

# Maillart's design methods and sustainable design

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## Summary

This paper examines the design methods of Robert Maillart (1872-1940), drawing mainly on his well-known Chiasso Shed (1924). It shows that Maillart's stiffened arch probably could not have been defined through structural analysis alone, which implies that sound structural principles would have had to precede any geometrical definition. His analogical design-based geometry demonstrates a good structural behaviour. Maillart achieved a reliable structure while relying mostly on graphics. It appears that the design maintains the concrete structure under at least partial compression or minimising traction.

We conclude that preliminary sound structural principles and Maillart's graphic methods for geometrical definition could help to design a durable and reliable structure with advantages comparable to contemporary goals of sustainable design.

**Keywords:** Maillart (Robert); concrete; design methods; calculations; computer analysis; morphogenesis; graphic methods; reinforcement steel; sustainable design.

## 1. Introduction

Robert Maillart is one of the most remarkable engineers of his time. To the engineer's trained eye, his structures are a very clever synthesis of all the requirements and common tasks fulfilled by a "good" structure: economy of material, cost-saving efficiency, a well-conceived procedure for construction and remarkable durability over time.

## 2. Tools and methods behind the design of the Chiasso Shed

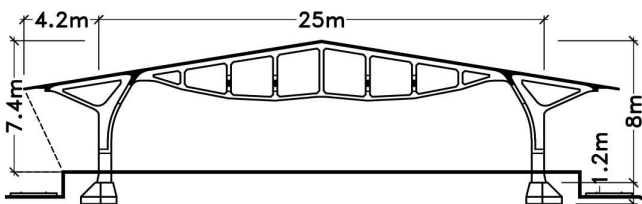


Fig. 1: section in Maillart's Chiasso Shed, 1924

In a recent paper, the author suggests that Maillart's Chiasso Shed (Fig.1) has been designed using a graphic procedure – a procedure using graphic statics, to be precise[1]. Having accepted the intrinsic logic of the structure's typology of an arch stiffened by the deck, a question emerges concerns its design: "Would a classical design procedure today based on structural analysis therefore naturally result in this

form?" It is likely that the answer would be: "Probably not."

To look for the genesis of the form of the stiffened arch, based on analytical results we used an undifferentiated geometric canvas and examples of loadings used by Maillart. We get major bending moments in the columns of the kind found in Vierendeel-like structural behaviour.

We could consider that columns are not supposed to be the masterpiece of an arch structural system and force the model to re-equilibrate the bending moments on the deck and the arch. Therefore, we

forced the dimensions of the columns to remain modest compared to those of other components: it means that we go against what the analysis is telling us. But even so, an iterative process will in any case make the section of the arch greater than those of the deck, and a principle of an inverse ratio of dimensions between the arch and the deck will not emerge.

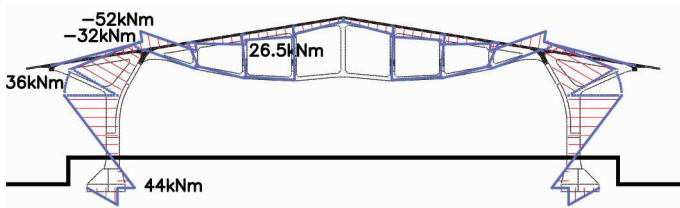


Fig. 8: Bending moments in the Chiasso Shed structure under dead loads and snow

Considering the structure of the Chiasso Shed, when we examine the steel reinforcement of all members, and evaluate their resistance, it appears that the role of the columns in supporting bending becomes anecdotal. Using a computer program to analyse the structure – with an upper chord belonging to the concrete roof – it demonstrates a structural behaviour where bending is mostly encountered in the upper chord, just as in a stiffened arch bridge.

### 3. Implications for the methods and characteristics of the structure

So what are Maillart's methods and principle used to achieve this principle?

