely, also giving a chance to inspect the inside of the hollow box, which had survived in excellent condition.[2] First, the 20 cm cover was removed from the deck, and the deck was subsequently demolished and removed from the bridge. The inside of the hollow box needed almost no repair, and the work consisted mainly of forming, reinforcing and pouring the new deck (Figure 2). Since the original design had been dimensioned for a 6 ton traffic load, and much of the reinforcement had rusted, the engineers specified that the bridge should not be loaded to the modern 12 ton limit. Rehabilitation focused therefore on covering the bridge to prevent further moisture from corroding the structure.[3] This was accomplished by roughing the entire surface of the bridge and then guniting it with concrete.

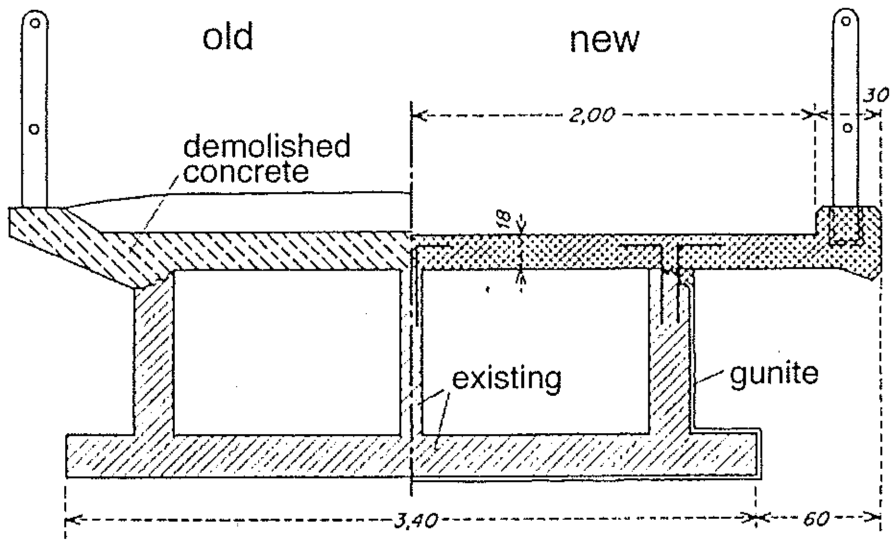

Figure 2: Zuoz Bridge deck replacement, 1967
(Favre, R., April 1969)

The Aarburg Bridge

Partly because of cracks in the 1912 Bridge, Maillart was stimulated in 1923 to design the first ever deck-stiffened arch bridge in reinforced concrete, a major innovation which led to his masterpiece of 1933 over the Schwandbach. Engineers in the 1960s debated whether or not to replace the bridge entirely, to replace only the deck while maintaining Maillart's original arch, or to restore the bridge to exactly the condition of Maillart's original construction. It was already clear that the principal danger to the bridge lay in its heavily cracked and corroded deck. In his original design for the Aarburg Bridge, Maillart had assumed the deck to behave as a continuous beam resting on the vertical supports which carried its loads to the 67.9 m long arch. He had therefore reinforced the deck only against negative moments above these supports and against positive moments between them. When the Aaburg deck eventually deflected with the arch under asymmetric loads, an entire side of the bridge was subject to positive bending. These bending moments, resulting from the bridge's global behavior under asymmetric loads, caused cracking in regions of the bridge which had been reinforced based on the assumption of local bending (Figure 3).

