

## **What ideas does Maillart's eighty-year-old approach give us about how a concrete structure could be designed in the 21th century?**

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### **Abstract**

With a summary of what the authors consider to be the fundamental challenges encountered in designing structures, this paper aims to explore elements of Maillart's approach to designing structures to show how these ends are encountered naturally as soon as the basis of the design approach is soundly established. While showing how Maillart proceeded to conceptualise and design the Zuoz Bridge (1901), the Salginatobel Bridge (1929), the Vatschielbach Bridge (1923) and the Chiasso Shed (1924), the main features of his methods can be summed up as follows: after carefully establishing structural behaviour, the lateral form was defined by developing a design from a series of graphic statics drawings, while algebraic calculations allowed him to determine the transversal section and details of the plan and profiles. It may be one of the first occasions when graphic statics have been used as a heuristic method to discover the right form, i.e. as a design tool for morphogenesis. Studying the geometry of the Chiasso Shed demonstrates the way Maillart used graphic statics – a powerful tool for equilibrating the structure with the aim of placing materials in the right position within a structural system. As Maillart was also a builder, he integrated aspects into his design taken from construction, which made his projects particularly cost-effective. Finally, we conclude from this analysis of Maillart's work that there is a sense – during the design process – of giving priority to thinking globally about form and the status given to concrete in order to come up with efficient and reliable designs.

**Keywords:** Maillart (Robert), concrete, visual and conceptual approach of design, economy, design methods, reliability, structural efficiency

## **1. Maillart's point of view**

Maillart began designing structures in around 1894 and started designing for himself by 1900. The first structure of real significance that made an impact dates from 1905 (the Tavanasa Bridge). The major works of his career began to appear in around 1925 when he was over 50 (Bill [1]). What we know of Maillart is that he was a mature engineer who was well into his stride. Retrospectively, his view on structural problems could prove to be very enriching, even in a contemporary context.

It is not possible to understand Maillart's methods fully without considering the principles he assigned to the very beginning of the design process. These principles are intimately bound up with the material he decided to use for his structures. It turns out that for the time and for the physical and social context in which he lived, this material had to be – according to Maillart – reinforced concrete

Maillart argued that Switzerland is a land of remote valleys where all that had to be brought in to build a structure was cement (the wood for formworks, and water, sand and gravel being on site already). Therefore the construction will bring in money for local workers and stimulate the local economy (Billington [2]). And Maillart argued more profoundly along those lines, considering the properties of steel structures, maintenance, security, etc. (Maillart [3]).

When Maillart began to design with concrete, suitable structural forms for this material still had to be invented, as did methods for analysing the concrete framework too.

At the origin of Maillart's designs are principles about the structural behaviour of a framework made in a given structural material and its intrinsic properties.

Since concrete is an artificial, reconstituted stone, the principles of masonry vaulting apply to concrete arches. Since it is a material that is reinforced for encountering traction stresses, the principles of bending beams apply. Since cracks in concrete cannot be avoided, and since cracked sections seem to behave like joints in masonry vaulting according to the principles expressed by Tetmajer (Maillart [4]), the image of discontinuous rigid sections articulated together applies. Therefore hinged connections in concrete are possible.

For designing, all that was left was to establish the structural behaviour of the entire structure (compressed, bent or stretched first etc.) to organise the components of the structure into a hierarchy according to the wide variety of loadings encountered. Considering this prerequisite, appropriate methods and tools for establishing the structural form in its details and dimensions can be considered.

### **1.1 A review of the determining principles of some of Maillart's structural forms**

The Zuoz Bridge (1901) was Maillart's first real invention with the proposition for a concrete box girder (for the arch profile), the first one ever built (Billington [5]). At the origin of the form is a three-hinged U-shape arch (fig.1) – apparently semi-circular – which has become monolithic by its connection with the longitudinal walls bearing the deck. The calculation

file seems to be very patchy and we know from D. Billington [2] about the difficulties encountered by Wilhelm Ritter, his former teacher, in finding ways of calculating this bridge (he failed to discover an appropriate method, but he agreed on the principle of the bridge, which allowed it to be built).

