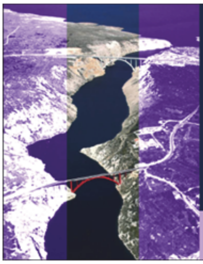

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TYPOLOGICAL DECISION-MAKING TREE FOR THE DESIGN OF ARCH BRIDGES FROM HISTORICAL STUDIES

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Abstract: *Designing structures like bridges is a complex task and the role that analysis, principles or optimisation should play in their design is worthy of consideration. These approaches ultimately result in typological arrangements: structural principles or geometries and their dedicated behaviours. Historical analyses of Robert Maillart's structures prove enlightening since he worked on a series of fifty bridges, the majority of which were arches. Maillart's methods placed hypotheses regarding structural behaviour at the centre of the definition of form. His singular methods became part of the organisation of structural principles in action. This is even more evident when some of his structures encountered physical contexts that did not fit with the assumptions that had been made during their design, therefore testing the limits of these hypotheses. A correlation of some typologies can be made with specific physical contexts. A typological decision-making tree is proposed for the design of arch bridges in Maillart's work as a synthesis for designers of arched structures.*

1 INTRODUCTION

Bridge designers are familiar with classical structural families or typologies. These typologies are linked to structural workings and associated with characteristic ranges of spans. Depending on the structural behaviours, joints or border conditions involved in the design, a link to types of materials can be made. Some materials are quite directly associated with known typologies, such as masonry for arches or timber for trusses.

However some materials, such as concrete, can be associated with a wide variety of structural behaviours and therefore typologies, introducing a more fundamental challenge.

An interesting way of tackling this issue is to turn to an expert in the exploration of structural forms made from concrete: the Swiss engineer Robert Maillart (1872-1940.]. His biography has been extensively documented in David Billington's reference publications [1,2]. Further information can be found in [3,4]. At the start of his career in particular, Maillart worked in a context in which designers were still seeking preferable forms for concrete structures. His bridges are of particular interest in this investigation given their wide typological variety. The physical context in which his bridges were built is quite specific and not all Maillart's structural typologies are interchangeable.

2 CLASSICAL TYPOLOGIES FOR BRIDGES

Historically, two materials were initially associated with the construction of bridges: masonry and timber. They are associated with massive and light structures respectively and specific structural behaviours apply to them. The behaviour of masonry structures is governed by a logic of thrust lines running within the thickness of the massive structure. Classically, massive construction refers to arches and piles. The behaviour of light timber structures mainly refers to truss mechanisms, even if timber has occasionally been used for hybrid arches or corbelled constructions.

In the 19th century, iron and steel profiles were considered for the construction of bridges and the typology of trusses was initially adapted. They joined the family of materials used for light structures. When their assembly had been mastered in greater depth, steel structures took the form of framed structures where bending was used extensively as in the Vierendeel typology [6]. With developments in manufacturing capacities, suitable material for devising suspended bridges – the inverted principle of the thrust in arches – finally appeared.

In summary, the logic that prevailed for massive structures is linked to arches in which thrust lines have to be considered. Light structures are associated with truss or frame structures with the option used depending on the mechanical properties of the chosen materials. Specific methods have to be followed for calculating and designing these structural families.

Considering its mass, characteristic joints and ability to sustain bending, with which material, structural logic and, consequently, typology will concrete be associated? Therefore, which calculation approach is concrete to be associated with since a link has been observed between calculation methods and structural families?

These are the questions Maillart had to address. Clarifying the situation is fairly straightforward: it involves observing his hypothesis and calculation method to understand the link he was establishing with the categories described above.

3 MAILLART'S STRUCTURAL TYPOLOGIES FOR BRIDGES

Maillart developed several typologies for concrete bridges: the three-hinged arch bridge, the massive classical arch bridge, the arch with a strongly off-centre thrust line, the stiffened arch bridge, the continuous girder bridge and, later on, cantilever bridges. He did not invent these typologies, but developed them for construction with structural concrete in line with its characteristics.

3.1 Three hinged-arch bridges

The principle of hinged arches is linked to iron/steel arch bridges that are mainly light, bent bridges. These bridges are very sensitive to thermal variations in dimensions and one of the reasons why these bridges have hinges. Incidentally, hinges give these bridges a relative insensitivity so that they can withstand movement in their supports.

However, concrete bridges were originally massive arch bridges that were quite rigid. When movement occurs, numerous cracks are therefore likely to appear, so hinging them was considered. This was proposed by Wilhelm Ritter when Maillart had to choose between options for the design of the Zuoz Bridge in 1901. The question remaining was which structural type Maillart would associate with this hybrid prototype. Design documents show that a logic of thrust lines was followed for the design of bridges in this family and the geometry was arranged around them.

