

What was truly innovative about Maillart's designs using reinforced concrete?

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ABSTRACT: This paper attempts to reveal the specific nature of the work of Robert Maillart [1872-1940], after carefully reviewing the historical context of concrete design. Maillart's favourite material was reinforced concrete, and he devised forms that synthesised all the characteristics of a relevant structure. He succeeded by establishing a clear status for each material used – concrete and reinforcement steel – which allowed him to define the geometry of his structures correctly. This is demonstrated here by an analysis of the design drawings for the Salginatobel Bridge and the Chiasso Shed. These examples offer clarification of the use he made of calculation and graphic statics for design purposes. We conclude with the specificity of his approach as a singular vision of how (reinforced) concrete can be used within a structural scheme, which in turn allows an original, expressive structure to be produced of great relevance and reliability.

INTRODUCTION

While the Swiss engineer Robert Maillart and his work seem to be well-known and the subject of more than 320 books and papers (Rigassi; Billington, 1988: 197-219), few authors have truly and thoroughly investigated the aim of his design methods.

Among others, David Billington (Billington, 1979; Billington, 1997) has highlighted important characteristics of his methods but totally neglected the use Maillart made of graphics methods. Beyond an original use of graphic statics to guide the form-finding of his structures, we will see that an important characteristic of Maillart's thinking was the specific status given to concrete within his realisations – this status evolving according to the type of structure.

HISTORICAL CONTEXT: CALCULATING CONCRETE STRUCTURES

Studying the history of the calculations methods applied to concrete, we will position Maillart's tools between the theories available at the end of 19th century and the beginning of 20th century.

Maillart's career began in 1894, the year in which he designed his first concrete bridge: a 6m-span bridge made from massive concrete. He designed his first concrete hinged bridge for the Public Works of the city of Zurich (the Stauffacher Bridge), erected in 1899. Reinforced concrete appeared in around 1847-49 in work by J-L. Labot, Lacroix and J. Monier. The first buildings in reinforced concrete appear to be by F. Coignet and by W. Wilkinson in around 1852-54 (Simonnet, 2005, p. 40; Guidot, 1997; Chambre syndicale etc., 1949, p. 74).

The first hypothesis of a calculation method seems to be by Mathias Koenen (1886). During this period, theories were put forward by Koenen (1886), Demay (1887, 1899-1900), Coularou (1889), Melan (1890), Coignet & de Tedesco (1894), von Thullie (1897), Lefort (1898) and W. Ritter (1899) (Simonnet, 2005, p. 49; Gori, 1999). Wilhelm Ritter was also one of Maillart's teachers.

These theories were occasionally published as scientific reports and, more rarely, in reviews. It explains why knowledge of reinforced concrete was not particularly widespread: all these methods in fact constituted the commercial secret of these constructions systems.

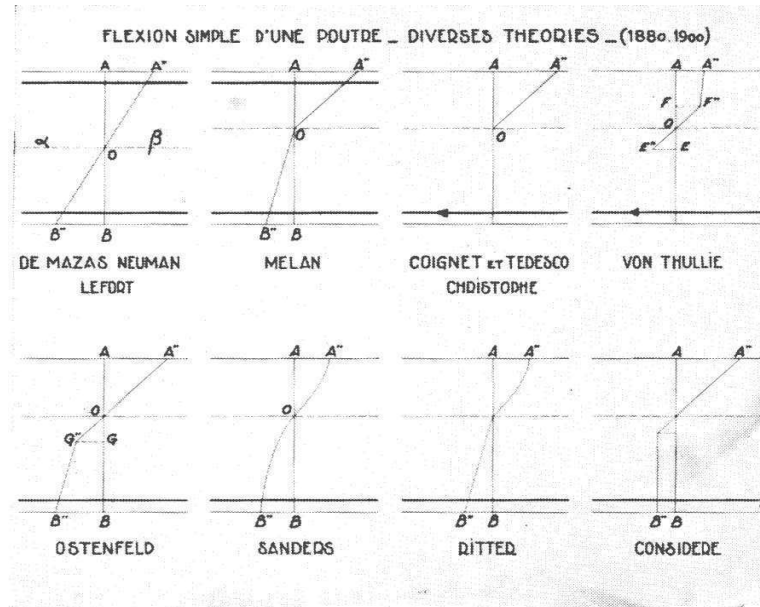


Figure 1: Various theories for concrete beams (Chambre syndicale etc., 1949, p. 74)

