Maillart's Practices for Structural Design [ETH-Bibliothek's Virtual Exhibition]

Denis Zastavni
Université catholique de Louvain, Louvain-la-Neuve, Belgium

The structure of the exhibition as detailed below reflects what is known to be representative of Maillart's approach: it is rooted in the specific features of ETH at the end of the 19th century, contextualised within the structural practice prevalent in the late 19th century, intrinsically connected with ways of constructing with concrete at that time and presents Maillart's major structural types. All these features of Maillart's work are reviewed below and an attempt is made to summarise what contributes to the specific nature of these works. The contents below are supplemented by visual material and descriptions that can be found online at the ETH-Bibliothek's [Eidgenössische Technische Hochschule-Bibliothek] CMS website (Fig. 1).

The origin of knowledge of Maillart's work

Robert Maillart (Fig. 2) was born in 1872 and he practised engineering between 1894 and 1940. His works gained a certain success as his career progressed. Certain facts had an influence on the extent of his renown during his lifetime: his great creativity, his writings, notably in the *Schweizerische Bauzeitung [SBZ]* and later recognition by *RIBA* in 1937. Shortly after his death, Sigfried Giedion's book (1941) and Max Bill's publication (1949) presented his work and made him famous in the world of engineering. Maillart introduced his work, structural thinking and analytical results in his own publications. He also presented some of his structural types at international conferences (Maillart 1930; Maillart 1932).

Sigfried Giedion (1941) showed his contemporaries – mostly in the field of art – that developments were being made in the creation of structural forms with concrete. He had already written papers on Maillart's work during Maillart's lifetime, but his masterpiece *Space, Time and Architecture* was published after Maillart's death. Giedion emphasised the innovative forms devised by Maillart and began to show his influence on architecture. Max Bill (1955) collected Maillart's work and documents, mainly from the material available at the SBZ, to compile them into a book that still offers the best pictographic synthesis of his work today.

Professor D. Billington has spent a significant part of his academic career studying Maillart's work. His first publications were in reviews (Billington 1973; Billington 1974; Billington 1980) and his first book on the subject of Maillart's methods was published some later (Billington 1979). He compiled Maillart's archives in the ETH-Bibliothek and published Maillart's complete biography twenty years later (Billington 1997). He subsequently spent time putting together exhibitions on Maillart's work and published books on Swiss masters of engineering. Other authors have since studied some specific aspects of Maillart's work, such as Fürst and Marti (1997) in *Robert Maillart's Design Approach for Flat Slabs*. From an exhibition on Maillart's work in 1995, an interesting synthesis in German was published in 1996 (Marti and Honegger 1996) and two later editions published (Marti and Honegger 1988, 2007).

