Robert Maillart's Innovative Use of Concrete

ROBERT Maillart's innovative views concerning the use of concrete come within the scope of the history of structures, structural materials and concrete as a material of structure. It will even lead us far beyond these issues. At the end, the point of view expressed in this article will be the view of a structural designer. When preparing this reflection, I realise that there is no straightforward answer to the question: "What is in fact Maillart's real innovation considering all the contributions he made to the art of engineering?"

Putting forward the different aspects mentioned above as an introduction seems to be a more relevant way to find a contemporary answer taking time and context into account. Consequently the first part of this text is a general presentation of Maillart's works. Following we will make a detour to make what I, and many others, consider to be the most revolutionary aspects of Maillart's practice fully comprehensible. So starting from the historical development of reinforced concrete as a structural material, we will move to the contemporary context to figure out how the intrinsic structural complexity of concrete is managed today. We will see that some difficulties emerge from the behaviour of concrete in relation to the classic theories of mechanics. If some Modern theories find an answer to the problem, it will become obvious that Maillart had already found a convincing way of dealing with these difficulties. We will then return to Maillart's works to answer the question through the status he was to give concrete when it came to structural design and the methods he used to achieve his objectives. I hope this will lead us to consider Maillart's approach as one of the most visionary ever devised.

By Denis Zastavni

Introduction to the Works of Maillart

THE Swiss engineer Robert Maillart was born in 1872 and died in 1940. He worked on more than 300 structures—of which 50 are bridges—between the end of the 19th century and 1940.[1, 2] Initially, Maillart became renowned for new structural forms using reinforced concrete. At a time when concrete was associated with massive material producing and heavy-looking structures, Maillart executed structures with a lightness that had never been seen before. He skillfully produced works of advanced structural executions, reliable and with a high degree of durability. This means that it is a matter of fully rational propositions for structural schemes.

It must be remembered that at the time Maillart was practising, research had been done into the most appropriate structural arrangements with concrete. Maillart's most visible innovation and contribution to research concerns structural forms and systems.

In terms of detail, he invented *Système Maillart* in 1901, a system based on concrete box girder.[3]

In terms of structure, there are proposals for different structural typologies, for example:

< Salginatobel Bridge in Schiers, Switzerland, built by **Robert Maillart** in 1929. Photo by Denis Zastavni.

– in arches for bridges:
  - three-hinged arches where he mainly proposed revolutionary forms for the arches:
  - stiffened arches exploiting principle suggested by his former teacher, Wilhelm Ritter.
  - arches with an off-centre thrust line, i.e. arches with high bending forces.
– in bridges: he promoted systems with continuous beams shaped in a singular way.
– in buildings, he promoted a personal vision of the structural arrangement of mushroom-slabs.

Maillart also introduced innovations in other areas. For example, he used graphic statics as a design tool. Indeed, when Karl Culmann devised graphic statics as a consistent discipline, it was with the prospect of using it for analytical purposes.[4] Maillart mastered the complexity of elaborate structural arrangements by intuitively using contemporary structural principles, in other words long before they were established. He mastered the complexity of the behaviour of reinforced concrete by relying on the specific status he gave the material within a structural scheme.[3] Similarly, he managed the complexity of the steel reinforcement needed within a structure by proposing reinforcement patterns that were easily implemented.[3]

After this first presentation of the main innovations of Maillart, let us return to historical perspectives on reinforced concrete as a structural material.

Figure 1. **Maillart**'s reinforced concrete arch Schwandbach Bridge near Berne, built in 1933.

History of Concrete

Maillart is central when it comes to understand the concept and character of concrete. The history of reinforced concrete began in around the mid 19th century. The idea of joining iron to concrete as reinforcement was introduced by Joseph–Louis Lambot and Louis Monier. Structures combining iron and concrete quickly followed with the achievements of François Coignet and William B. Wilkinson. Structural elements, particularly beams, in reinforced concrete began to be patented and developed in around 1880. The first concrete bridges appeared at this time.[6, 7, 8]

Joseph–Louis Monier, Mathias Koenen and François Hennebique contributed to the perfection of the (internal) design of concrete beams and associated reinforcement patterns. Hennebique's stirrup illustrations appeared in 1892. From then on, the logic of a reinforcement pattern became complete. Meanwhile the history of concrete began far earlier, somewhere at the dawn of history. But a better illustration of the birth of concrete as a new material is found in Lambot's work. In 1848 Lambot used a "coating" of cement on a metallic armature to make a small boat (barque). In 1930, concrete ships were still being produced and used in different contexts. Concrete changed its status: from then on it was able to fully replace steel and timber. It is light, thin, watertight, even *elastic*.

