STRUCTURAL CONCEPTS AND ARTISANAL CONSTRUCTION IN R. MAILLART'S DESIGN PRINCIPLES

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ABSTRACT

During the first decades of 20th century, Robert Maillart (1972-1940) developed series of inventive structures on the basis a renewed vision of reinforced concrete. Projecting forward the conceptual principles of the pioneers (Lambot, Hennebique, Mesnager), structural forms liberated themselves from structural schemes protected in the first patents. Maillart went more steps further in this way, reinventing three-hinged arches, mushrooms slabs, and stiffened arches. Maillart was as an entrepreneur too: specific construction methods, that enabled these forms to be efficiently built in specifics contexts, were crucial in his research. For the works built in Switzerland, for example, artisanal know-how and not skilled local manpower were the reference point. This paper, starting from the research of the author in the field of structural design, summarise the evolution of Maillart's structural invention in parallel with the related fabrication approaches. A last part of the paper is dedicated to the further development of Maillart's structural invention in the dimension of the artisanal construction site.

RESUMEN

Robert Maillart (1972-1940) desarrolló series de estructuras inventivas sobre la base de una visión renovada del hormigón armado. Proyectando los principios conceptuales de los pioneros (Lambot, Hennebique, Mesnager), las formas estructurales se liberaron de los esquemas estructurales protegidos en las primeras patentes. Maillart fue más allá en este camino, reinventando arcos de tres bisagras, losas de setas y arcos rígidos. Maillart también fue un emprendedor: los métodos de construcción específicos, que permitieron que estos formularios se construyeran de manera eficiente en contextos específicos, fueron cruciales en su investigación. Para las obras construidas en Suiza, por ejemplo, los conocimientos técnicos artesanales y la mano de obra local no calificada fueron el punto de referencia. Este trabajo, a partir de la investigación del autor en el campo del diseño estructural, resume la evolución de la invención estructural de Maillart en paralelo con los enfoques de fabricación relacionados. Una última parte del documento está dedicada al desarrollo posterior de la invención estructural de Maillart en la dimensión del sitio de construcción artesanal.

Keywords: *artisanal construction, concrete, R. Maillart, structural design.*

1. INTRODUCTION

Robert Maillart (1872-1940) was a Swiss civil engineer and bridge designer that deeply influence the design of concrete bridges. His influence on the design of concrete structures and the world of engineering is also fundamental. Maillart is manly known for his design of about fifty bridges well documented in [1] and his invention of mushroom-slabs. His design methods: simplifying calculations [2], using implicit principles of lower bound theorem of plastic design [3], the use of graphic statics [4, 5], and of a geometrical thinking [6] are from now well known.

Nevertheless, it is worth to come back to dimensions of his work more focused of his conceptual approaches and constructive aspects since it highlights crucial steps in the invention of efficiency in building with concrete. This will be true about constructing concrete bridges but also in a more general way for concrete structures.

This paper starts with Mallart's very first bridges designs where he started giving attention to building methods to demonstrate how constructive rational can develop about concrete and influences his designs, then will review his further designs to show evolutions in his construction methods.

2. BASICS FOR BRIDGES DESIGN

One of Maillart's very first bridges is Solis Bridge (1900) made of stone. In this design, techniques used by roman construction as successive rings of stone masonry arches to build the structure of the bridge is used also [11]. This method will be reused for Maillart's first concrete bridges: Zuoz Bridge (1901), Billwil Bridge (1903), Tavanasa Bridge (1905) and is linked to Maillart's patent for box arch-bridges [7], that he will be calling: "the System Maillart". The basic idea was to build the hollow section of an arch made of a lower arch-slab, several longitudinal supporting walls and deck-slabs forming a box-section arch where his contemporaries built massive concrete structures. These, instead, had thickness of the arch between 90 cm and 120 cm. (Maillart also built this type of bridge as it was demanded so, but this leaded him to invent later his stiffened arch bridges.)

Box sections could be built as a sequence of three steps: first the lower slab of the arch, with starter rebars, supported by a light scaffolding, then longitudinal concrete walls supported by the poured arch bottom collaborating with the arch scaffolding, then the deck's slab closing the concrete box. In Tavanasa Bridge's promotional folder [8], Maillart argued that his characteristic form of three-hinged bridges was for lightness: "*The walls-tympanum, generally without opening in the bridges of this system, are here open so as to leave only the strictly necessary materials, so that the weight reaches a minimum*". This is therefore for economy of material, but also to reach a maximal lightness of the scaffolding.