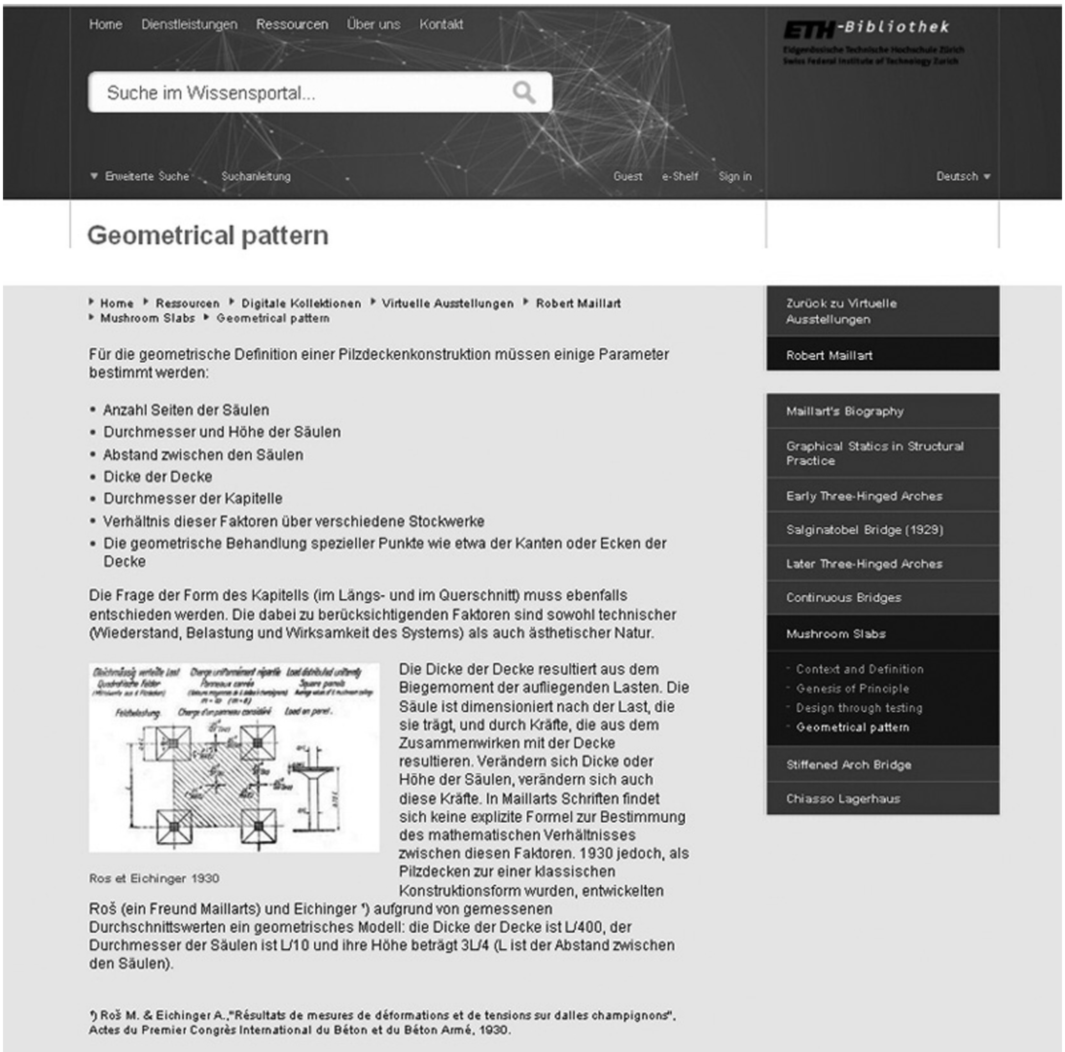

Fig. 1: ETH-Bibliothek's virtual exhibition at the CMS website (ETH-Bibliothek).

From 2007, we have contributed to supplementing knowledge of Maillart's approach by studying his specific use of graphic statics to create his forms and taking into account parameters such as geometrical patterns, the status of the materials and the structural consequences of deformations under stress in some of his structures (Zastavni 2008a; Zastavni 2008b; Zastavni 2009; Zastavni 2012; Fivet and Zastavni 2012). From the beginning of 2011, the project to build a virtual exhibition making use of Maillart's archive in the ETH-Bibliothek has seen the light and is still under construction at the time of writing this paper.

Maillart's biography and the context of his practice

The virtual exhibition will cover the major periods and relevant facts of Maillart's career. It began

Fig. 2: Robert Maillart [1872-1940] (ETH-Bibliothek Zurich, Image Archive).

in 1894, but he only designed his first significant bridge, the Zuoz Bridge, with the invention of the concrete box girder – the Maillart System – in 1901 (Billington 1997, 28). This marked the beginning of a series of three-hinged arch bridges as detailed below, soon followed by other typical typologies in reinforced concrete. The fact is that Maillart's innovations do not appear outside a specific context. On one hand, Maillart was trained in the use of the Hennebique License; on the other, he studied engineering under very enlightened teachers and furthermore was trained to use graphic statics to analyse bridges.

The first structural applications of reinforced concrete came in around 1880, with the first important bridge in reinforced concrete being François Hennebique's Châtellerault Bridge in 1889. Maillart was sensitive to architectural expression in industrial facilities such as silos. The construction system of reinforced concrete is comprehensive from Hennebique's patent for stirrups (1880). Reinforced concrete began to be codified from the very early 1900s. What still needed to be produced was the synthesis of these particular features of reinforced concrete into new appropriated forms for the structural arrangement of various types. This was exactly the area in which he was to excel. The fact is that Maillart had a deep understanding of the workings of concrete depending on the way in which it was loaded, so Maillart invented scenarios for its workings: strictly compressed concrete [vaultings and assimilated structures, with or without reinforcement], bent concrete as real reinforced concrete [mainly beams or stiffeners], strictly stretched concrete as a protected steel, concrete membrane and finally hybrid concrete works. Each of these particular concrete statuses corresponds to specific typologies.

Also to provide correct dimensioning for a concrete structure depending on the forces encountered is not the same as devising the most suitable form for the structure according to its role. Some may think that this is a matter of optimisation, but more fundamentally there is a specific approach in Maillart's work to give form to these structures. It is supported by graphics: geometry and graphic statics. It implies the careful choice of reference loadings, recourse to geometrical patterns, recourse to specific geometrical curves to establish the structural arrangement and subsequently the use of an equilibration configuration to improve structural behaviour.