Since we are aware that there were no tools suitable for analysing structures, Maillart used approximations or simplified structural mechanisms and combined them as tools to achieve a structural typology. The simplicity of the mathematical model gives him the freedom and opportunity to think a great deal when taking into account construction phases to minimise costs, to integrate parts of the work together with the same aim and consider the various aspects of the design. He also used graphic statics to calculate forces and moments but most profoundly, he used graphic statics to define the geometry of his structures. It implies that he was thinking in terms of struts and ties – mostly favouring struts – which leads to an expectation of a good durability. Simultaneously, it allows him to reduce the amount of steel reinforcement (and costs).

The simplicity of his methods gives him far more freedom to shift his attention to other issues like construction methods. His methods permitted him to master his design to maximise the savings in materials, reduce building costs and achieve very long-lasting structures. And it will not be difficult to prove that the longer a structure's life, the greater the savings in terms of resources and costs – in other words, how sustainable the design has been.

## 4. Conclusions

### 4.1 Maillart's teachings

What is characteristic about Maillart's methods is that he was relying on an association of simple structural models and graphic statics for designing structures, which allows him to master every aspect of the structural question (with an element of 'local' involvement in the design: he argued in favour of concrete structures in Switzerland since – except for cement and reinforcement steel – all the resources required were already on site [2]).

This mastery of the final geometric features permits good structural behaviour, which in turn gives reliability and structural safety and, as a consequence, durability. In relation to our modern methods, we could assume that all design procedures and tools allowing invention ought to give us a similar degree of design freedom to the kind Maillart arranged for himself. Let us be critical. We could also suppose that thinking in terms of clear structural behaviour is quite obviously one of the better ways of achieving reliability and therefore sustainability as well.

### 4.2 References

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## Summary

This paper examines the design methods of Robert Maillart (1872-1940), drawing mainly on his well-known Chiasso Shed (1924). It shows that Maillart's stiffened arch probably could not have been defined through structural analysis alone, which implies that sound structural principles would have had to precede any geometrical definition. His analogical design-based geometry demonstrates a good structural behaviour. Maillart achieved a reliable structure while relying mostly on graphics. It appears that the design maintains the concrete structure under at least partial compression or minimising traction.

We conclude that preliminary sound structural principles and Maillart's graphic methods for geometrical definition could help to design a durable and reliable structure with advantages comparable to contemporary goals of sustainable design.

**Keywords:** Maillart (Robert); concrete; design methods; calculations; computer analysis; morphogenesis; graphic methods; reinforcement steel; sustainable design.

## 1. Introduction

Robert Maillart is one of the most remarkable engineers of his time. With his collaborators, but most of the time on his own or as the project leader, he designed more than three hundred structures – more or less exclusively with reinforced concrete – including fifty very expressive bridges.

To the engineer's trained eye, his structures are a very clever synthesis of all the requirements and common tasks fulfilled by a "good" structure: economy of material, cost-saving efficiency, a well-conceived procedure for construction, remarkable durability over time. Anyone who has an understanding of engineering will probably find the whole exercise a beautiful one: on the one hand, the physical result of his design is of great interest, but on the other, the way he goes about it is itself rather ingenious.

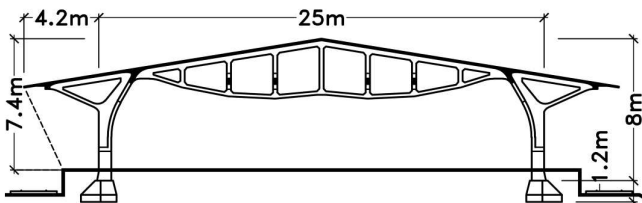


Fig. 1: section in Maillart's Chiasso Shed, 1924

We will be attempting to explore Maillart's methods using the Chiasso Shed structure (Fig. 1) – a form derived from stiffened arches – and draw conclusions about their possible sustainability for structural designs today.

## 2. Tools and methods behind the design of the Chiasso Shed

### 2.1. Origins of the Chiasso Shed structure

In a recent paper, the author suggests that Maillart's Chiasso Shed has been designed using a graphic procedure – a procedure using graphic statics, to be precise [1].