These bridges belong to the series of three-hinged arch bridges and incorporate specific devices to assume articulation at springs of the arch and at the middle of the span. At that time, they were only made of simple sheets of lead that Maillart simply incorporates in the thickness of the arch. These bridges were kind of objects-structures finished with a metallic parapet and water could flow freely on both sides of bridges.

3. THEORETICAL FOUNDATIONS

Maillart inherited knowledges about reinforced concrete from several key-leading persons: Lambot, Hennebique, Mesnager. From Lambot who built a small boat made of reinforced concrete, he learned that this material was not a specific kind of masonry, but that can be comparable to timber and steel as it can be thin, light, floating, "watertight", uncracked, bending forces-resistant. From Hennebique, he learned way to calculate the structure and techniques to place reinforcement bars including stirrups for resisting shear forces. From, Mesnager, he learned ways to create hinges in concrete structures through thinning locally the concrete section and using crossing rebars to ensure the continuity of compression and shear forces through the hinge. Maillart also learned ideas that are more specific as in Tetmajer's work when cracks are assumed to be kinds of hinges in a continuous structure and therefore enable redistributions of the structural behavior.

All these theoretical foundations enable Maillart to capitalize on sound basis to devise the principle of the behavior of his bridges and sometimes devise some specific approaches for their design as for his stiffened arch bridges, processing by assembling separate structural components. If these principles are very valuable to design efficient and smart structural systems, they can lead to specific problems in terms of life span of the structure and its good behavior. Inattention to the fact that crack remains unwilled kinds of opening can lead to damages for the structure and are preferably to be avoided; concrete is not that watertight and can heavily suffer from moisture.

3. SALGINATOBEL BRIDGE (1930)

With a central span of 90 m, Robert Maillart's Salginatobel Bridge is his first large masterpiece using the principle of three-hinged concrete arch bridges. David Billington [1] and Maillart Archives demonstrate how its geometry originates from his previous there-hinged arch bridges as Tavanase Bridge (1905) and on more geometry-based dimensions from the arrangement of stiffened arch bridges as Valtschielbach Bridge (1925).

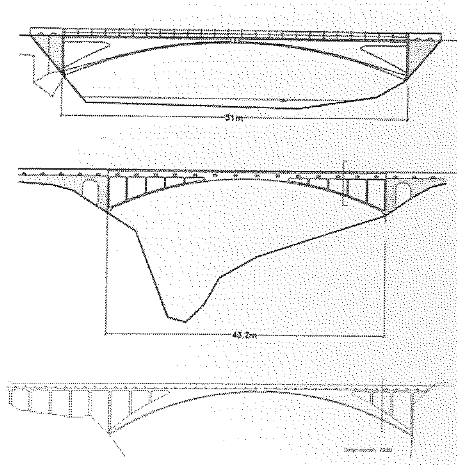

Figure 1: Tavanasa, Valtschielbach and Salginatobel Bridges [9]

His Salginatobel hinged arch Bridge integrates now perpendicular supporting walls as constitutive elements of the transfer of forces from the deck to the arch, due to the span of the deck between his supports, as for his stiffened arch-bridges.

It includes a not-bearing parapet – at the difference of stiffened arch bridge where they were constitutive of the structural system to manage live loads. Salginatobel Bridge's parapet includes semicircular opening to simply evacuate water on both sides, while concrete was considered as watertight. Nevertheless, we know from Figi [10] that the bridge has been restored a first time in 1975/1976, even if he fulfilled his role thanks to the geometry of a regularly compressed arch with very few bending moments, guaranteed its viability despite the very mediocre quality of concrete.

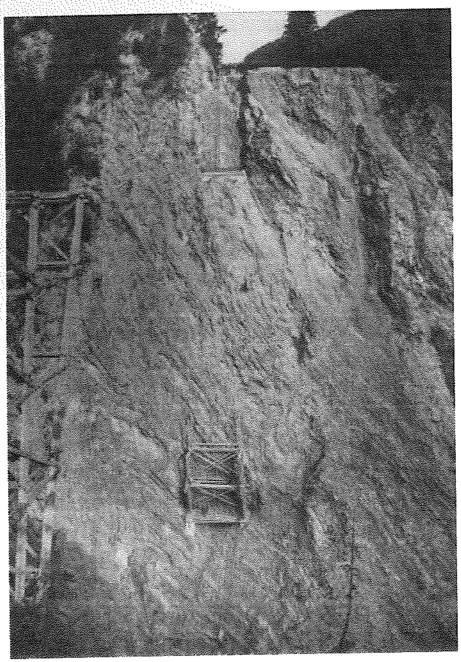

Figure 2: Preliminary carvings, Salginatobel Bridge [Hs 1085 1929-30-1 Salginatobel-Bruecke, ETH-Bibliothek, Archives and Private Collections, Maillart collection]

On the other hand, during the last restoration, the semicircular openings in the parapet have been closed and a regular system of drainage installed as it is henceforth visible under the bridge.