Designing concrete sections is not the same as calculating them. Various other aspects must be considered to achieve a sensible design. Thinking about suitable forms and sections is one of these aspects. For most concrete designers at the time, it meant reasoning in terms of a system. Most systems were a given association of steel and concrete in a predetermined section. For instance, Hennebique's system came from translation of the form of other materials into concrete ones. To make it viable, he worked empirically to develop an adapted steel reinforcement pattern.

The history of this material is full of attempts at characterising concrete behaviour. Before the 1900s, a series of theoretical modellings was in existence, emphasising various aspects of elastic or plastic collaboration between concrete and steel reinforcement. Some of the methods used, such as Hennebique's, were rather unorthodox.[6] Even if calculation methods existed, they were far from being widespread. For all these reasons, some countries decided to appoint commissions dedicated to establishing norms. Maillart contributed to Switzerland's national commission[9] and the Swiss recommendations were the first official ones to be made in Europe.[6]

Contemporary Approaches

Nowadays, those times seem far removed from today's practice: all calculations methods are described in norms and there are marvellous numerical tools to support complexity in design. Concrete structures can be modelled as bars, grids, plates and shells in all possible arrangements and the behaviour of materials can be modelled in a very precise way. For instance, the behaviour of concrete is modelled by use of a parabolic law as described in Eurocode 2.

However some difficulties remain. Concrete has anisotropic properties considering traction compared to compression resistance. As a result of this, concrete cracks so that:

- the mechanical properties of sections change in an unpredictable way, depending on the history of loading.
- the reinforcement of concrete by steel bars is necessary, which in turn...
- changes the mechanical properties of sections

And there is an additional difficulty. In a considerable number of situations, classical theories of mechanics, based on theories of elasticity, do not apply, so that:

- structural analysis requires accurate specialised numerical simulations...
- for which precise mechanical properties are unavailable, leading to a theoretical issue of the legitimacy of numerical simulation.

Even for classical theories of mechanics, there are some insurmountable difficulties. The historical notes that follow come from Jacques Heyman's studies.[10] In 1914, Gábor Kazinczy published in Hungarian the result of tests that he did on steel beams embedded at their ends (encased in concrete):

- he was not able to reproduce the results predicted by mechanical theories for beams with fixed ends considering bending forces.
- he showed a tendency for bending moments to equilibrate along beams.

In 1926, John Baker was commissioned by the British Steel Industry via SSRC (Steel Structure Research Committee) to bring some order into practical steel design, which comprised conflicting rules. Design and analysis were completely elastic processes, at that time. The results of his experimental work was published between 1931 and 1936, and showed that stress measured in real structures bore almost no relation to those produced by the designer's calculations. These results lie at the origin of detailed work on the real behaviour of structures.

Plastic Design

The solution lay in reformatting mechanical theories. In 1938 Nikolas Gvosdev published in Russian the statements and proofs of the two theorems of plasticity (presented during a conference in 1936). His writings remain unknown due to the choice of language in which he published. In 1949 the Americans Greenberg and William Prager established the version known worldwide of the two fundamental theorems of plasticity:[10]

- the static theorem, lower-bound or safe theorem.
- the kinematic theorem, upper-bound theorem.

Each of those theorems leads to a specific dimensioning method.

In 1950, Horne established proof of the uniqueness theorem: solutions of the two theorems are identical at the ruin point. For two decades, structural principles relating to plastic behaviour were now being implemented into codes' practices.

Let us express what, in my opinion, is the most important theorem of plasticity—the static theorem:

If a set of bending moments can be found that satisfies the equilibrium at a load factor Qi, then Qi is always less than, or at best equal to, the true load factor Qu, for a perfectly plastic material.

This means that if it is possible for a structure to provide the working of one structural mechanism sufficient to bear the encountered loads, the stability of the structure is guaranteed, whatever the real structural behaviour might be, if the conditions of plasticity are encountered. All this means that:

- a numerical simulation using computers is a possible, and valid, lower-bound solution.
- a simple model is a possible, and valid, lower-bound solution.
- a drawing using graphic statics is a possible, and valid, lower-bound solution.
- an approximate calculation using, apparently excessive, simplifications is a possible, and valid, lower-bound solution.