There are arguments backing this hypothesis. First, a drawing showing the vectorial equilibrium inside the structure was published in Bill Max's book [2], up to now the best review of the plans and drawings of Maillart's works. From this drawing, only the force polygon is missing. In this perspective, the lower chord of the structure appears to be a funicular line and it could be demonstrated that Maillart used graphic statics to draw this kind of profile. Proof of a procedure like this exists for the Schwandbach Bridge (1933), a stiffened arch bridge, where the arch is perfectly funicular [3].

Second, as commented on by David Billington [4], the Chiasso Shed structure was designed at the same time as his first bridges in the form of a slender arch stiffened by the deck. We will see parallels between the two structures.

Third, the reinforcement pattern, as we will see below, excludes any kind of behaviour characteristic of Vierendeel-like structures. It can be assumed that graphic statics is a tool adapted to designing structures like stiffened arches. It should be remembered that this kind of structure combines a funicular arch bearing dead loads and a stiffening longitudinal beam to take over other loadings. The role of this beam is fulfilled by the structure of the deck. The high level of this structure's relevance can easily be demonstrated when looking at cost savings and structural efficiency.

### 2.2. Designing a stiffened arch bridge

Having accepted the intrinsic logic of this kind of structure's typology, the question emerging now concerns its design: "Would a classical design procedure today based on structural analysis therefore naturally result in this form?" It is likely that the answer would be: "Probably not."

To look for the genesis of the form of the stiffened arch, based on analytical results and starting from an undifferentiated geometric canvas, our geometric starting point is an arch + a horizontal deck + columns, or a structure between the two. It is practically the same geometric canvas as with every arch bridge structure requiring a horizontal surface to be used as a road. Below we will be using the geometry of the Valtschielbach Bridge (1925, Fig. 2) whose arc line is circular.

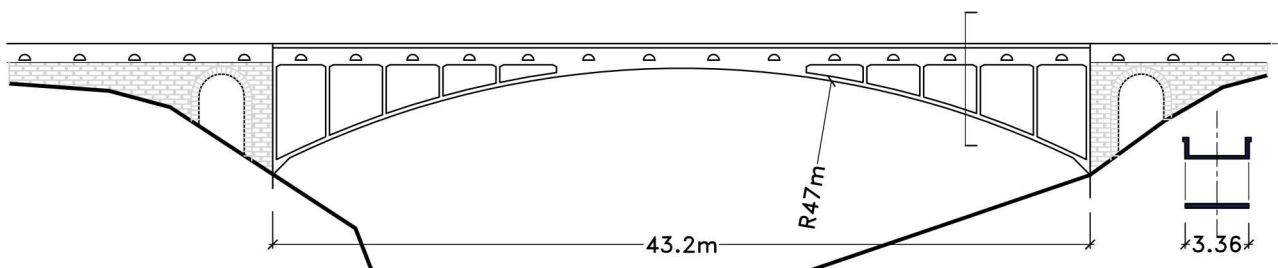


Fig. 2: Maillart's Valtschielbach Bridge, 1925

This bridge is the third in Maillart's series of twelve stiffened arch bridges.

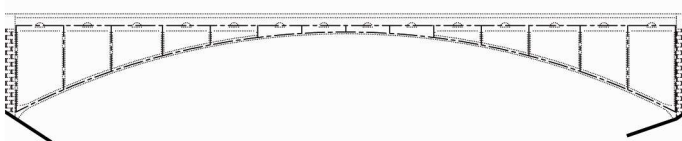


Fig. 3: elementary model of Maillart's Valtschielbach Bridge used for computations

We will be using this elementary model with undifferentiated sections in computer software (Fig. 3) and using a vertical loading on the deck (our reference loading cases: a distributed loading both for dead loads and living loads; dead load + living load on half of the length of the bridge; dead load + a

moving punctual load. In the first iterations, the dimensions of all sections are 160mm x 3,000mm.