This explains why there are so few publications on this subject before 1900. What is considered to be the first calculation treatise for concrete, produced by C. Boitel, was only published in 1899 (Boitel, 1899) in French. However with regard to the German language, Emil Mörsch's treatise was only published in 1902 (Mörsch, 1902). That was also the year of publication of the legendary work by Paul Christophe, a former colleague of François Hennebique (Christophe, 1902).

Seemingly, the first lectures on constructing with concrete seem to have been given by Charles Rabut to the Bridge School in Paris during the 1897-98 academic year. In this course, Rabut examines the different existing systems (Hennebique, Matrai, Cottancin, Harel de la Noë, Considère etc.) (Simonnet, 2005). We can also pre-suppose that Wilhelm Ritter anticipated the creation of a course on reinforced concrete by giving his students a basic grounding in it.

As regards concrete calculation, the first commission for normalising methods – at which Maillart made a contribution – took place in Switzerland during 1902 and 1903, with its initial recommendations published in 1903 (Billington, 1997, pp. 44, 255). The first recommendations in Germany and France date from 1904 and 1906 respectively (Simonnet, 2005, pp. 85, 93).

During the entire normalisation process in Switzerland, Maillart demanded simplified methods based on resistance to charge and requested that engineers be given greater responsibility, but in vain. For decades, normalisation meant stress validation and total submission to established codes in strictly restricted scenarios.

These historical reference points are a reminder of how new the theory of concrete calculations was. The possibility of theorising about the calculation of certain materials therefore necessitates an in-depth understanding of their behaviour when they are subjected to stress. However concrete is a complex material and Robert Maillart decided to use his own formulas.

Furthermore, designing is not calculating and it is easy to imagine how difficult it was then to theorise about the form that concrete structures should have in order to respect the intrinsic characteristics of the behaviour of this material.

DESIGNING CONCRETE STRUCTURES AS FULLY CONSISTENT

As a system of construction, reinforced concrete only used stirrups – an inescapable feature today – when they were patented for a fifteen year term in August 1892 by Hennebique (Hennebique, 1892). The proposal to put concrete beams in a T-form was made the same year by Edmond Coignet (Simonnet, 2005, pp. 51-54). In fact, the enlightened choice of deciding on an appropriate transversal section for a structural member implies integrating the behaviour of the material and the parameters of its resistance.

The technology suggested by Hennebique came from empirical observations and from translating wood, metal or masonry technologies into concrete executions. We know that Maillart inherited Hennebique's meth-

ods from the time he worked for Froté & Westerman – who used Hennebique's system under licence – and by examining Maillart's empirical methods used to define his mushroom-slab system. Of course, Maillart benefitted from the first bridges made in concrete as an albeit rather poor source of inspiration – the first concrete bridges were built in around 1885 – but there was something else that had a more profound influence on Maillart's views about concrete while he was still a young man: Tetmajer's ideas.

When the Eiffel Tower design was published in 1883, Maillart's attention was drawn in the same review to a concrete 12-metre span bridge by Tetmajer. In the paper presenting this bridge, he explained about structures made from Portland cement concrete in a form of a vault where "cracks seem to behave like vault joints that in themselves involve no risk of failure." (Maillart, 1932).

And that is a crucial point that enables us to explain the genesis of forms and the status of reinforced concrete as a construction material in Maillart's works. Firstly, it explains Maillart's perception of how (reinforced) concrete works – sometimes as a kind of masonry despite its artificial monolithic stone character, and sometimes as something else: a bending material. Furthermore, it also allows us to begin to integrate the necessity for concrete to crack to activate the action of reinforcement steel, and to reconsider how it works with the prospect of designing partially adaptive structures, i.e. to think in the terms of elasto-plastic materials.

Lastly, it could clarify the genesis of Maillart's detailing of the concrete hinge... but that is another story.