It is no accident that graphics were at the heart of his training. The ETH was founded in 1855 and both Gottfried Semper and Karl Culmann contributed to the spirit of the school of engineering. Semper was known for his influence in the world of construction and he strongly promoted the approach of "rational" architecture, sustained notably by its structural dimension. Karl Culmann is considered to be the founder of graphic statics as a fully constituted method for analysing structures (Culmann 1866). Maillart attended lectures with the direct successors of each of the two men, Benjamin Recordon and Wilhelm Ritter respectively. It is known from his archives that

Maillart attached great importance to Benjamin Recordon's lectures (Billington 1979, 6). Ritter also extended Culmann's work with the applications of graphic statics, published in four volumes from 1888 to 1906 (Ritter 1888, Ritter 1890, Ritter 1900, Ritter 1906), but also for his sound knowledge of concrete systems (Gori 1999; Ritter 1899) and bridge construction (Ritter 1895).

It therefore appears that Maillart could practise in a fertile environment where the knowledge of concrete, techniques such as graphic statics and a culture of the construction provided his own background. What had to be promoted were suitable forms for constructions made of concrete and a wide range of structural forms were still to be invented. Maillart took up the challenge brilliantly.

Maillart's three-hinged arches

From the beginning, the principle of hinged arches seems to be alien to the intrinsic nature of concrete: a material which becomes monolithic as it sets. This idea is nevertheless central to the invention of the Maillart system in the Zuoz Bridge of 1901. The first concrete box girder was a complementary association between the arch, the supporting walls and the deck of the bridge. Nevertheless it did not escape the attention of Prof. Wilhelm Ritter on the occasion of his recommendations concerning this bridge or Prof. Ludwig von Tetmajer as early as 1883 (Maillart 1932b) – both associated with ETH Zürich – that cracking is an intrinsic feature of the behaviour of concrete which has to be anticipated with the risk of unexpected consequences. Maillart came round to this opinion and from the outset envisaged hinging his arched bridges to anticipate variations in dimensions or movements in the support, but also the cracking of concrete as a particular type of vaulting joints. Zuoz was to be his first experience of a three-hinged concrete arch – partially successful – that subsequently led to his masterpieces: Tavanasa Bridge [1905], Salginatobel Bridge [1929], Felsegg Bridge [1933], Vessy Bridge [1936] and Lachen Bridge [1940]. Initially, lead sheets served as hinges, interrupting the arch by being inserted within the thickness of the concrete sections. Later – actually from the Salginatobel Bridge (Fig. 3) onwards – Maillart adopted the Mesnager-Freyssinet system of concrete hinges by using Considere's system of a hinge made from crossing bars in a concrete section [Considere's patent of 1907] and the principle of something similar to a plastic hinge as defended by Freyssinet. Calculations of the Salginatobel Bridge show that both aspects were taken into consideration when estimating the resistance of the hinges (Maillart 1928).

A series of three hinges enabled the trajectories of thrust lines to be defined. All that was required was to organise the positioning of appropriate amounts of material depending on the variation of the position of thrust to control the associated bending. This method of capitalising on the geometry of his own earlier reference constructions, relying on regular geometry such as the circle or parabola even if they had no relation to a funicular configuration, simplified evaluations of load distributions enabling thrust lines to be drawn [using graphic statics], the recursive evaluation of thrust lines depending on trial elevations and transversal sections drawn around the thrust line drawn in the previous step are all methods used for the design, as shown elsewhere (Zastavni 2009; Fivet and Zastavni 2012). This approach goes beyond Culmann and Ritter's conception of graphic statics as a science intended for structural analysis to become a morphogenesis method enabling the bridge to be drawn. This way of thinking through the structural issue was shown particularly with the design procedure evidently

Fig. 3: Salginatobel Bridge [1929] (D. Zastavni).

adopted for the Chiasso Shed (Zastavni 2008b). This makes Maillart a challenger for the title of inventor of the application of graphic statics from the perspective of morphogenesis, since from what we currently know no one had ever done anything similar before him. Another aspect that has not been revealed until now is the positive influence of the differential settlings under foundation blocks that – while they might appear a logical consequence of limited latitude in designing the support of the foundation blocks – nevertheless have a very positive influence on the arched bridge. The advantages, as shown in Maillart's Vessy Bridge (Fig. 4), are to maintain compression and lessen the vertical displacement of the key of the bridge. These aspects all, to some degree or another, constitute Maillart's approach to designing three-hinged concrete arches. The virtual exhibition planned on the ETH-Bibliothek's servers includes all the hinged bridges mentioned above.