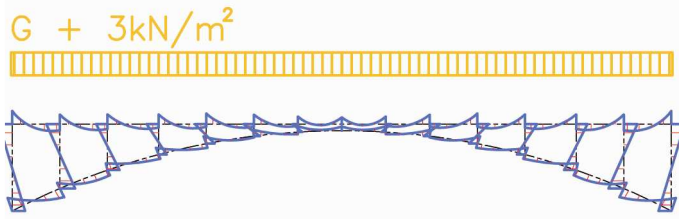


Fig. 4: Bending moments in the geometry scheme of Maillart's Valtzschiel Bridge 3kN/m<sup>2</sup> on a half-bridge

We get major bending moments in the columns; in other words, we get Vierendeel-like structural behaviour (Fig. 4). In reality, all the moments are comparable throughout the whole structure. With results like this, we will be reinforcing all the members in a similar way to optimise the use of material in the design. But the arch will probably be slightly thicker since it must resist compression forces too (in comparison, compression forces are negligible in the columns and the deck).

Compression forces and bending moments are given in Table 1.

Table 1: Force and moments in the generic model for the Valtzschielbach Bridge

Position	Normal forces (kN)	Bending moment (kNm)
Deck in quarter-span	119	22.8
Columns in quarter-span	110	45.6
Arch in quarter-span	1,930	25.5
Deck in mid-span	385	30.8 *
Columns in mid-span	101	58.5
Arch in mid-span	1,470	59.9

\* Up to 72.7 kNm due to a local connection with a column (but not exactly at the centre), non-existent in reality since the centre of the structure has become monolithic.

As a consequence, for pre-dimensioning the structure, considering concrete without cracking, a medium working stress of 6 N/mm<sup>2</sup> (not that far removed from what was used during the 1920s) and a width of 3,000 mm,

we could calculate the members as follows (Table 2) :

Table 2: Pre-dimensioning the structure considering only resistance

Position	Width (mm)	Thickness (mm)
Deck in quarter-span	3,000	90
Columns in quarter-span	3,000	126
Arch in quarter-span	3,000	160
Deck in mid-span	3,000	112 (if*:166)
Columns in mid-span	3,000	142
Arch in mid-span	3,000	187

We can observe that the most important dimensions will be encountered in the arch, and undertaking a new simulation will lead to major bending moments in the deck etc.

We could consider that columns are not supposed to be the masterpiece of the structural system and force the model to re-equilibrate the bending moment on the deck and the arch. One solution

could be articulating – totally or partially – the extremities of the columns but, in concrete, this is far from easy to do – and certainly costly! Another solution is to force the dimensions of the columns to remain modest compared to those of the deck and the arch. But to do this, it means that we have to influence the structural modelling which is no longer a pure consequence of the results of the mechanical analysis. And it assumes that you are able to go against what your analysis is telling you.

To limit the contribution of the columns to the structural system, let us limit the columns' dimensions to a viable minimum for casting concrete properly: 160 millimetres (like the transverse walls used as columns in the Valtzschielbach Bridge). To avoid any synergy with the columns, the mechanical properties of the deck and the arch must be far in excess of those of the columns. For a new simulation, we could assume that the deck's mechanical properties could be obtained for technological reasons. To define the deck's dimensions we will be using a 160mm slab like this and two lifelines of the same thickness – with a height of about one meter – forming with the slab a

monolithic U-shape (the profile has been used for the deck of the Valtschielbach Bridge). It will give inertia about 100 times greater than that of the columns.

A new simulation using this U-shape for the deck as well as for the arch – but with “columns” 160mm thick – will lead to comparable bending moments in the deck and the arch. The difference is between 6% and 20%, depending on the kind of loading for modelling the live load. But again, the presence of significant compressive forces in the arch will make all the difference. In this U-shape section of the arch, stresses due to compression forces are nearly four times those due to bending moments. Total stresses are about 3.71 N/mm<sup>2</sup> in the quarter-span of the arch. Stresses are only 1.03 N/mm<sup>2</sup> in the deck and the designer will probably reduce this section (by using a metallic lifeline, for instance). An iterative process will in any case make the section of the arch greater than those of the deck, and a principle of an inverse ratio of dimensions between both will not emerge.