At this point, we can only conclude that Maillart took from this to integrate the way concrete could really work in bridges: sometimes as masonry vaulting, sometimes as a natural cracked partially-bent section where steel is conditionally essential. After this he was able to imagine structural forms, basing his thinking on empiricism as well as on the engineer's tools.

MAILLART'S PRINCIPLES BEYOND CONCRETE BEHAVIOUR AND CALCULATIONS: INTEGRATED

From D. Billington's publication, we know that Maillart invented the concrete box girder (Billington, 1979, p.23]. But what lay behind the genesis of this principle?

Obviously the integration of forms!

Indeed, the characteristic transversal section of the Zuoz Bridge emerges from integrating the walls bearing the deck to the easily identifiable bearing arches, and furthermore integrating the deck to the bearing walls as soon as all these composing elements become monolithic when the concrete sets. Joining components becomes possible as the technology of reinforcement steel enables reliable connections to be made. It is the same process when lifelines become part of a U-shaped section with the deck, or when capitals become part of the slabs as mushroom-slabs etc.

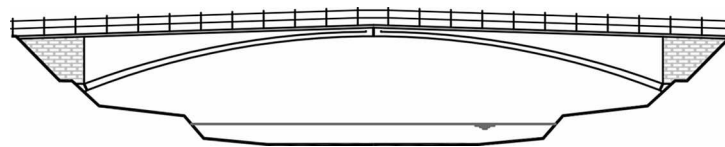


Figure 2: Maillart's Zuoz Bridge (Zastavni, 2008a)

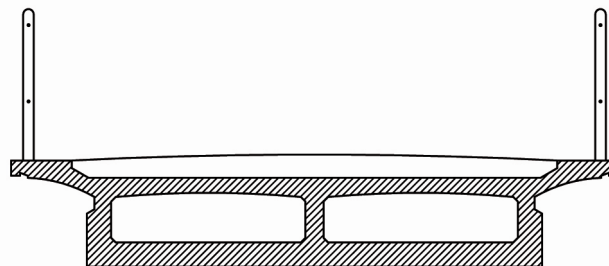


Figure 3: Maillart's Zuoz Bridge transversal section (Zastavni after Maillart's 1901 plans)

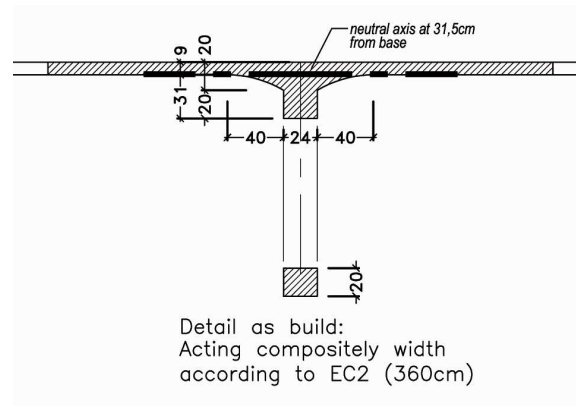


Figure 4: Section in the longitudinal direction of Maillart's Chiasso Shed roof
Not a T-beam, not a ribbed plate, not a truss-beam, but a clever synthesis
of the three principles (Zastavni after Maillart's 1924 plans)

So why should Maillart have maintained a bulky concentration of material in the arc since it is no more identifiable from the rest of the structure after setting? And meanwhile, in the case of differential behaviour between these components, cracks re-establish the independence of the elements in a way that offers a good illustration of our plastic vision of structural behaviour.

It was therefore possible to design these components separately, integrate them into a section where their contributions strengthen each other, and finally at another time consider the transversal section as massive and unique. (It can be justified by our modern lower bound plastic theorem (Ochsendorf, 2005).)

What is next?

A careful definition of the mechanical properties of transversal sections, and an equally careful definition of the geometry of the structures. There we will encounter the status of the constituent materials – graphic statics as a morphogenesis tool – and simplified algebraic calculation in a transversal section.

It is only by relying on the principles presented above that we will be able to justify the use Maillart made of engineering calculations and drawing tools.

GRAPHIC STATICS AS A DESIGN (MORPHOGENESIS) TOOL

Firstly, we have to say that all the presentations in reviews of Maillart's early bridges show thrust lines and force polygons, i.e. tools of graphic statics.