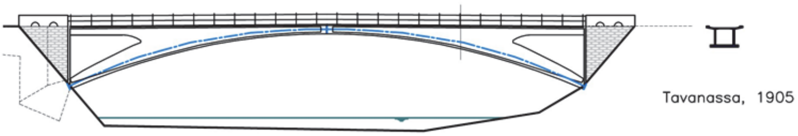


Figure 1: Robert Maillart's Tavanasa three-hinged arch bridge, 1:750

For a long time, the only reference loading cases for drawing the reference thrust lines intended to give the arch its geometry remained dead loads.

In summary, the basic principle is a compressed arch bridge taking the form of an (open) box enabling some bending to be sustained and intended for construction on weak ground.

3.2 Massive classical arch bridge

Classically, bridges in concrete were built as a massive continuous non-hinged arch, with or without steel reinforcement. Arch bridges without reinforcement are closely linked to classical masonry bridges. The arch supports columns bearing the deck. The deck comprises continuous beams and its only role is to transfer the applied loads via columns to the bearing arch. The scale of action of its structural role is confined to the interspacing between two columns. Maillart designed the Stauffacher Bridge (1899) in this way without steel reinforcement. Bern Bridge (1930) is a variation made of concrete blocks. Since this structural typology is massive and rigid, whereas masonry arch bridges adapt thanks to the ability of their joints to open, wide cracks are often found in concrete massive bridges. This is due to restrained movements or an undesired interaction between their constituent elements.

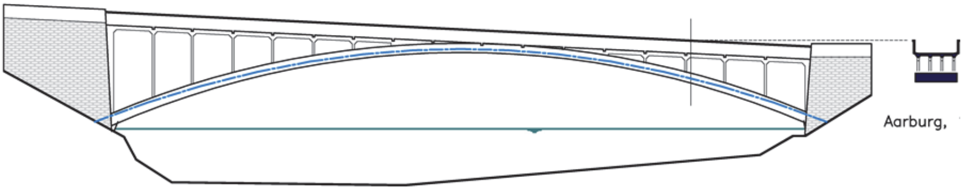


Figure 2: Robert Maillart's Aarburg massive arch bridge, 1:750

These bridges are also very sensitive to movement affecting the geometry which leads to cracks. This is why Maillart further investigated the geometry of this structural principle and it led him to design his first stiffened arch bridges in 1924.

3.3 Arch with a strongly off-centre thrust line

Arches with a strongly off-centre thrust line appear on just a few occasions during Maillart's career. The Aare Bridge in Innertkirchen (1934) is the only prototype built. This typology was also considered by Maillart as an alternative design for his Vessy Bridge (1936) which is a three-hinged arch bridge. In both contexts, the bridges had to be built on a river bed, so offered weak supporting conditions. Large deformations therefore had to be anticipated. These bridges include a central hinge and two unexpressed supporting hinges. The geometries of theses bridges were not constructed around thrust lines at all. Here, thrust lines exit the concrete section around the support zone where there is a wide reserve of material connecting the hinge and the deck in a continuous zone. The principle is therefore reliant on bending to sustain mechanical constraints. This typology is therefore to be associated with the family of light, hinged bridges but with a rather different geometry.

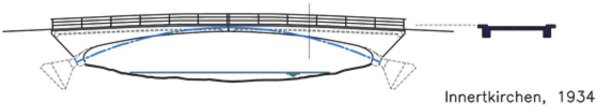


Figure 3: Robert Maillart's Innertkirchen off-center arch bridge, 1:750

In summary, the basic principle is a bent, hinged arch bridge, capitalising on the large quantity of concrete around the support to sustain forces using bending in concrete walls.

3.4 Stiffened arch bridges

Stiffened arch bridges appeared in 1924 in Innertal (Wäggital) on the Schrähbach River and are a quite elaborate structural principle combining thrust lines in a funicular arch and bending in the deck complex. These solutions were developed in response to issues that emerged from concrete bridges in the form of a thick arch capable of sustaining bending. This classical approach encountered undesired interactions between the different components that made up the structure. It resulted in damage to various parts of the structure. Maillart therefore had the idea of giving the components a specific role and matching their dimensions exactly to their structural action. The second idea was to dissociate the resistance to the forces present according to their nature and the type of loading. It resulted in structural elements that were highly specialised in their structural role: columns became thin slender walls, arches became funicular with a dimensioning matching only the axial compression force coming from the symmetrical dead load increased by its symmetrical counterpart from live loads.

The stiffening member is made from the slab of the deck mechanically associated with parapets initially or, subsequently, with supporting beams acting as ribs [7].