Maillart's mushroom slabs

Chronologically, the second structural type developed by Maillart was the mushroom-slab system [Maillart's patent no. 46928 of 1909]. Maillart was aware of experiments across the Atlantic with systems of rigidly connecting slabs to supporting columns using capitals of various forms. Faced with this issue, Maillart started his analysis with a theoretical analysis of the punching stresses and a series of full-scale tests (Fig. 5) from 1908 to study the interaction between different parts of the continuous hyperstatic slab and its supporting columns (Maillart 1926). There was no way of studying the behaviour of the slab theoretically – and *a fortiori* the interaction with its supporting columns – at that time due to the excessive mathematical complexity involved. In any case, the results he obtained depended on the geometrical definition of the system itself, including: the number of sides of the columns; the width and height of the columns; the distance between columns; the thickness of the slab; the width and form of the capitals [the geometry of the rigid connection of the columns to the slab]; the evolution of these dimensions over different storeys; the geometrical treatment of special points, such as the edges or corners of the slab. Maillart built a system on a geometrical canvas that to a certain extent could be adapted using tables including specific coefficients (Maillart 1932a). An evolution took place from the first prototypes of mushroom slabs with octagonal columns and capitals presenting a hyperbolic line – as built in Zürich-Gieshübel in 1910 (Fig. 6) – to the last arrangements with the columns becoming square and capitals evolving towards a parabolic line.

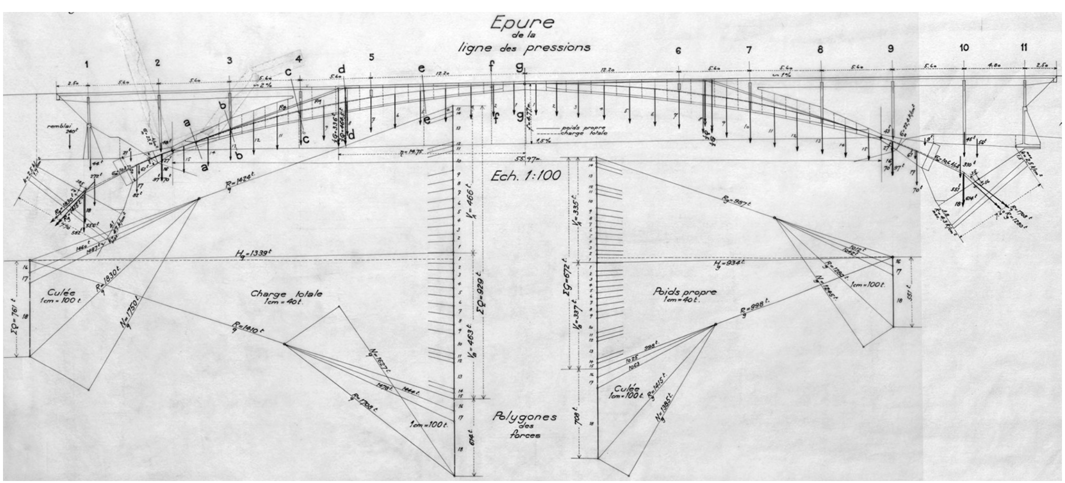

Fig. 4: Vessy Bridge [1936] (ETH-Bibliothek Zurich, Image Archive/Robert Maillart Archive).

Fig. 5: Full-scale tests of Maillart's mushroom slabs [1908] (ETH-Bibliothek Zurich, Image Archive/Robert Maillart Archive).

Fig. 6: Zürich-Gieshübel Warehouse [1910] (ETH-Bibliothek Zurich, Image Archive/Robert Maillart Archive).

From the basis of a canvas that to a certain extent could be adapted, the integration of the system has to be seen in the perspective of the resulting appearance, considering the issue of superimposing storeys and adapting the system to specific situations such as a sloped roof or wide spans. The question of steel reinforcement also arises, with Maillart's answer being the *Zweibahnensystem* [a two-way system only].

From the new issue faced of the continuous system of a concrete slab [as Maillart noted in this context in particular that concrete becomes monolithic as it sets], Maillart devised what he called the European system and the experimental method to develop it. The result is an arrangement where no specific aspects have been left out. He proposed a fully functional and rational system promoting a new aesthetic for industrial spaces, while reducing costs lay at the core of his approach.