An examination of sketches or design drawings of the Salginatobel Bridge (1929) shows a series of graphic statics plans for minimal changes in the structure's geometry between drawings. Why come up time and again with new vectorial drawings on (nearly) the same profiles, if not because these graphic constructions contribute to perfect structural forms?

In fact, these series include multiple profile drawings, some simplified calculations by hand and detailing for specific areas of the structure related to resultant forces from equilibrium polygons.

Indeed, the entire design-stage documents of the Salginatobel Bridge include some missing sketches, annotated technical profiles related to detail sections, graphic statics constructions and geometrical parametrisation, and calculations by hand based on the resulting geometrical outcome of graphic statics drawings – plus a graphical synthesis of calculated influence lines – for a total of seven sketch sheets.

More precisely with regard to the profile documents, drawings primarily have the aim of defining the orientation of the reaction vectors at the support of the arch, before being able to draw a thrust line which permits a sketch and calculation of the transversal section.

On these plans, we note simultaneous workings on calculations – principally determined by graphics, but also simplified by hand – and on drawing elevations and sections.

It can be useful to examine the aims of each of these drawings, which suggest the methods underlying the objectives of the graphic constructions.

A complete analysis of the seven sketches can be summarised as follows (Zastavni, 2008a, pp. 162-181):

three of them mainly concern the lateral elevation, plan, typical sections and graphic statics of the lateral view. One concerns the foundation block, attached to a manuscript sheet where stresses encountered in different directions towards the ground are calculated. One sketch sheet concerns the calculation under wind loads of the reinforcement steels inside the lateral pier situated between the arch and the deck.

Two of them aim to calculate the bending moments due to exploitation loads (on the deck) and wind loads (on the arch), probably drawn up at a later stage of the validation file.

Let us specify the purpose of the first three: the definition of the lateral elevation and the geometry of the whole structure.

Reinforcement steel for concrete has the feature of being able to correct the mechanical properties of sections without being visible from the outside. But steel is expensive and the rule of the game is to reduce its use to a minimum. Therefore a careful definition of the geometry must be considered, at least in the mainly compressed sections, so as to avoid bending moments and also to rationalise the amount of concrete used to build a section.

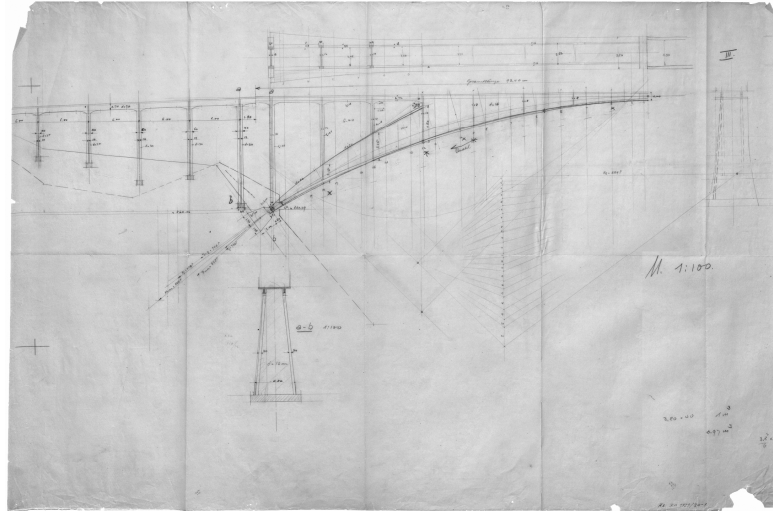


Figure 5: Sketch plan "III" of the Salginatobel Bridge (Maillart, R., 1928)

On the first sketch plan we encounter the following graphic elements (fig. 5):

- an elevation of a half-arch;
- a partially defined plan;
- an elementary transversal section (defining a partially implemented "geometral" definition with the two above-mentioned graphic elements);
- a sketch of the highest pier;
- a graphic statics drawing for the dead load created on the elevation with, as a result, the reaction forces at supports and the thrust line along the arch;
- reaction forces at the support of the arch for five different loading cases.