We are forced to observe that there is very little chance that such an analytically-based design process could lead to the structural prototype where the role of a stiffening member is played by the deck while the arch remains thin. Therefore it is perhaps lucky that the kind of analytical tools suitable for an analysis like this were not around in Maillart’s day.

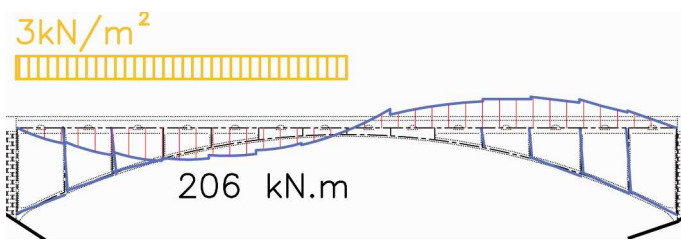


Fig. 5: Bending moments in the Maillart’s Valtschiel Bridge as build

However, using mechanical analysis on the structure as it was built will confirm the correct distribution from the bending moment between the arch and the deck, where the deck assumes most of the bending moments. All values are within set limits of admissible stress. The arch and the columns are at a stress level of 4 N/mm<sup>2</sup>, while the deck is over-sized with a stress of 2.4 N/mm<sup>2</sup>. But for the deck, the dimensions remain given by the geometrical constraints, as seen above.

### 2.3. Mechanical behaviour of the Chiasso Shed

The intrinsic nature of the structure of the Chiasso Shed has been questioned more than once. Indeed, the structure’s appearance suggests a bending diagram so much that practically everyone thinks that the geometry was worked out by reflecting on this diagram.

Since the structure did not include diagonals between what appears to be the upper and the lower chord, it appeared clear to some that this structure must be a Vierendeel-type structure.

Didn’t our simulation of the above on an undifferentiated model show that this kind of geometry (without a break in the line of the lower chord for stiffened arches) implies bending moments in the columns as well as in the opposite chords? In other words: a Vierendeel-like behaviour for the structure?

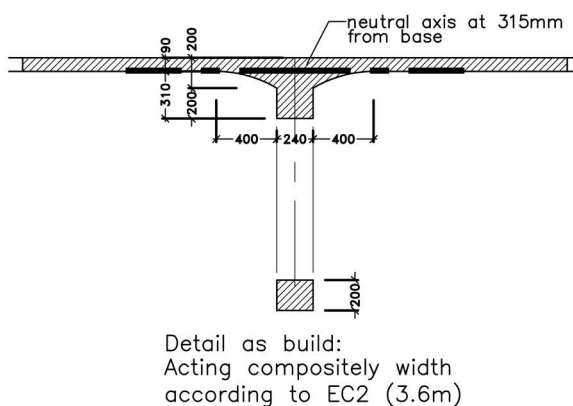


Fig. 6: Section in the Chiasso Shed roof, 1924

Didn’t Maillart strongly suggest this kind of structural behaviour by using similar apparent dimensions for all the members? (Vertical members = 240x240; lower chords = 200x240; apparent upper chord = 200x240: see Fig. 6). Furthermore, the drawing of the connections between vertical members and ones with an orientation near the horizontal suggests rigid connections (Maillart used chamfers).

This would mean forgetting two fundamental facts: the presence of the roof and the reinforcement pattern.

The roof of the structure is made of a 90mm continuous concrete slab. The upper part of the

upper chord is therefore included within this slab's material. The height of the upper member of the structure is therefore 400mm. But adjoining concrete sections accompanied by steel rods leads to a monolithic section when the concrete sets. The section of this upper member is no longer rectangular, but has become a tee-section. The width acting compositely according to EC2 is 3,600mm. The bending rigidity becomes far bigger than that of other sections of the structure.