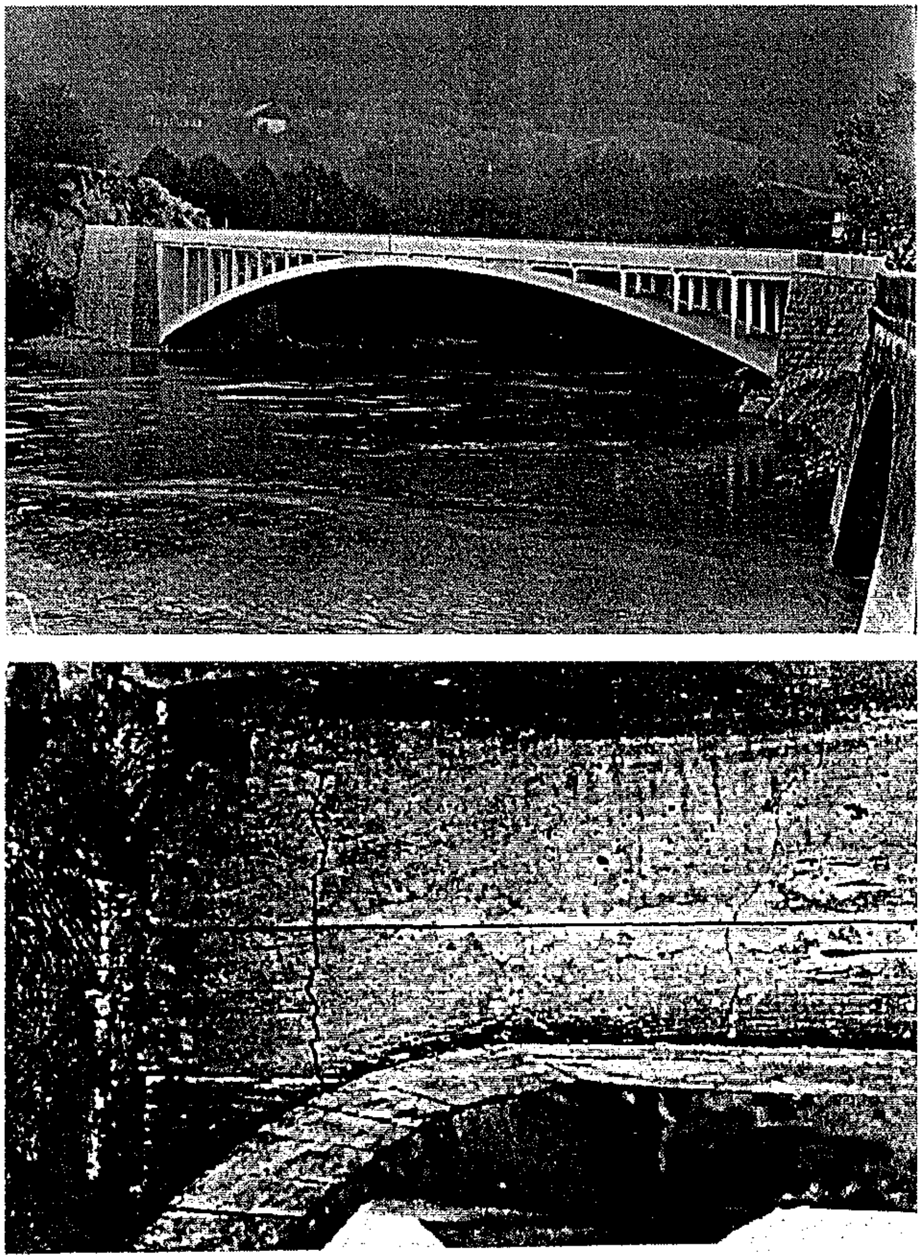

Figure 3: Aarburg Bridge, 1912, cracking caused by liveloads
(Maillart et Cie/Billington, D.P., 1979)

In November of 1966, the canton engineers of Aargau had recommend that traffic be reduced from two lanes to one lane, centered on the bridge's longitudinal axis. They recommended that the connection between the vertical supports and the deck be strengthened either by supporting the deck on transverse, vertical walls which carried the full width of the deck, or by strengthening the existing vertical supports with steel angles at each corner.

Furthermore, much of the concrete had spalled off, exposing many of the reinforcing bars to further corrosion.[4] Within another year, this carbonation had increased significantly, new cracks were observed and more concrete cover had fallen away due to the expanding reinforcing bars (Figure 4). This accelerating degradation led the engineers to recommend urgently that 16 ton trucks be forbidden to use the bridge until it had been repaired and that if it were not repaired soon it should be shut off from traffic all together.[5]

Figure 4: Aarburg Bridge, exposed reinforcement
(Baudirektion Aargau, 1967)

In 1968 the canton of Aargau decided to replace only the existing deck, widening it from 5.0 to 9.5m. It rejected the other options of replacing the entire bridge or restoring the original 1912 Bridge on the grounds that the first option would cost 50% more than renovation and that the second option would fall victim to the same structural problems as the original bridge. Citing later Maillart bridges such as the Salginatobel and the Rossgraben, the engineers defended their choice of renovation to a more rational design because it not only stiffened the bridge against buckling and vibrations but also avoided loading the arch near the supports where its curvature was flattest. In addition, the engineers had decided to prestress the new deck transversely due to its widening. Since grooves had to be cut in the arch for the placement of vertical stiffening walls, the engineers also had a chance to inspect both the concrete and the reinforcement in the arch.[6] The reinforcement was reported in excellent condition and the concrete had risen in strength from around 150 kg/cm^2 to above 500 kg/cm^2.