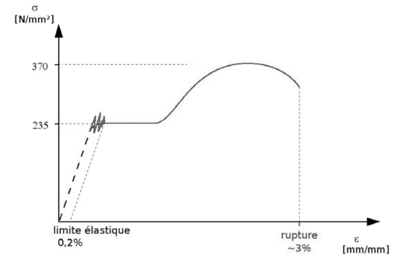
All these solutions can be equivalent when considering resistance at the ultimate state, collapse.

Let us illustrate briefly this notion of the *perfect plastic material*.

Figure 2 is a stress-strain diagram showing the evolution of the deformation related to applied forces. This diagram is not regular. Steel, after an elastic, regular, linear, zone shown in dashed line, demonstrates a zone of high deformation in continuous grey. The continuous grey zone represents the zone of plasticity on the diagram.

It is simplified in figure 3 which is a diagram used for calculations, where stretching capacities have been voluntarily restricted for safety reasons. So, plasticity is effective, up to a certain point, for metallic materials like steel.

Perfectly plastic materials go a step further: it is possible to stretch the material infinitely without breaking



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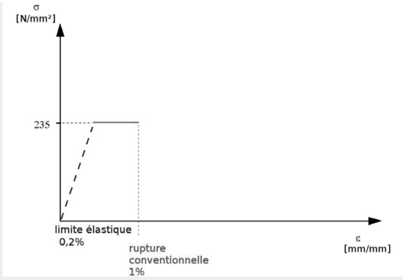

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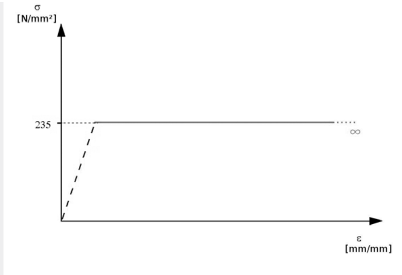

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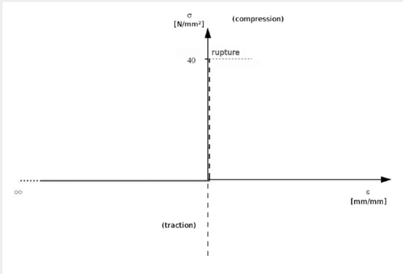

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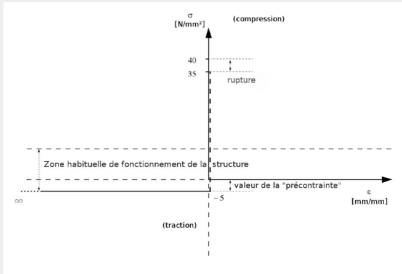

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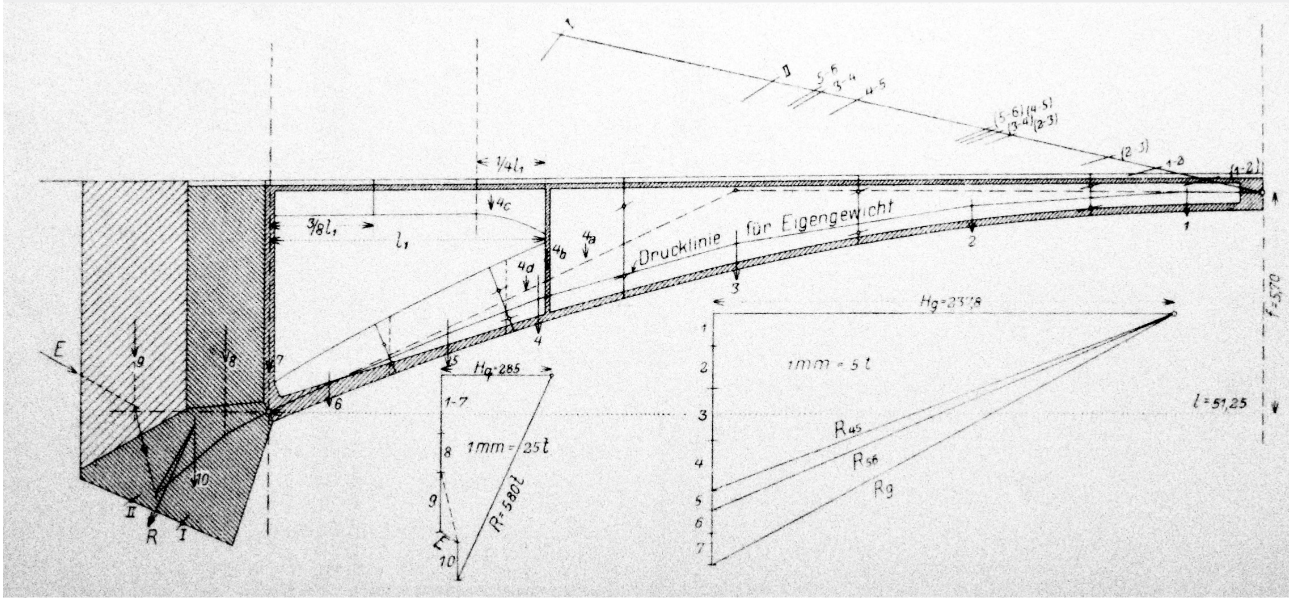