As geometric rules for drawing, we encounter simultaneously:

- a semi-geometric definition since $\frac{4}{7}$ th of the length of the lower line of a half-arch is annotated as being "parabolic", and the central $\frac{3}{7}$ th of the span is more likely to be a semi-circular curve;
- the use of the force direction to define the geometry of the spring of the arch.

At this point, we can conclude that graphic statics is used by Maillart at a very early stage of the design process, and that the purpose of his first plan is to come up with a general definition of the bridge profile.

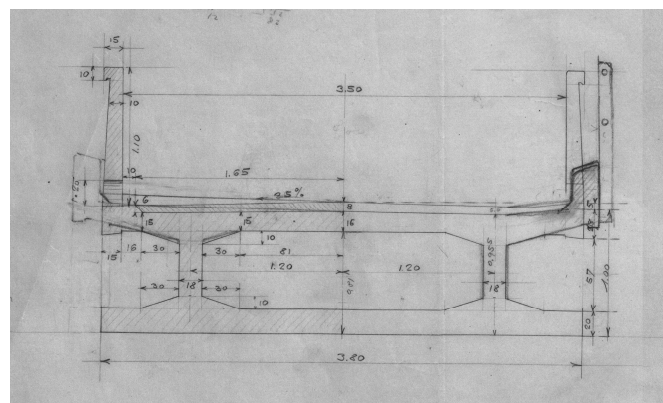


Figure 6: Part of the 2nd sketch plan of the Salginatobel Bridge (Maillart, R., 1928)

In the second sketch plan we again encounter the complete geometrical definition of the structure (plan, section and lateral elevation) but some graphic elements have become more complex:

- the transversal section is now drawn on a scale of 1:20 (fig. 6) instead of 1:100, and four different profiles are explored;
- the graphic statics constructions now explicitly include two different loading cases (g and $g+p/2$) and we encounter plotting marks for the positions of the gravity centres along the arch.

The purpose of the drawing has become one of preparing statics calculations by hand on transversal sections, which in turn enables the geometric definition of the structure to be specified (mainly on the transversal sections which have an influence on the line of the arch). Following this step, the plan and elevation will become more precise in the sketch plan that follows.

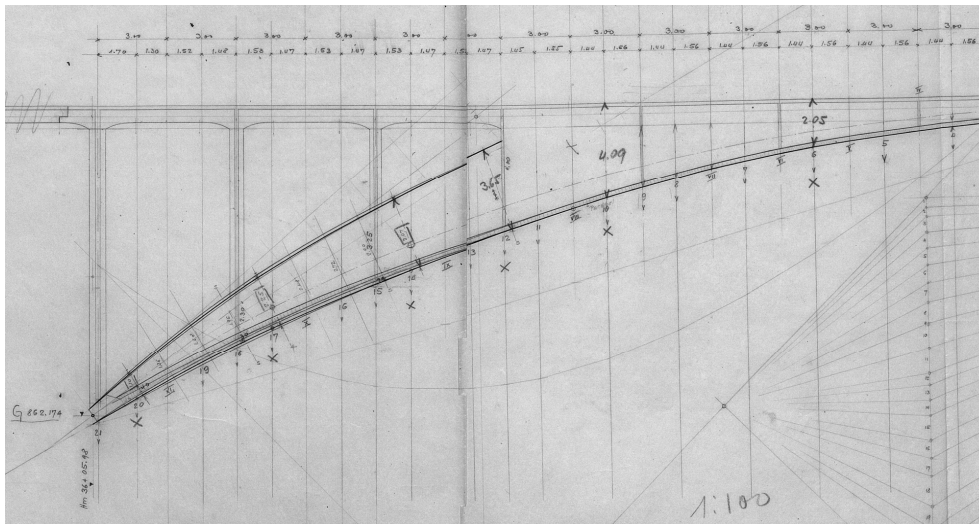


Figure 7: Part of the 3rd sketch plan of the Salginatobel Bridge (Maillart, R., 1928)

In the third working plan, the following graphic elements are encountered:

- a lateral elevation (3 successive layouts for the underside line of the arch in different colours);
- a revised plan;
- a transversal view of the underside of the arch;
- an elevation of the highest pier, very similar to the underside view of the arch;
- a graphic static construction under g loads (own weight).