The bridge was reopened on November 19, 1968, only six months after construction had begun (Figure 5). With the arch already in place, there was no need for extensive scaffolding. The proposed cost of Fr. 790,000 had fallen to Fr. 600,000 thanks to intensive planning and a simplified construction procedure. The canton of Aargau paid 2/3 of this cost, 20% of which was paid by the town of Aarburg, while the canton of Solothurn paid the remaining 1/3. The engineers treated Maillart's Aarburg Bridge as a monument, worthy of great care and respect. "It is of course too bad that Maillart could not renovate his bridge himself, but we may hope that he would not have done it differently than we have."[7]

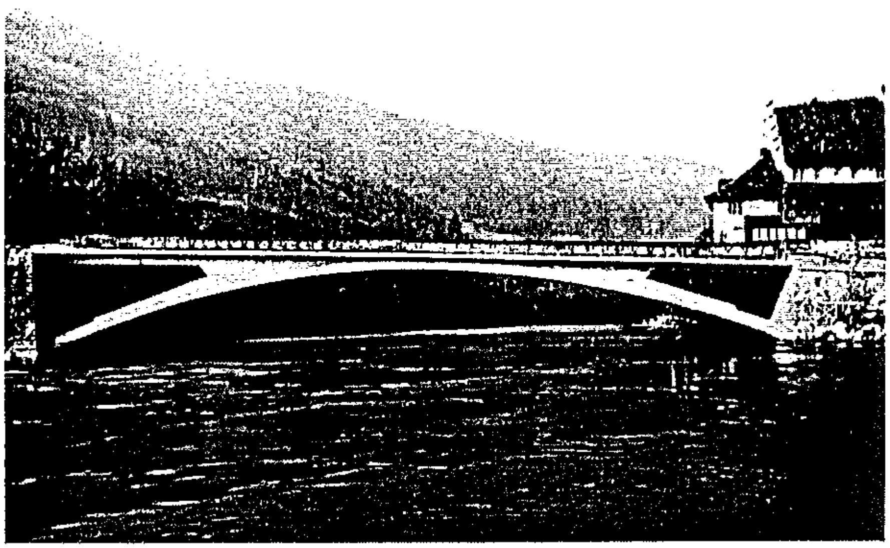

Figure 5: New Aarburg Bridge, 1968
(Favre, R., April 1969)

The Muota Bridge

Maillart designed this bridge as a hollow-box, cantilever beam, 39 meters long, under special consideration for the sandy bedrock which lay 5-7 meters under the Muota river bed. He doubted that such soil conditions could support a three-hinged arch, and therefore reinforced his bridge to carry tension in the top flange of its cantilever arm (Figure 6). Longitudinal cracks, up to 2 mm wide, eventually developed on the downstream side of the cantilever compression flanges. In 1977 these cracks were traced back to the fact that since the bridge had a walkway on the downstream side, the heaviest live loads always acted on the upstream side, eccentric to the bridge's centerline.[8] Engineers also concluded in 1977 that the bridge, after 64 years of settling, behaved more like a fixed arch than a cantilever under live loads. As an arch, compression forces between 500 tons and 700 tons appeared in the bridge effectively prestressing the middle portion of the span which had originally been designed as a beam.[9] Under live loads the bridge deflected 4 mm. Because the engineers had calculated the maximum theoretical deflection of this bridge as a fixed arch with E = 500,000 kg/cm^2 to be 5 mm, they could assume that the elastic modulus of the actual concrete, which was observed to be in good condition, was close to 600,000 kg/cm^2, far greater than the 140,000 kg/cm^2 assumed in 1913.[10] The bridge was protected against future weathering by an additional 2 cm thick concrete cover and was strengthened by filling in the entire underside compression flange, making it a true arch.[11]