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Figure 2. Steel E 235: real diagram.

Figure 3. Steel E 235: diagram for calculations.

Figure 4. Ideal elasto-plastic material.

Figure 5. Ideal rigid-plastic material.

Figure 6. Structural behaviour of masonry (simplified).

Figure 7. Structural behaviour of a masonry acting in compression (simplified).

Figure 8. Tavanasa Bridge: drawing.

[figure 4]. This one has a zone of elasticity; figure 5 no longer has an elastic zone: continuous grey curves being infinite, the whole diagram can be condensed near the origin. These laws can be applied to real material in certain conditions. But what about a brittle material like concrete?

Let us take an extreme example: masonry. With poor mortar inside joints, masonry resists compression, but not in traction: you can infinitely displace a piece of masonry taken from the whole [figure 6]. Things change when a certain amount of pre-stressing is encountered. And it is indeed the case when its own weight or compression forces pre-stress masonries.

In figure 7, the lower zone corresponds to the stresses due to pre-compression or pre-stressing.

This graph is very similar to that of a perfect plastic material. So we see that the law of a perfectly plastic material could apply to a brittle material like masonry, or unreinforced concrete.[11] And some ductility can be joined to concrete by using steel reinforcement. So it seems that the only reasonable theory to apply to concrete is indeed the principles of plastic design.

We are now ready to embrace all of Maillart's innovative views applied to concrete design.

Maillart's Innovations

For his own use Maillart defined a set of implicit rules or views for concrete structures and their structural behaviour:

- he saw in concrete an artificial, moulded stone and applied principles of masonry to it.
- despite that, steel reinforcement permitted him to work in more depth on joins and, almost systematically in a secondary phase, on the bending abilities of structures.
- concrete tends to be monolithic so that the principle of integration, or continuity, between elements is the rule for designing sections.
- but cracks are unavoidable, capable of acting as joints so that it is possible to articulate discontinuous rigid sections and interrupt continuity.

With this elementary structural vocabulary established, we are ready to review the principles of Maillart's structural design.

The Zuoz Bridge of 1901 is Maillart's first real invention with his proposition for a concrete box girder, the first ever built.[3] At the origin of the form is a U–shape arch, derived from the principle of masonry vaulting. From the outset, a U shape is already a different conception compared to his colleagues' massive unreinforced or reinforced rectangular sections.

In line with the recommendations of some of the leading intellectuals of structural practices of the time, even concrete arches had to be hinged to avoid damages so three hinges were added to the arch. Thereafter, his principle of integrating sections simply led to the creation of a rigid connection between the arch and walls bearing the deck, and thereafter with the deck itself. Rigidly connected walls were indeed cheaper than columns or the stone façades usually suspended on both sides that these longitudinal walls replace.

The first concrete box girder was created even though there was no way of calculating the whole structure, according to ETH professor Wilhelm Ritter, who failed the task of mathematically checking the structure, but agreed with Maillart's principle.[3] Maillart therefore had to disregard or leave aside any awkward elements to check the stability of the whole. It means that Maillart first defined the independent mechanisms (arch, deck's slab, deck's beams, etc.) and associated them in a whole. Secondly, he only considered some specific elements within a complex arrangement; in other words, he only referred to one static scheme inside the real structure.