The principles of this bridge were to capitalise on the respective stiffness of the structural elements. The funicular arch is the stiffest mechanism activated under dead loads; the composite section of the deck is the stiffest bending mechanism against all other loading cases.

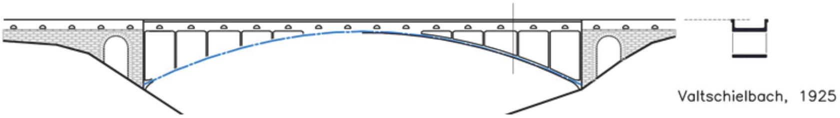


Figure 4: Robert Maillart's Valtschielbach stiffened arch bridge, 1:750

The result is also a very rigid bridge, but an unactivated structural element turns out to be relatively flexible against loadings intended to be sustained by other specialised structural mechanisms, leading to no damage or undesired interaction. This principle is the inversion of the mechanism of a suspended bridge. Since the bridge is quite rigid, it is particularly sensitive to supporting movements that prevent the mechanism of the funicular arch from being activated and the whole bridge acts like an arched Vierendeel-like structure.

Other characteristics are that this typology of bridge has been used to support railways (i.e. heavy loads), similar to the continuous girder bridge typology, and are quite high above their supports.

In summary, the basic principle is one of a rigid bridge made from a thin funicular arch, supporting walls of minimal thickness and a stiff bending section with the deck, this bridge only being effective on very good supporting ground.

3.5 Continuous girder bridge

Maillart designed and built his first continuous girder bridge in 1935: a railway bridge on the Birs River nearby Liesberg. This category is supported on four points along the girder: two intermediate supports resting on columns and two supports at the far end of the girder resting directly on the embankment. Depending on its location, there are variations in the length of the respective spans: from being fairly equal to having the widest span at the centre, with remaining subsequent spans becoming insignificant.

This bridge typology is mentioned here because if funicular or thrust lines had to be used to evaluate and draw bending moments, the trajectory would remain inside the material of the bridge everywhere (its form fits the diagram and evolution of bending moments). This is therefore a borderline case of an arch bridge becoming horizontal.

Compared to stiffened arch bridges, this typology has been used to support similar loadings, but is quite low over its supports.

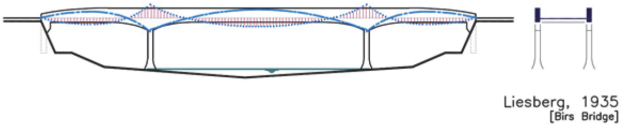


Figure 5: Robert Maillart's Liesberg continuous girder bridge, 1:750

In summary, the continuous girder bridge is a low bridge intended to support heavy loads, taking the form of a continuous girder on supporting columns, but with variations in the thickness of the beam that – depending on the its chosen interpretation – fits with bending moments or arched thrust lines.

3.6 Cantilever bridges

It seems that cantilever bridges appeared during Maillart's career in 1935 with an (unbuilt) design for a bridge on the Rhine near Schaffhausen. In a way this bridge is quite similar to continuous girder bridges, but differs slightly with regard to some typological features.

These bridges have three spans, but the central one is not as long proportionally. The role of the longer approach spans is to equilibrate the loads applied to the central span. The average expression of the bridge is more like a girder with varying dimensions since it rested on columns that were clearly distinct from the beam. The upper line of the bridge is an arch. Combined with the varying lower line of the girder, the geometry expresses the idea of a cantilever and is very thin at the centre of the central span.

So if the principle remains one of a girder, it is the upper line that refers to an arch, but with all other geometrical features contributing to expressing the idea of flexural operation. The slab of the deck runs – at varying levels – between the two longitudinal girders that constitute the profile of the bridge. The spans are also significantly longer than those of a continuous girder bridge.

In summary, the basic principle is a long girder relying on bending and an equilibration of loads with approach spans. The lines of the bridge refer both to the arch in the upper part and to varying cantilever beams in the lower part. The average geometry is consistent with the way girder concrete bridges are designed today.

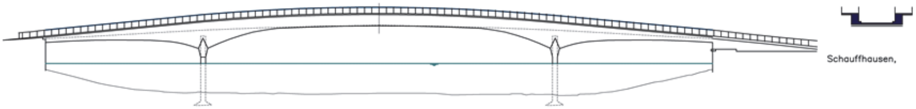


Figure 6: Robert Maillart's cantilever Schaffhausen bridge, 1:1250

4 TOWARD A SYNTHESIS OF TYPOLOGICAL APPROACHES

Five quite characteristic typologies for concrete bridges have been identified in Maillart's work. The question of whether this is a free exploration of concrete's possibilities in bridges or a more rationalised approach considering the structural status to be given to the material has been answered above with the latter interpretation. Another fact that reinforces this view is the examination of Maillart's bridge typologies with other materials. There are very few examples, but the Solis masonry arch bridge (1894) or a design for a trussed timber bridge in Innertkirchen (1933) confirm that it was logical for Maillart to follow classical typologies when they suited the mechanical properties of the materials.