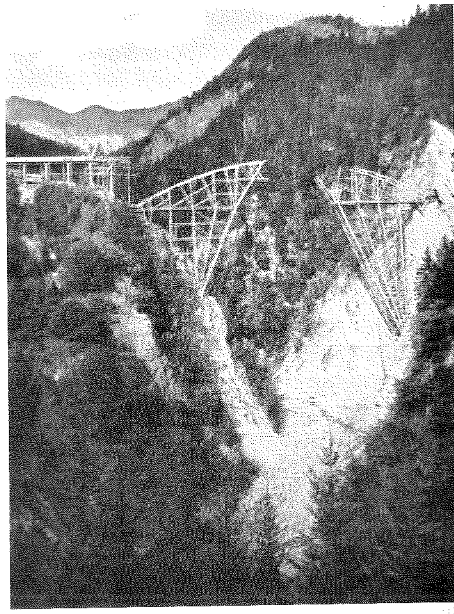

Figure 3: Scaffolding of the Salginatobel Bridge [Hs 1085 1929-30-1 Salginatobel-Bruecke, ETH-Bibliothek, Archives and Private Collections, Maillart collection]

R. Coray designed the formwork and its scaffolding of Maillart's Salginatobel Bridge in 1929 as a complex truss system taking some support in lower parts of the valley. Carvings were made in the rock of mountains walls to prepare the support of scaffoldings and massive foundations of the arches. His scaffolding remained quite light and narrow since the bridge was only 3.5 m wide. It is described by successive level quotation instead of providing the characteristics of the geometries that define the arches. The same technique of successive layers for the arch, longitudinal ribs, transversal support walls, girders and slab of the deck was used. But executions plans shows that even the lower slab was supposed to be poured in three successive steps or strips: a central one and two lateral ones with stepped joints for connection.

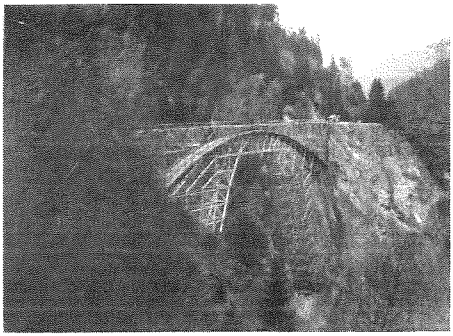

Figure 1: Salginatobel Bridge under construction [Hs 1085 1929-30-1 Salginatobel-Bruecke, ETH-Bibliothek, Archives and Private Collections, Maillart collection]

If this method to pour the concrete seems appearing nowhere else in the technical dossier, we can expect that this method was close to the way Maillart realized the supporting arch of the Lorraine Bridge in Bern (1928-1930) with concrete blocks, as described by Billington [11]. As visible on plans, Maillart sometime used projected graphite at specific construction joints as a kind of anti-bound material, what is a technique that seems not been used somewhere out of his work.

Steel reinforcement of concrete works is very similar to the one still in use today, with classical longitudinal bars, stirrups and surface meshes to control cracks. The arches included concrete hinges constructed this time following the Mesnager's model: the section of the arch is reduced, with wedgings made of hard wood on one side, and cork on the other side. The steel reinforcements from arches and ribs change their trajectories to cross simply in the middle of the hinge. Most of the constructive arrangements as described for this bridge will remain in use for Maillart's further works.

A special attention was given to local work and material. Maillart frequently argued in favor of reinforced concrete for structures in Switzerland – a land of remote valleys – since all that was needed was to transport cement and steel reinforcement on site where gravel, sand, water and wood for scaffolding were already there. Salaries would be paid to local workers and suppliers too [1, p. 10].