Put in yet another way, this intuitive way of proceeding was very close to Modern plastic approaches while using the lower bound theorem.[12] It had not been used in the most elegant and considered approach as employed by Maillart for the Zuoz Bridge design, but things were to become more convincing and rational in later works.

The Tavanasa Bridge of 1905 [figure 8] reinforced the position he took in Zuoz. Attention was no longer given to reconstituting a façade along the bridge, and this time changing inertia was conscientiously applied to the bridge profile according to the principle of the three–hinged arch. So, sections were further refined according to their structural function, leading to hybrids, sometimes between U–shapes and double T–shapes, sometimes between box girders and open sections.

Things began to evolve with Maillart's later structures and particularly with his stiffened arch bridges.

The stiffened arch bridge is the supplementary association of a funicular arch with a rigid deck fulfilling the role of a stiffening girder for the arch [figure 9]. This is the perfect inversion of the principles of a suspension bridge, as suggested by Wilhelm Ritter.[13] It was also a new application of the lower–bound theorem of plasticity: two different and effective elementary structural systems inside the whole structure.

To design a structure like this, the principle is simple: design a sufficiently high stiffness ratio of different elements against bending [figure 11] and also design a sufficiently high stiffness ratio against compression forces. But the importance of these ratios is inverted when comparing elements involved in bending or compression resistances respectively. The stiffness ratio against bending is attained with the dimensions of the section, their mechanical properties to be precise. The stiffness ratio concerning compression forces is attained geometrically rather than mechanically. The correct arrangement of members is the key to develop high resistance using axial forces. It is not a measurable dimension like stiffness against bending. At the same time, this *stiffness ratio* against compression forces is only fully valid for one configuration of loads, unlike stiffness properties considering bending. And unlike stiffness against bending, the issue is rather one of balancing compression forces to the disadvantage of bending forces.

By correctly defining the stiffness ratio between the arch and the deck, the mechanism is effective without producing undesirable interactions, despite the complexity