Now, when we examine the steel reinforcement of all those members, and evaluate their resistance, it appears that their role in supporting bending becomes anecdotal.

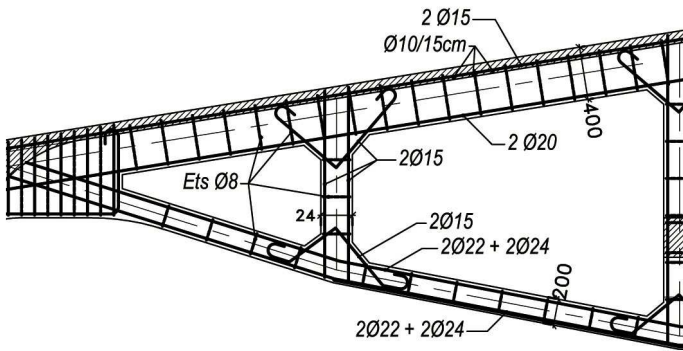


Fig. 7: Steel reinforcement in the Chiasso Shed structure, 1924

Starting with the vertical members, steel reinforcement is four Ø15 mm rods, i.e. a technological reinforcement. The steel reinforcement of the lower chord is doubled up :  $[(2 \text{ Ø}22 + 2 \text{ Ø}24)]$  (Fig. 7), giving a total of two times  $1,660 \text{ mm}^2 = 3,320 \text{ mm}^2$ . Working at a stress level of  $120 \text{ N/mm}^2$  [5], it gives a resistance of 398 kN. The forces in this member due to dead load and snow loads are said to be 380 kN [2]. It becomes clear therefore that dead load + snow is the reference case for giving the structure its geometry, so that no bending moments will overload this member. For other loading cases, slightly below this, it could be demonstrated that the capacity to resist bending of the lower member (3.5 Nm under dead load) corresponds to a maximum off-

centring default of the traction force of 10mm, which only represents the dimensional tolerance for the construction.

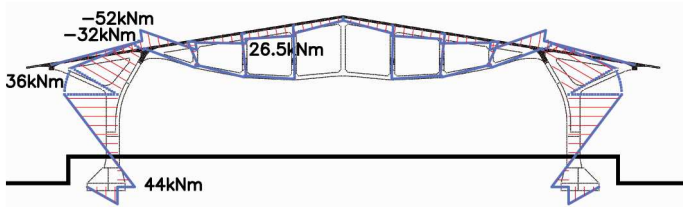


Fig. 8: Bending moments in the Chiasso Shed structure under dead loads and snow

Finally, using a computer program to analyse the structure with an upper chord as described above demonstrates a structural behaviour where bending is mostly encountered in the upper chord, just like in a stiffened arch bridge (Fig. 8). The position of the major bending moments along the member concerned will vary from what could be anticipated from careful analysis using graphic statics. But both the extent of the bending moments and the traction or compression force is correct.

And in one sense, the results of the computer elastic analysis and the analysis using graphic statics are both equally approximate.

### 3. Implications for the methods and characteristics of the structure

So what are the methods and tools used by Maillart to achieve a structural principle like this?

Since we are aware that there were no tools suitable for analysing structures, Maillart used approximations or simplified structural mechanisms and combined them. The simplicity of the mathematical model gives him the freedom and opportunity to think a great deal when taking into account construction phases to minimise costs, to integrate parts of the work together with the same aim and consider the various aspects of the design without getting caught up in analytical complexity to resolve the problem. In particular a consequence of this is to reduce costs, which differentiates his structures from those of other engineers.

To combine the elementary models of the bending beam and compression arches, he therefore relies on principles very close to those of our contemporary lower bound theorem of plastic design [6], but long before they were first formulated [7]. Algebraic relationships were used to define the dimensions of transversal sections, and sometimes to calculate bending moments. He also used graphic statics to calculate bending moments, compression forces and reaction forces in structures. But most profoundly, he also used graphic statics to define the geometry of his structures.