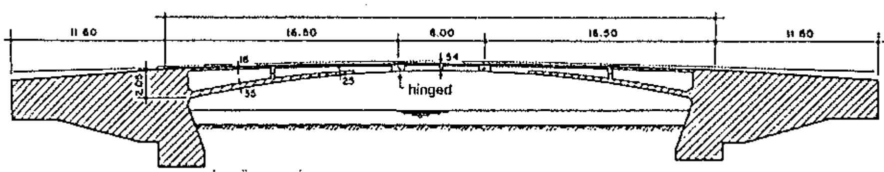

Figure 6: Muota Bridge, 1913, longitudinal section
(Weber, H., May 1979)

The Salginatobel Bridge

In 1991 the American Society of Civil Engineers designated this three-hinged, hollow-box arch over the Salgina Brook as an International Historic Civil Engineering Landmark (Figure 7). It was only the 13th work to be so honored and the first concrete bridge. It is Maillart's longest-spanning bridge (90 meters), his most famous work, and the result of a 1928 design competition in which his was the least expensive among 19 other designs. Completed in 1930, the bridge exhibited cracking in the deck and supports by the early 1970's and was rehabilitated in 1975.

Besides the badly worn hinge on the Schudders side which had collected water due to the explosives box attached to it, the entire deck needed to be strengthened and a concrete overlay added.[12] The 6 cm wearing surface as well as some of the concrete from the original deck were removed and replaced by 8 cm of new, reinforced concrete which gave the deck a new structural depth of 18 - 22 cm. The new deck received then a layer of insulation and 3 - 4 cm of new asphalt. In addition, a 10 cm width of the semicircular openings in the parapet were filled in with concrete, preventing runoff from dripping on the arch but still leaving a visual imprint of the original openings on the elevation view.

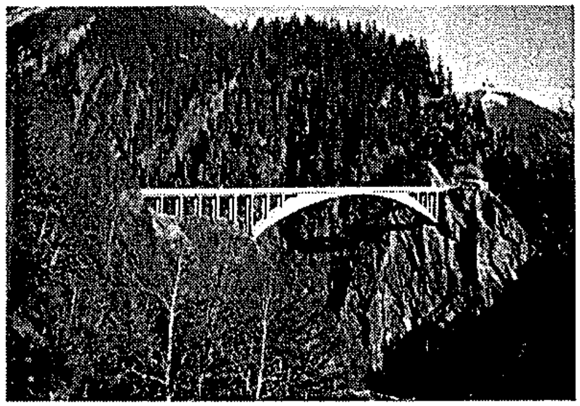

Figure 7: Salginatobel Bridge, new deck, 1975
(Maillart)

Conclusions

While many of Robert Maillart's bridges have needed significant restoration after 60 years of service, due to the slow degradation of concrete cover and corroding reinforcement, the aged concrete in these bridges has demonstrated strengths well above the levels for which it was designed. Clearly, major problems have occurred only in details such as concrete cover or at joints in the bridges, and these have been stopped or slowed simply by adding new cover on the order of 2 cm. Bridges in need of repair commonly owe their endangered condition not to overall degradation of materials, but to increasing traffic loads and to long-term settling. The foundations of the Zuoz Bridge had spread, and the Muota Bridge had deflected to the point that its original analytical model was no longer valid. Of course, for the strength of the Muota Bridge this was an advantage. In the case of the Aarburg Bridge, where an entire deck literally needed to be replaced, the arch had only grown stronger, and its preservation was decidedly less expensive than an entirely new bridge.

This supports Rey's 1979 statement, "The in-service behavior of bridge's is little influenced by the action of exterior load. On the other hand, service conditions which are often not taken into sufficient account, e.g., winter service, sharp temperature fluctuations and geotechnical conditions of the site, are determinant."[13] The experience of rehabilitating specific Maillart bridges suggests further that small concrete bridges of historical significance can and should be preserved. The concrete in these bridges, if originally high quality and if maintained, will endure and even grow stronger over time. Frequent inspection of such bridges is crucial in order to save time and money in their rehabilitation.

Acknowledgments

Acknowledgments

The authors would like to thank Kathy Posnett, Nicolas Janberg and Moira Treacy for their assistance in bringing the paper to its final version.

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