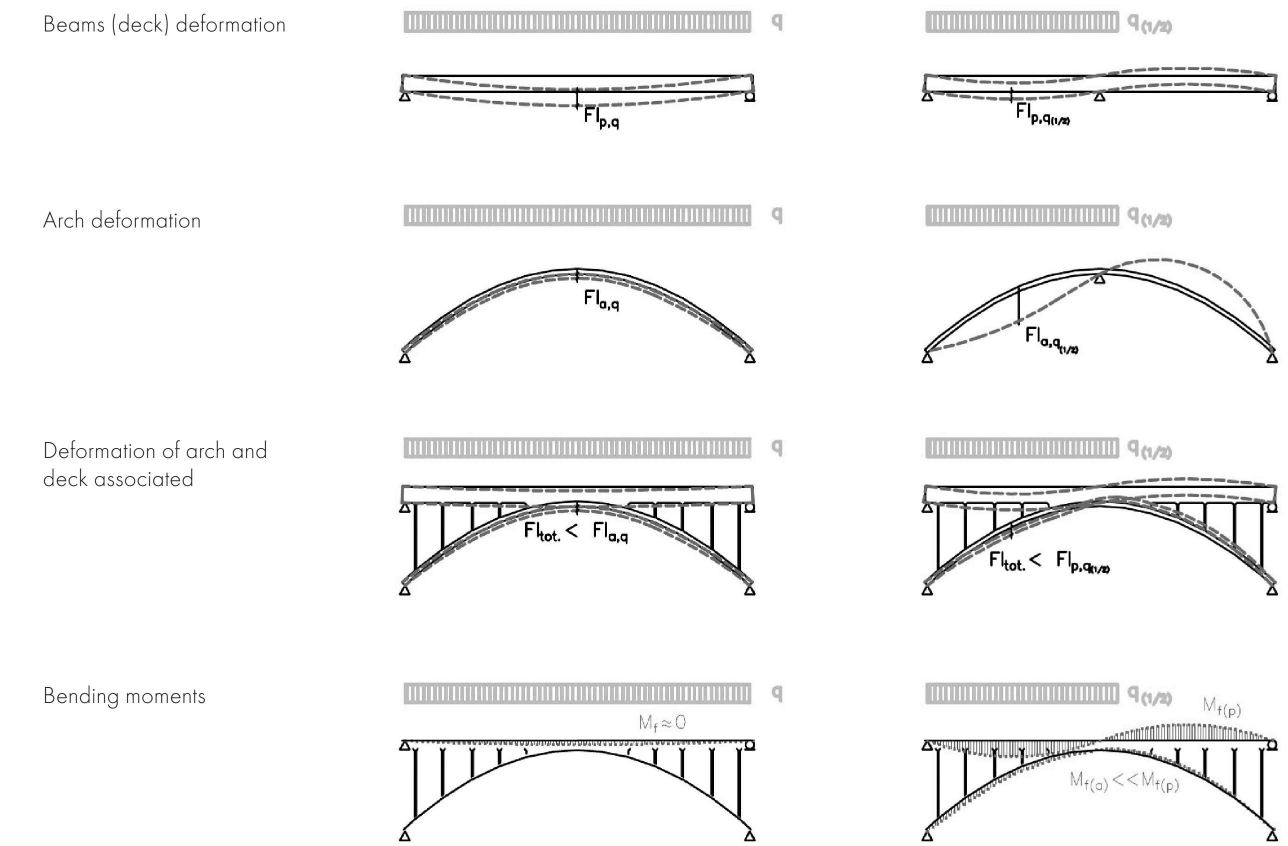

Figure 9. Principles of **Maillart**'s stiffened arch bridges.

of the structure [figure 10]. This is precisely the condition that enables a real material to be employed instead of a perfectly plastic material in using the lower-bound theorem. This condition conveys the fact that where structural behaviour is relatively close to the one that exists naturally in the structure, large preliminary deformations do not need to occur in the structure before the theoretical behaviour can be activated thanks to a geometrical modification, relying the possibility of this deformation on the structure's plastic capacities. The best way of matching theoretical behaviour to the one that exists naturally in the structure is to define the geometry intentionally through its design to activate preferentially the intended theoretical behaviour. These ratios for compression forces are similar considering the section areas but the deck is 19 to 22 times stiffer than the arch when bending is taken into consideration. Therefore, elementary graphic procedures, to guarantee geometrical stiffness in compression, i.e. a funicular line, and the correct stiffness ratio are sufficient for designing such a bridge [figure 12]. The principle is structurally efficient and suitable for an efficient way of building a bridge in the early 20th century; in short, it is highly rational. On the first occasion when this principle was interpreted, specifically for the Valtschielbach Bridge of 1924 [figure 13], the arch line remains circular but the funicular thrust line remains very close to the axis of the thin arch's line. Considering the accuracy of the geometry, things will change later.

Geometric rules evolved slightly with the Salginatobel Bridge [figure 14]. Here we observe the convergent influences of the previous three-hinged arch bridges and the stiffened arch bridges of Maillart. However structural behaviour is strictly defined as seen in his previous hinged bridges. More in-depth work has been conducted on the definition of the section. Meanwhile mechanically speaking it remains a symmetrical box-girder section. But a recursive use of working drawings of graphic statics allowed Maillart to carry out detailed work on designing cross-sections.[14] Indeed, proportions and mechanical characteristics continuously evolve along the bridge. And later, the geometries of arches were studied to be perfectly funicular for the compression forces according to one reference loading case, as with the Schwandbach Bridge for instance [figure 1].

Up to this point, it could be considered that I am undertaking a kind of interpretative review of Maillart's work. Indeed, I am offering an interpretation of the structural mechanism at work in Maillart's bridges or structures. However what is a particular and constituent part of his methods is that these behavioural principles were

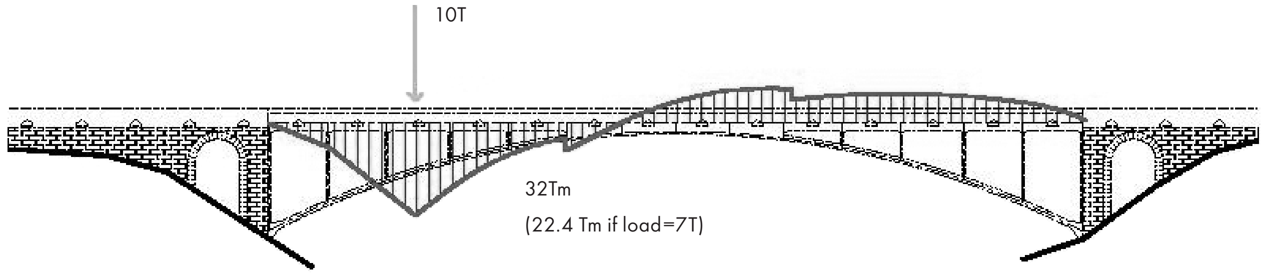

Figure 10a. Valschielbach Bridge: bending moments.