This latter use requires further developments as it will have a positive impact on the design.

We all know about using graphic statics to analyse a truss following Cremona's rules or for estimating a bending moment by drawing funicular polygons. But what do we know about using this technique for designing the geometry of structures?

Maillart's use of graphic statics for design implies that a significant number of his structures have had their geometries influenced a great deal by a funicular line – acting in most cases in compression – or by a vectorial equilibrium sketch, or by the association of both. It implies among other things that Maillart was thinking in terms of struts and ties – mostly favouring struts – which leads to an expectation of a good durability. Indeed concrete without cracks – compressed in most cases – is not as fragile to moisture as concrete with wide cracks. And it does not need steel reinforcement which could be essential to the stability of the structure. On the other hand, reducing the zones of traction means reducing the amount of steel reinforcement and therefore costs.

The simplicity of his methods, as we said, gives him far more freedom in designing his work, where others were afraid of the complexity of calculations implied by geometrical complexity. But Maillart was conscious of this: it suffices that important differences exist between dominant and accessory geometry, and between dominant and accessory bending-resistant sections, to control the structural behaviour of a structural unity. He could therefore imagine geometric combinations in section. He could also shift his attention to other issues like construction methods. (Should we doubt that Maillart's main justification for using the stiffened arch bridge was to sequence the construction, as the Romans did, enabling scaffolding to be considerably lighter?)

In short, Maillart's methods permitted him to master his design to maximise the savings in materials, reduce building costs and achieve very long-lasting structures: the Magazzini Generali Store and Shed are now 85 years old; the Saginatobel Bridge, built in 1929, has fulfilled its role for 60 years despite the very mediocre quality of its concrete and continues to do so following its 1975/1976 restoration [8, 9]; and the Stauffacher Bridge of 1899 is still being used after being restored in 1991 [10]).

And it will not be difficult to prove that the longer a structure's life, the greater the savings in terms of resources and costs – in other words, how sustainable the design has been.

What about local resources? Maillart frequently argued in favour of reinforced concrete for structures in Switzerland – a land of remote valleys – since all that was needed was to transport cement and steel reinforcement on site where gravel, sand, water and wood for scaffolding were already present. Salaries would be paid to local workers and suppliers too [11].

## **4. Conclusions**

### **4.1. Maillart's teachings**

We have reviewed the characteristics of some of Maillart's works, such as stiffened arch bridges and the Chiasso Shed. Using the geometry of the former, we have devoted ourselves to showing the very low probability of achieving such a design guided only by the outcome of structural analysis starting from undifferentiated typologies. With the example of the Chiasso Shed, mechanisms governing the design and structural behaviour have been explained.

What is characteristic about Maillart's methods is that he was relying on an association of simple structural models and graphic statics for designing structures. It permits him to master every aspect of the structural question and achieve his goals of reducing all kinds of costs and with an element of 'local' involvement in the design.

This mastery of the final geometric features permits good structural behaviour, which in turn gives reliability and structural safety and, as a consequence, durability.

Problems that arose in his later works were due to water sensitiveness (drainage), the quality of the concrete and hinges requiring restoration.

In relation to our modern methods we could assume that all design procedures and tools allowing invention ought to give us a similar degree of design freedom to the kind Maillart arranged for himself. We could also suppose that thinking in terms of clear structural behaviour – as graphic statics allows Maillart to do – is quite obviously one of the better ways of achieving reliability.

Breaking records with the help of technical means and complexity is perhaps not the best way of developing sustainable infrastructures. Simplicity has allowed Maillart to produce great works.

Therefore, wouldn't it be wise to think clearly about structural behaviour and be more attentive to the possible shortcomings of our elaborate tools?

## 4.2. Acknowledgements

The Belgian National Scientific Research Foundation (FNRS) supported this research by financing a visit to the special collections at ETH Zürich. The author is indebted to Michael Gasser and his colleagues for giving him access to documents in the Maillart archive at ETH.

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