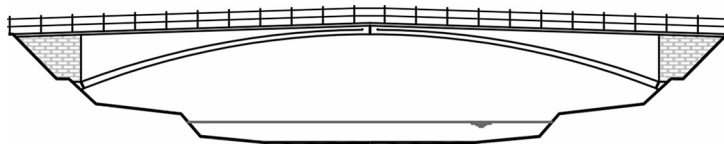


Figure 1: Maillart's Zuoz Bridge (1901)

The principles regarding the form of the bridge's arch are not so far from those of a massive concrete bridge (the Monier system) which are derived from a principle of masonry vaulting. But hinges along the arches already changed some of the data of the problem encountered.

With the second major work of his career, the Tavanasa Bridge (1905), we see for the first time the characteristic forms Maillart gave to his three-hinged arches. What led him to envisage the lines of his revolutionary arches was an elimination of the cracking zones of concrete where it encounters no forces or stresses.

To draw his lines, Maillart made use of funicular polygons to calculate the thrust lines in the structure, but its geometry remains – from what we can see by working out the drawings – very classic: a circular underside for his arch. Transversal sections are defined using graphic statics, in a similar way to what we will see below.

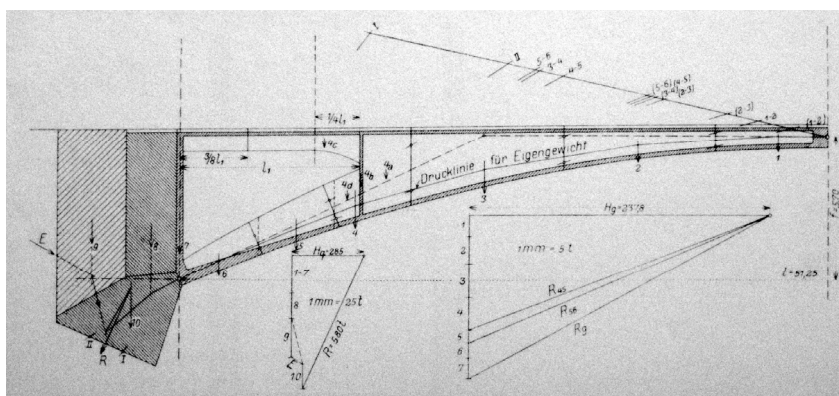


Figure 2: Tavanasa Bridge (1905) Schweizerische Bauzeitung 1914: 64(24)

Things began to evolve with Maillart's later structures and particularly with his stiffened arch bridges. The stiffened arch bridge is the complementary association of a funicular arch with a rigid deck fulfilling the role of a stiffening girder for the arch. This is the perfect inversion of the principles of a suspension bridge, as suggested by W. Ritter [6]. On the first occasion when this principle was interpreted – specifically for the Valtschielbach Bridge of 1924 – the arch line remains circular; but things will change later.

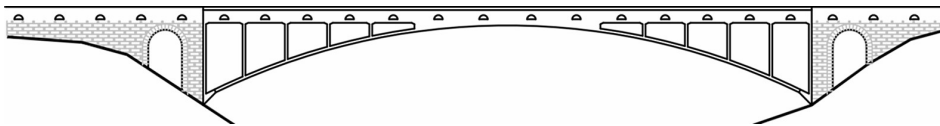


Figure 3: Maillart's Valtschiel Bridge (1923)

The first step of this change seems to be the Salginatobel Bridge (1929) – a three-hinged arch unstiffened by the deck: here the arch is said to be parabolic (i.e. a funicular line for a uniformly distributed load), but remains circular on the central third of the arch. When Maillart perseveres later with the stiffened arch bridge, he makes use of perfect funicular lines as seen in the Landquart Bridge (1930) or in his famous Schwandbach Bridge (1933). Up to this stage, classic geometric forms have governed the details of the form of his bridges (initially the classic image of the semi-circular arch). Its reference is the Roman stone arch. Graphic statics permit a study of the reaction of the ground on the spring of the arch, and measurement of the distance between the thrust line and the centre of gravity line of the arch. From these distances come lever arms that are at the origin of bending moments; as is now known, they permitted Maillart to calculate the amount of reinforcement steel in the characteristic double asymmetric tees that he used to draw transversal sections of his arches (or eventually to adjust some of their dimensions).