At this stage, the drawings contain multi-numbering of sections, annotations, and a lot of corrections on marks and dimensions (fig. 7). The underside of the arch is a slab whose thickness varies along it (the arch is a kind of a mix between a double-tees section and a U-shape section, both variable along the bridge span).

The purpose of this third sketch plan is clearly about specifying the exact dimensions of the bridge related to calculations, except perhaps for the deck which is studied elsewhere.

In my opinion, the sequence of the documents mentioned above is not totally straightforward since, for example, the reaction forces at the source of the arch on the first document cannot have been determined at such an early stage of the design. The drawing has therefore probably been used as a graphic basis for graphically re-transcribing an outcome of structural analysis. But on the whole because evolutions are observed in the form of the components reinforcing our hypothesis, the order of the sequence such as it is presented here would be difficult to challenge.

What becomes clear is the huge difference between the use Maillart made of graphic statics, and the tool originally devised by Karl Culmann. In the two successive editions of his founding treatise (Culmann, K., 1866); (Culmann, K., 1880), graphic statics is primarily conceived as the central tool of mechanical analysis for structures. Structural analysis mainly takes place when all the geometric features of the structure have already been done.

For Maillart, it becomes a design tool in the sense that it helps define the geometry (morphogenesis) at a very early stage. We could therefore suggest a complete design procedure based on graphic statics to obtain the general lines of the lateral elevation of the Salginatobel Bridge (Zastavni, 2008a).

This design role also becomes particularly evident in the interpretation that can be made of the genesis of the geometry for the structure of Maillart's Chiasso Shed using graphic statics (Zastavni, 2008b).

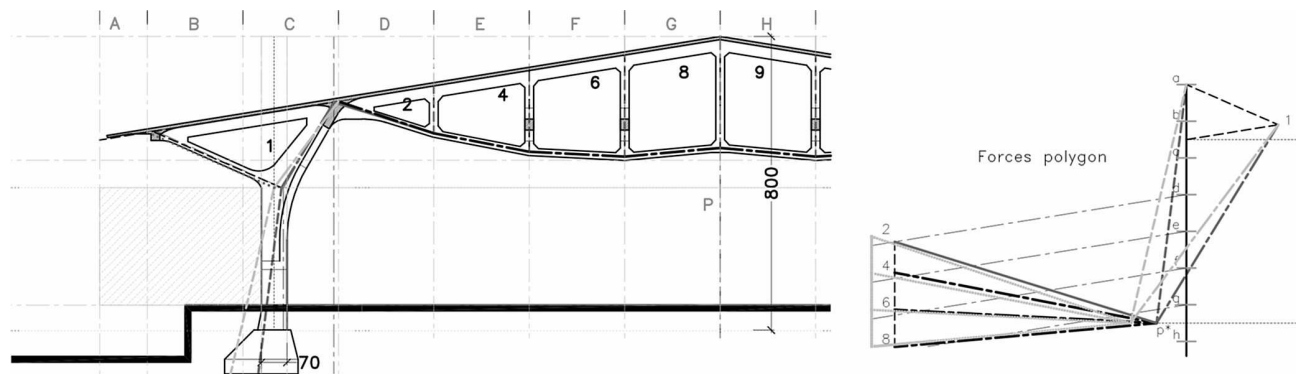


Figure 8: Graphic statics used as morphogenesis tool on Maillart's Chiasso Shed (Zastavni, 2008b)

DISCUSSION

Our examination of the available design plans of the Salginatobel Bridge shows how early in the design process graphic statics are used by Maillart, and the fundamental difference in his appropriation of this tool when compared with Culmann's ideas.

But what must be clear is that this approach presumes Maillart knew exactly how the entire structure would behave – depending on the kind of loadings – and that he knew which (kind of) forms had to be designed. It presupposes that he made up his mind beforehand on how to set concrete in its form depending on the particular circumstances of the structural issues within a complete structure.

For the arch of the Salginatobel Bridge and its hinges, the structural behaviour chosen refers mainly to masonry vaulting. During a second stage, Maillart completed the system locally with reinforcement steel to overcome the natural weakness in the masonry when thrust lines are intended to move under a variation in loads... and when major cracking has to be avoided.