4. EVOLUTIONS IN LATER WORKS

Evolutions in Maillart's methods for design and construction occurred for further bridges. For these, variations in the average geometries, sections, structural features and construction techniques will be observed. In Maillart's Rossgraben Bridge, substructures supporting scaffoldings have been prefabricated on banks of the river. Such structures will then be lifted and set in place with techniques depending on the type of supporting structures they have. Either cantilevering from banks with towers and retaining cables, or funicular cables running above the bridge to be built have been used for this.

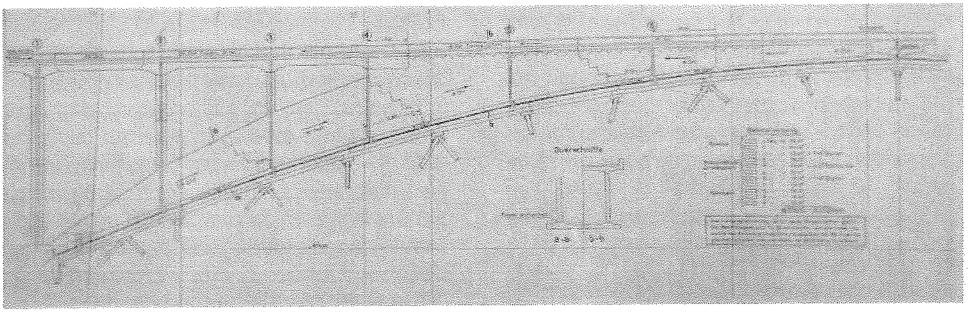

Figure 1: pouring stages of the Rossgraben Bridge [Hs 1085 1932-3 Rossgrabenbrücke über das Schwarzwasser bei Schwarzenburg, ETH-Bibliothek, Archives and Private Collections, Maillart collection]

Variation in the sequence of pouring phases will also be observed. Larger segment of the arches will be casted in one step: segments including the arch and their ribs where poured together, with something as 4 steps for half an arch. For the Salginatobel Bridge, even the lower slab of the arch – without its ribs – was poured in three parallel strips in the longitudinal direction, for a width of the bridge of only 3.5 m.

General geometries evolve, becoming more and more flatten along time, depending also on the span of the bridge: from arc of circles and parabolic lines in the Salginatobel Bridge, evolutions can be seen toward two arcs of a circle on each half a bridge [Rossgraben Bridge, 1932]; a straight line and an arc of a circle [Maillart's 'projet 1' sketch for the Vessy Bridge, 1936]; collections of straight line segments to make a funicular polygon [Schwandbach Bridge, 1933]; one arc of a circle on half a bridge, with a broken line at the key of the arch [Lachen Bridge, 1940]; only two straight lines with a broken line at center [Garstatt, 1939-40]. Simultaneously, bridges became wider and new techniques could be used to construct them. The Vessy Bridge (1936, 10 m wide) is made of thee parallel box-arches for which a complex system of scaffolding and formwork was designed: a fixed part underneath of the width of the bridge, and a mobile part of the width of an arch only, that was reused three times.

More flatten arches are not without problems since they require multiple supports in the riverbed: During the construction of the Vessy bridge, flooding damaged the system of scaffolding of the bridge. Another point is that first Maillart's box sections for his arches become more and more flat in his last bridges so that a nowadays well-known problem for box sections start occurring: still water is kept on the bottom of boxes that are at the origin of serious damages to concrete. Simultaneously, for the Vessy Bridge, Maillart implemented a system of suspended drainage in box section to solve problems that were met in his previous bridges, where managing water was not supposed to be a problem… but lead to problems, as we have seen for the Salginatobel Bridge.

Considering steel reinforcement of

concrete, Maillart's prescriptions are quite canonical and very few evolutions could be seen compared to contemporary structures. Maillart nevertheless sometimes required rather complex forming for rebars to be integrated in his structures, that we would not use any more today. Maillart's correspondence in preparing the call for biddings stances on the point that his bridge required well-skilled workers as for him his Vessy was a complex structure.

Another type of bridge, that Maillart used extensively before his invention of arches with a strongly off-centre thrust line (1934) and his use of continuous girder bridge (1935) [12], is stiffened arch bridges. These bridges illustrate perfectly the principle of the sequential construction of arch structures, since the "funicular arch" – sometime included as a polygonal thrust line into a circular arch – is poured first and alone on a light formwork; then transverse supporting walls, and finally the deck's structure will be added as soon as the supporting arch has set. Even if Maillart seems to have abandoned this structural type at the end of his career, it remained used by other designers, most of the time in remote places, namely in Switzerland and in Italy.