But when he designed his later stiffened arch bridges, graphic statics permitted him to draw the exact geometry of the arches. For complex systems like the Chiasso Shed structure, graphic statics even becomes a tool for equilibrating compression and traction forces and defining the trajectories of forces (Zastavni [7]). It becomes the tool that regulates the whole geometry.

The use of graphic statics in this way implies that concrete is primarily considered as a material to be placed along the loading path in compression, meaning that concrete remains a kind of moulded stone.

Reinforcement steel for its part is to be placed along the traction path.

It is a kind of strut-and-tie design long before the term existed; the thrust line is indeed the evolving trajectory of a strut's sequence in a compression structure.

It is only at a second stage that concrete and its reinforcement are considered for a new technology capable of resisting bending forces: reinforced concrete. Steel as a means of

technology (to control cracking, to permit joints or hinges) seems to come far ahead of steel as a constituent in the technology of bend-resistant stone

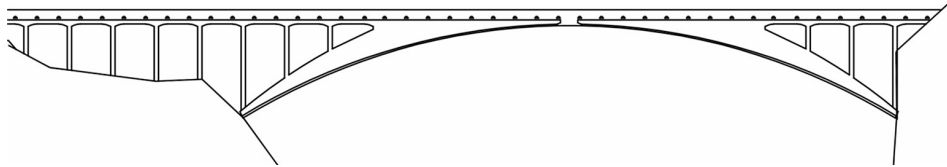


Figure 4: Maillart's Salginatobel Bridge (1929), 1:1000

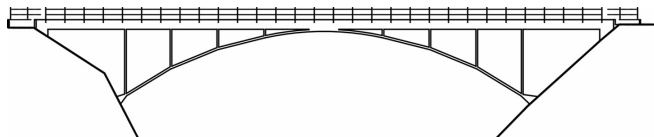


Figure 5: Maillart's Schwandbach Bridge (1933)

Therefore it was only with Maillart that graphic statics really prevailed as a tool for defining geometry over mechanics, whose use was limited to being a means for determining the necessary amount of reinforcement steel.

## **1.2 What Maillart's views suggest as regards tackling a structural problem**

We have seen that Maillart's design methods are rooted in a pre-established behaviour for the structural scheme he worked out. Points of weakness (hinges) are foreseen. The material is not used in places where it is superfluous.

The process led him to very expressive structures – a didactic body of work for users of it – since he only placed concrete along the loads' paths. The material is mainly used compressed, sometime stretched, and only bent incidentally. It makes the system very efficient, and means use of it can be particularly sparing. It also makes his structures very economical, especially since thought was also given to the assembly methods used to make them as efficient as possible.

There is no doubt about the behaviour of the whole structure since it has been drawn to fulfil a given structural behaviour. All this serves to make the structure reliable.

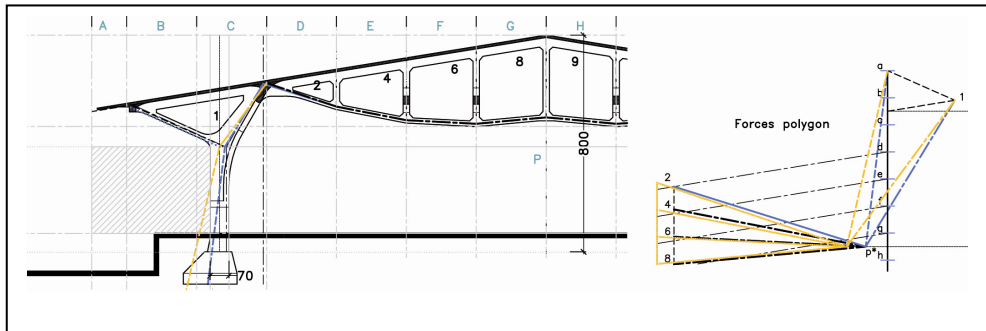


Figure 6: Maillart's Chiasso Shed Structure (1924)

## 2. Contemporary context

If we consider the context of the “tools” available to engineers for designing structures, it is clear that something has changed. Since the early 1970s, new computing tools have fundamentally revolutionised the art of engineering.