The genesis of these particular transversal sections in his structure lies in the principle of integration, and reinforcement steel contributes to making these junctions possible.

Meanwhile, for the deck and for the piers under lateral wind, these components are specified as more traditional concrete beam systems. It reminds us that the multiple statuses concrete members are able to assume in a structural system are one of the reasons for the richness of Maillart's structural vocabulary.

All this presupposes a thorough reflection by Maillart about which we know nothing – initial sketch plans showing the earliest stages of his thinking and the form it could have taken have been lost – but that we know took place during an eventful period in the characterisation of concrete behaviour related to structural design. Therefore Maillart's visionary approach to concrete structural design becomes evident.

CONCLUSIONS

Graphic statics as a morphogenesis tool still has a promising future since it is in traction or in compression that materials are the most efficient. But each material has its own rules for integration within a complete structural scheme. Maillart shows us:

- the use of graphic statics as a morphogenesis tool;
- what is possible when the status given locally to materials can be determined in advance according to their own characteristics.

History suggests to us that materials will only find their own appropriate structural form and tools for their design on condition that their behaviour has been understood in-depth within the particular conditions of their use in construction systems. That being the case, we can imagine that the best is yet to come for the creation of design tools that are inspired by the past, by its designers and by the history of structural materials.

REFERENCES

- Billington, D., 1979: *Robert Maillart's Bridges, The Art of Engineering*. Princeton, NJ: Princeton University Press.
- Billington, D., 1997: *Robert Maillart, Builder, Designer, and Artist*. Cambridge: Cambridge University Press.
- Boitel, C., 1899: *Les constructions en béton armé, calcul de résistance, détails d'exécution*. Paris: Berger-Levrault.
- Chambre syndicale des constructeurs en ciment armé de France et de l'Union française, 1949: 1849-1949, Cent ans de béton armé. *Revue Travaux*, 194bis, pp. 34-41.
- Culmann, K., 1866: *Die graphische Statik*. Zürich: Meyer und Zeller.
- Culmann, K., 1880: *Traité de Statique Graphique*, traduction de la 2de édition allemande par Glasser, G., Jacquier, S., Valat, Paris: A. Dunod.
- Christophe, P., 1902: *Le béton armé et ses applications*. Paris-Liège: C. Béranger.
- Gori, R., 1999: Theoretical Performances of RC Elements Built at Turn of the Century. *Journal of Performance of Constructed Facilities* 13(2), pp. 57-66.
- Guidot, R., 1997: Béton armé. In : *L'art de l'ingénieur. Constructeur, entrepreneur, inventeur*, A. Picon (éd.). Paris: Centre Georges Pompidou, pp. 79-82.
- Hennebique, F., 1892: *French patent, No. 223.546* 1892, for a term of 15 years from August 8, 1892, limited to expire on August 8, 1907.
- Maillart, R., 1928: *Salginatobel-Brücke bei Schiers, Pläne* u. Berechnungen*. ETH-Bibliothek, Archives and Private Collections, Hs 1085: 1929/30-1, Maillart collection.
- Maillart, R., 1932: Die Wandlung in der Baukonstruktion seit 1883. *Schweizerische Bauzeitung* 100(27), pp. 360-364.
- Mörsch, E., 1902: *Der Betoneisenbau, seine Anwendung und Theorie*. Stuttgart: Wayss & Freytag.
- Ochsendorf, J., 2005: 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.
- Rigassi, C.; Billington, D., 1988: *Publikationen zu Robert Maillarts Leben und Werk in Handschriften und Autographen der ETH-Bibliothek: Robert Maillart (1872-1940) Ingenieur*. Zurich: Wissenschaftshistorische Sammlungen der ETH-Bibliothek.
- Simonnet, C., 2005: *Le béton, histoire d'un matériau*. Marseille: Editions Parenthèses.
- Zastavni, D., 2008a: *La conception chez Robert Maillart: Morphogenèse des Structures Architecturales*. Louvain-la-Neuve: Unité d'architecture, Université catholique de Louvain.
- Zastavni, D., 2008b: The structural design of Maillart's Chiasso Shed (1924): a graphic procedure. *Structural Engineering International* 18(3), pp. 247-252.

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