Maillart's stiffened arch bridges

This structural type is probably the most characteristic of Maillart's approach to structural design. His first bridge of this type was in 1924 when he was 52 years old. This was therefore the work of a mature engineer, while noting that the majority of his most famous structures came after this time. Much has been said about this issue of designing this structural type and D. Billington has described it very well (Billington 1973; Billington 1979; Billington 1997). Maillart designed 13 bridges taking this approach, of which 12 were built. The most famous are probably Donath's Valtschielbach Bridge [1925], Hinterfultingen's Schwandbach Bridge [1933] and Winterthur's Töss footbridge [1934]. D. Billington has shown the recurrent use of simplified – or approximated – calculations or analysis (Billington 1979). In Maillart's day, it was considered improper, as a fault in managing the complexity of the arrangement of this structure. These structures are an example of managing complexity: considering the Valtschielbach Bridge (Fig. 7) – perceived by his contemporaries as an arched Vierendeel-like structure with the characteristics of the various members being radically different – he solved the complete system in just three-and-a-half pages, whereas the approach envisaged by his contemporaries required at least one hundred or so pages, with no guarantee that the result would be relevant. It has been shown that the structure was nevertheless correctly dimensioned.

Maillart's approach was to superimpose elementary structural mechanisms to build the complete structural response for the arrangement, but ignoring the interactions between various elements. This approach was typical of that taken by engineers in the 19th century. Maillart nevertheless ensured that such interactions would not occur by providing a preliminary dimensioning of the proportion ratios of the constituent elements' mechanical properties [stiffness], adding another

Fig. 7: Valtschielbach Bridge [1925] (D. Zastavni).

type of property to this: the "geometrical" stiffness [against axial forces depending on the kind of loading]. This "geometrical" stiffness was designed using graphic statics to define the suitable geometry. This reasoning for an arch is only viable if supports are excellent and do not settle under loading. An interesting contribution has been made by J. Ochsendorf (2005) linking this structural method of design by adding separate structural mechanisms to plastic design. This enables the simplified calculation to be perceived not as a dereliction of duty or an easy way out, but as an illustration of the use of the lower bound theorem of plastic design. Thanks to this, from someone considered negligent, Maillart can now be seen as something of a forerunner, since theorems of plasticity would not be fully developed until the middle of the 20th century. His approximations therefore become a central part of a consistent method.

More structural types designed by Robert Maillart

Maillart contribution to the art of designing structures was no trivial matter. While he invented the notion of the shear-centre (Timoshenko 1959, 405), he became known more for the realisation of actual structures. Other structural arrangements are worth mentioning as they invite yet another mode of reasoning. One is the continuous bridge in the shape of a hyperstatic girder. In this specific structural family, Maillart's designs include the Liesberg Bridge [1935] and Grindelwald Bridge [1937]. Here it was a matter of bending as the overriding behaviour and their design also illustrates the simplified formulation used to calculate resistance against such loading. The analogy with the form of the diagram of bending forces is well set out, with some creative solutions such as when insufficient depth was available to Maillart and he chose to deploy the material in the transverse direction. These structures could be seen as heralding the latest developments in concrete bridges in the shape of integral bridges built today. A final design, even if it dated from 1924, is the remarkable structure of the Chiasso Shed. In this design, Maillart reasons with funicular trajectories to be equilibrated within the arrangement of surrounding members [columns, the roof's covering slab, supports for the cantilever edging], where the roof is a kind of elaborate variation of the mushroom slab, while ensuring resistance to various loading cases with stiffening mechanisms, such as the one found in his stiffened arch bridges.

The wide range of structures designed by Robert Maillart, considering their great aesthetic and environmental qualities, certainly merit such attention being accorded to his work However, what is even more interesting is that this creativity is sustained by original design methods that contrast heavily in their inventiveness and results with the approach taken by modern engineering sciences. It is not possible to summarise Maillart's contribution satisfactorily in this paper. At each step this requires an evaluation of the outcome of the design by illustrating it with numerous photographs from archives while attempting to show how he attained this result. This is the challenge we face in our attempt to create a virtual exhibition for release in 2012 in collaboration with the ETH-Bibliothek. We hope this will help keep in mind this rare example of the complete mastery of the structural issue as achieved by Maillart in the first part of the 20th century. Therefore, his approach is taken with the conscious involvement of the designer in defining structural behaviour and features, and crossing technical motives and practical considerations with aesthetic perspectives. This reasoning has all the features of a fully assumed approach to the design of engineering masterpieces.

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