With the calculator, and later the computer, mathematical difficulties encountered in solving each and every mechanical problem began to disappear. Today we have very effective tools for structural analysis at our disposal: we finally seem to be living in a (mechanical) world we have been able to master.

Meanwhile, if we consider the purposes of it, it seems on the whole that the “need for relevance” remains the same. Irrespective of the socio-economic and technological context, the purpose of structures is to be reliable and relevant. These terms – despite intuitively covering a simple reality: the safety of goods and people (which implies resistance ability), aesthetics or economy – cover a lot of new and different aspects today: such as ecology, comfort, social well-being, sustainability, etc.

This leads us to ask why Maillart’s structure, despite the different context, appears relevant to us today.

The response cannot be found directly in the tools (these have changed), but probably in the general process used (the intention, the point of view). What may appear to be a process and which can appear as a consequence of the context – the limited tools available force Maillart to make his conception process this way – is probably more profoundly a question of “intention”, of a point of view which today does not appear to be an “implied necessity” but rather a “choice”.

The only difference between engineering practices today and yesterday is that the means and technology available have enabled us to go beyond everything that should be self-evident. If we agree with this, applying these principles is quite another matter.

The old methods of the Swiss engineer Robert Maillart [1872-1940] can lead us to reflect on the use we make of our tools, on what they should be and on what our view of structural problems should be.

Such methods may contrast greatly with our methods of behaviour discovered by calculation for designing structures. Proceeding in this way does not protect us from unexpected events (more precisely: an accident concerning a neglected detail that unfortunately threatens the whole device) or from ad hoc expensive solutions.

Why therefore not do as Maillart did and consider the definition of structural behaviour first when commencing a design, instead of hoping to discover this behaviour by tiresome computations? The facts seem to suggest that our new tools do not exempt us from thinking hard about our structural goals. Perhaps the engineer should continue being the one setting the rules of the structural game.

Today, shouldn't we be concentrating our efforts on researching and developing new heuristic tools or aids – perhaps inspired by old and occasionally forgotten tools – to make use of a conception process based on the synthetic search for a form leading to a “relevant” structural concept?

### **3. Conclusion**

Structural design – like all problems encountered with design – remains a complicated matter. This complexity is directly linked to the number of constraints that are to be encountered. Except for very specific problems related to the site, all structures seem to have to meet the following requirements: structural efficiency, reliability, taking the constraints of the construction into account, functionality, economy of the design – which includes low building costs as well as low maintenance costs – with social progress and expressiveness a consequence of all these requirements.

Managing its complexity requires an overall view of the process of morphogenesis with the aim of realising the subject of the research. It seems that structural objects produced analytically are the result of a succession of resolved problems (with the risk of missing one out) whereas a more holistic view permits the roots of a sound thought process to be established which has more opportunities of resulting in a design that has been mastered.

Establishing the modes in the structural behaviour first, like Maillart did, is certainly one possibility. Likewise, Maillart went further by using analogical methods to set out the structural scheme of load bearing using graphic statics. In this perspective, the tool becomes a tool of morphogenesis instead of an analytical one. It appears a contrario that following an analytical path does not simply permit some structural principles to emerge (the stiffened arch for instance) (Zastavni [8]).

Perhaps then, like Maillart, we should look again at engineering tools that allow freedom of choice in establishing the geometries of our structures and equilibrating the interplay of the forces within it, and express clearly and wonderfully the structure's “load paths”.

## **Acknowledgements**

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