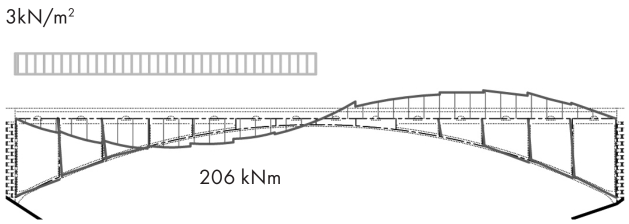

Figure 10b. Valschielbach Bridge: bending moments.

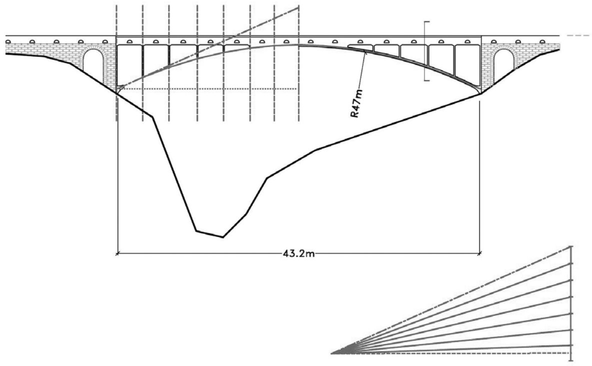

Figure 12. Sketch of the arch of **Maillart**'s Valtschiel Bridge (1925) using graphic statics: the arch is semi-circular but thrust line remains inside.

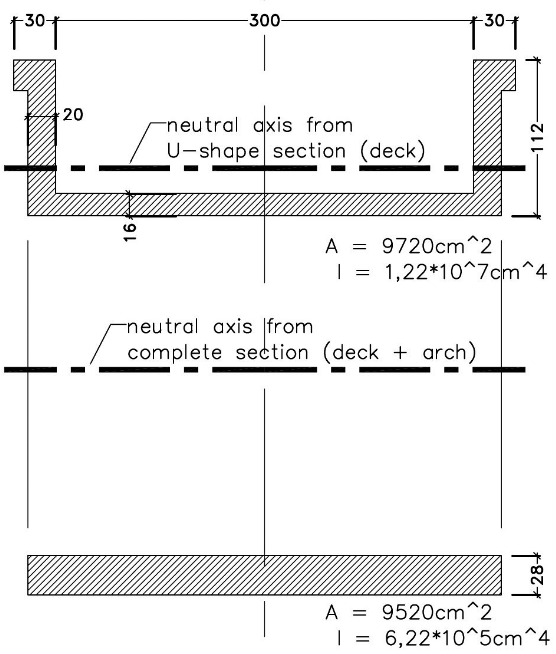

Figure 11. Valschielbach Bridge: stiffness ratios.

initially defined in his design procedures. This is easy to demonstrate when looking at his design calculations. In a way, these behavioural principles for the structure are at the core of his work on structural design. The structural form is, so to speak, constructed around them.

Similarly, one may think that Maillart was forced to use graphic statics as the only available tool to calculate his structure. Indeed, we encounter working drawings of graphic statics almost systematically along with the files that still exist in the archives. But the history of engineering sciences is initially full of algebraic methods or methods using differential analysis. Indeed, his contemporaries despised what they considered to be Maillart's unorthodox way of performing structural analysis.[3, 9] This is certainly due to a poor understanding of Maillart's structural systems, and obviously Maillart disregarded these analytical methods being inappropriate to calculate his structures.

On the contrary, we may observe Maillart using graphic statics again and again on the same structure with the same loading case, mainly dead load, to draw the same elevation every time to ensure that he has attained the right form to enable the determined structural behaviour to be effective.[14] Thus graphic statics is not analysis, it is morphogenesis.