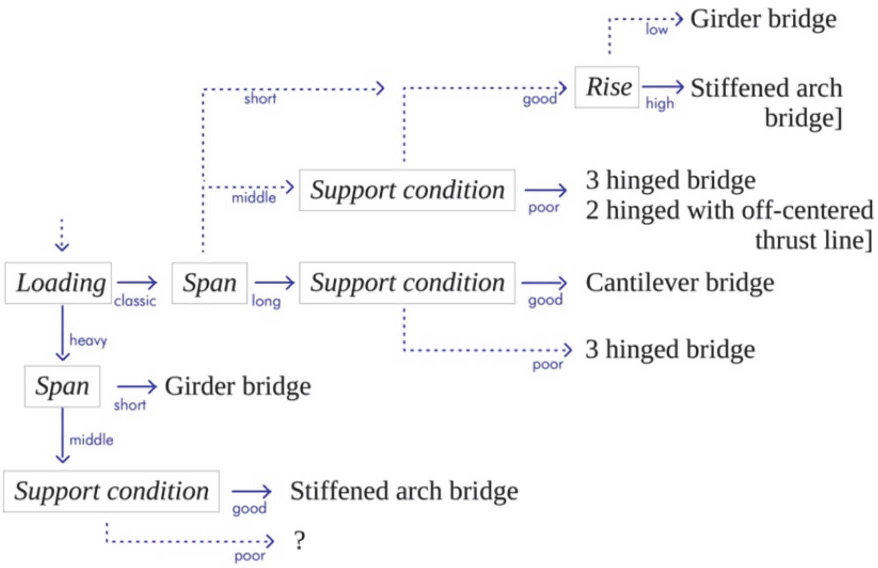
Returning to concrete typologies, a synthesis will now be proposed of the features defining Maillart's typologies to be considered for a given structural context.

	support condition	typical span	height over foundation	heavy loads	hinges	massive section	box	thrust lines	bending
three-hinged arch bridge	indifferent	middle-long	middle		●		●	●	o
massive classical arch bridge	good	short	low			●		●	
hinged massive classical arch bridge	indifferent	short - middle	middle		●	●		●	
stiffened arch bridge	really good	short-middle	high	●				●	●
arch with a strongly off-centre thrust line	indifferent	middle	low - middle		●				☐
continuous girder bridge	good	short	low	●		●			●
cantilever bridge	good	middle-long	low			●	●		●

Some features of the different typologies are already known, but new ones appear: stiffened arch bridges, continuous girder bridges and cantilever bridges are shown to belong to the same family (the latter two later succeeding the stiffened arch chronologically); the cantilever bridge is the version of a continuous girder suited to long spans. The typical dimensions of continuous girder bridges are quite close to those of hinged massive classical arch bridges.

	useful width [m]	span [m]	sag or height [m]	span/sag	dates	number
three-hinged arch bridge	3.2 – 9.8	32 – 90	2.35 – 9.7	7.05 – 13.62	1901 – 1940	10
massive classical arch bridge		6	1,2	5	1896	2
hinged massive classical arch bridge	5 – 7.6	21 – 67	2 – 6.95	8.9 – 17.97	1899 – 1924	4
stiffened arch bridge	2 – 7	14.4 – 43.2	2.55 – 7.89	3.8 – 10.86	1924 – 1934	13
arch with a strongly off-centre thrust line	7.2 – 9.8	30 – 56	3.5 – 4.8	8.6 – 11.7	1934 – 1936	2
continuous girder bridge	4 – 11.6	20 – 39.6	2.2 – 3.3	8.9 – 14	1935 – 1939	5
cantilever bridge	6 – 7	58 – 75	6 – 8	9.4 – 14.2	1935 – 1939	2

From these result, the following typological decision-making tree can be proposed:



5 DISCUSSION

This paper reviewed the characteristics of six concrete bridge typologies as designed by Robert Maillart. It appears that some typologies are linked to specific features, such as the stiffness of the supporting ground, the characteristic span, the importance of loading or the elevation of the structure. Grouping some of these typologies into families, according to these features, or into chronological considerations would seem justified. Taking these features as parameters for the structural issues enables choices to be made in the design of the geometrical characteristics of the reinforced concrete bridge being built. This analysis establishes once again that Maillart's geometrically characterised typologies are not interchangeable and that every design should start with considerations concerning the structural principles to be referred to in order to determine the geometrical features of the bridge being designed.

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