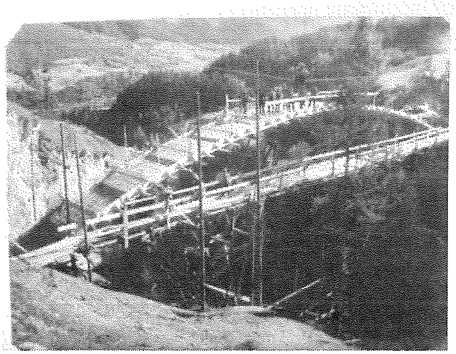

Figure 1: Valtschielbach Bridge under construction [HS 1085 1926-1 Valtschiel-Brücke bei Donath, ETH-Bibliothek, Archives and Private Collections, Maillart collection]

CONCLUSION

This paper illustrates developments in construction of bridges with concrete during the first 40 years of the 20th century in Robert Maillart's work. If his first realization were made by poorly qualified workers, Maillart reached progressively such a complexity level that at the end he strictly required skilled workers on building sites [13]. In reviewing the successive evolutions, we measured all his inventiveness, even without mentioning the development he made of mushroom-slabs with an elaborate system of geometrical definition and a smart work in the direction of simplifying steel reinforcements. Maillart's works or techniques have been hold as reference points: Ricardo Morandi (1902-1989), for who Maillart was a reference, use similar techniques of parallel arches for his Fiumarella Viaduct in Catanzaro (1962), Chistian Menn (1927-1918) built stiffened arch-bridges as in Reichenau (1964) or for the Rhine-Bridge in Tamins (1963); more examples still exist in Italy also. Maillart's box-sections are from then used universally for bridges design. Only few specific problems existed in Maillart's bridges: they are linked to moisture and carbonatation... For them Maillart had simply overestimated properties of concrete.

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REFERENCES

[1] M. Bill, *Robert Maillart, Ponts et Constructions*, 2nd edition, Zürich: Girsberger, 1955

[2] D. Billington, *Robert Maillart's Bridges, The Art of Engineering.* Princeton: NJ, Princeton University Press, 1979

[3] J. Ochsendorf, "Practice before theory: The use of the lower bound theorem in structural design from 1850-1950," in *Essays in the history of the theory of structures*, Madrid: Instituto Jean de Herrera, 2005

[4] D. Zastavni, "The structural design of Maillart's Chiasso Shed (1924): a graphic procedure," Structural Engineering International, vol. 18(3), 2008, pp. 247-25

[5] D. Zastavni, "What was truly innovative about Maillart's designs using reinforced concrete?," in *Proceedings of the Third International Congress on Construction History,* Berlin: Neunplus1, 2009, pp. 1539-1546

[6] D. Zastavni, C. Fivet (2015). "Purely geometrical considerations during the design of bridges in the early 20th century – The case of R. Maillart," in *Proceedings of the Fifth International Congress on Construction History*, B. Bowen and Al., & Donald Friedman, Thomas Leslie, and John Ochsendorf Eds, First Edition, 2015, Vol.3, pp. 637-644

[7] R. Maillart, "Bogen-trager armiertem Beton", Switze Patent 25712, Fev. 18, 1902

[8] Maillart & Cie, ingénieurs entreprise de travaux en armé, Genève, "Pont sur le F Tavanasa" in *HS 1085 1905 Brücke über den Rhein Tavanasa.* Zurich: ETH-Biblic Archives and Private Collec Maillart collection

[9] D. Zastavni, "La conception Robert Maillart: Morphogenès Structures Architecturales," dissertation, LOCI/ UCLouvain, Louvain-la-N 2007

[10] H. Figi, "Rehabilitation of Salginatobel Bridge", *Struc Engineering Internati* Vol.10(3), 2000, pp. 21-23

[11] D. Billington, *Robert Ma Builder, Designer, and A* Cambridge University Press, 1

[12] D. Zastavni, "*Maillart's de approach: Where graphic st and geometry start... and e* Research Workshop, Chair Structural Design – Prof. Joseph Schwartz, - Villa Garb Castasegna, 28-30 August 201

[13] R. Maillart, "Letter 2 Oct. 1935 *Hs 1085 1935-36-1 Brücke übe Arve bei Vessy-Genf.* Zurich: E Bibliothek, Archives and Priv Collections, Maillart collection

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