We see that Maillart continuously used graphic statics for different purposes. Beyond working on establishing loading paths intended for materialisation in the concrete structure, he also used graphic statics to correct geometries to be able to equilibrate forces in a structural design. For the design of the Chiasso Shed, traces of a funicular can be recovered from the geometry and it is no longer possible to explain the geometry without resorting to constructing equilibriums using graphic statics.[15]

Even the reinforcement pattern will contribute to characterising the geometrical definition of the elements of the structure. In the Chiasso Shed, for instance:

Figure 13. Valtschielbach Bridge, 1925.

Figure 14. Salginatobel Bridge, 1929.

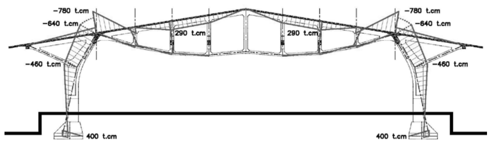

Figure 15. Chiasso Shed (1924): bending-moments.

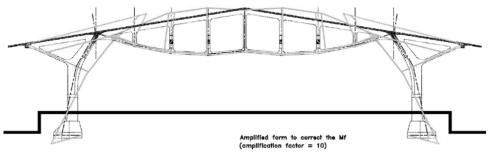

Figure 16. Chiasso Shed (1924): A correction of the geometry to set bending to zero under maximal loading means translating nodes to maximum 5 cm. Any correction is meaningless.

– in funicular members, steel reinforcement is just sufficient to respond to axial forces.
– in the junction–columns it is no more than technological.
– the upper T beam concentrates both bending–stiffness properties and reinforcement steel.[5]

And where is the analytical part of the design?

Essentially at the very beginning when the structural behaviour is devised, before the structure exists and before it is calculated; analysis is used incidentally to accompany the geometrical definition of sections during the form's design; and lastly it is used to write the design calculations.

Indeed, analysis is unnecessary if the result is known: there is no need to undertake a large degree of structural analysis to grasp the intrinsic nature of the structural behaviour. Initially devising the structure's behavioural principles, related to the application of the static theorem of plastic design, does this before the form even exists.

By the use of numerical simulation it is possible to evaluate the quality of the structural response to loadings. Naturally Maillart did not have an analytical result like this at his disposal, and of course, this is an elastic simulation; this means it is another type of approximation, a new static configuration within the scope of the application of the lower–bound theorem of plasticity. But even there, we see on figure 15, the behaviour in bending is consistent with the one of stiffened structures. Indeed this corresponds to the method used for designing this structure, i.e. a complex variation of stiffened arches integrating principles of mushrooms-slabs!

Figure 16 shows the correction to apply to the geometry to be sure that any bending forces are eliminated, i.e. to optimise the configuration by retaining only the most efficient forces, that is compression or traction. The figure shows these corrections multiplied by ten. The maximum correction is 5cm, this means 1mm on the working drawing at a scale of 1 to 20, so it is impracticable geometrically speaking.[5] For a structure with a span of 23.6 m, this corresponds to a tolerance of 1/472. It means we could consider this structure as being perfect... even without considering the impreciseness due to the use of a real material that will crack.

Conclusion

In summary, we have reviewed Maillart's use of some graphical methods. Graphic statics are used to:

– organize the load paths and thrust lines.
– draw funicular curves or equilibrium schemes for form-finding.
– study the magnitude of forces along force trajectories or schemes.

One can extend the use of graphic statics by converting bending to thrust lines for interpretation and eventual corrections, corrections that prove not to be of use to the Chiasso project. We could also compare the kind of method that is used today in plastic design to manage zones where Bernouilli's hypothesis does not apply, non-linearity in strain distribution: the Strut-and-Tie Models.[16, 17] And we will be forced to note that it is very similar to Maillart's method of managing equilibrium at the scale of the structure. This again demonstrates the great relevance of his approach.

First of all, it has been concluded that Maillart's approach is simplification supported by graphics. And we recognize the strong connections with contemporary principles of plastic design. For Maillart, concrete is used firstly as a *thrust material*. Due to his conception of this material as such, great structural efficiency is achieved with few cracks and therefore little damage over time. Maillart was also a builder, integrating aspects taken from construction into his design, making his projects particularly cost-effective. He paid attention to aesthetics, controlled and steered technical rules according to how the projects would look. When all is said and done, by using these methods, he managed to produce works of great architectural quality and relevance. To me, certainly among the cleverest ever devised.

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