THE SALGINATOBEL BRIDGE
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Abstract: This article is based upon the author’s findings of the Salginatobel Bridge in Schiers, Switzerland. It is a reinforced concrete, hollow box, three pinned arched designed by Robert Malliart. Built in 1929-30 across the Salgina valley ravine, it connects 2 small villages.

Keywords: Three-pinned-arch, hollow box, reinforced concrete, centring.

1 Introduction.

A competition was launched some time after World War I for the design and construction of a bridge to connect two villages, Schiers and Schuders in Switzerland, across the Salginatobel valley. 19 entries were submitted for tender. Malliart’s design won through a combination of design and price and resulted in a world renowned bridge.

Reinforced concrete has proved to be a marvellous construction material. Taking the strength of concrete in compression and the strength of steel in tension. It can be formed to nearly any shape, and have good weather resistance. Because of these properties it has proved to be very cost effective.

Malliart’s design for the Salgina crossing was the lowest of all the tenders. The design evolved through his clever use of materials, and simple but accurate calculation. Making use of high quality, expensive materials sparingly this at this time was the steel for the reinforcement.

Fig 1: Salginatobel Bridge. From [1]
2 Bridge Components

Salginatobel Bridge is 135m long, the arch spanning 90m and rising 13.5m. The deck is at a slight angle rising from Schiers to Schuders by 3.97m or at a 3% gradient.

Fig 2. Bridge Components

2.1 Foundations

1: Foundations for supporting columns and for arch springing point. Schiers is situated this side of the bridge.

2.2 Approach Road

2: Approach Road labelled as such for simplicity, and a pin point at 5 makes this continuous deck separate from the main bridge deck. Approach roads are traditionally labelled for roads leading up to a bridge and not on the bridge.

2.3 Support Columns

3: Support columns for bridge deck. This are spaced at 6m centres (except at mid-span of arch) and continue behind arch walls, where then cannot be seen.

2.4 Foundations

4: Foundation for springing point of arch. A hinge also occurs at this point.

2.5 Road Deck

5: Road deck. The concrete deck is not connected either side of this hinge, making two continuously supported decks.

2.6 Arch plate

6: Arch plate which decreases in thickness towards the centre and arch supported walls, which increase in length towards the quarter-span point.

2.7 Road deck/Arch Plate

7: Here the arch plate becomes the road deck. Another concrete hinge occurs at this point.

2.8 Foundations

8: Foundation for second springing point and a third hinge completes the 3-pinned-arch. Schuders is situated this side of the bridge.

3 Choice of Bridge

It was the choice of bridge which lead to its design. The inhabitant’s of the villages either side of the valley had requested a more accessible route over the valley rather than the existing rough and rocky path. The Salginatobel valley walls were relatively weak and sharp angles. The flaky walls and numerous loose rocks from a number of rock slides are proof of this relative weakness.

Fig. 3 The rocky valley walls

Because of this, a deeper arch would have been inappropriate as this would require greater strength from the foundations and therefore unnecessary deep rock excavations.

3.1 Three-pinned-arch

A three-pinned-arch was chosen for its ability to move and adjust to the slight movements of the mountain. Whereas a fixed arched would experience massive stress from the movement, would crack and possibly fail. Stresses also build up from temperature changes within the structure. The three-pinned-arch is unaffected by these temperature changes. A three-pinned-arch is also statically determinate and therefore analyse of the bending moments is easier, simpler and more accurate, allowing Malliart to minimise material used as forces calculated are lower than other methods which require amplifying factors to make up for the uncertainty.

Malliart used his experiences from previous bridges he had constructed to help make choices in designing Salginatobel. Malliart believed that full scale loading was better than any calculations. A bridge he had constructed in Zuoz, also in Switzerland, was of similar design to the
Salginatobel. It was a three-pinned-arch, hollow box design constructed from reinforced concrete. The bridge spanned 38m and a difference with the Salginatobel was that the supporting arch walls connected to the deck for the whole length of the bridge.

[2] Reports that a couple of years after construction was completed Malliart was called back to assess some cracks that had formed in the supporting arch walls near the supports. He concluded that they were not serious; they had been caused by differential temperature changes in the bridge. The arch had been wetted by the close flowing river underneath, and the deck wetted by the weather. The arch walls had received no such wetting, and in the sun (the cracks had only appeared on the sunny side) had dried and contracted causing the cracks. The cracks were not structurally serious, but it was this experience which aided the Salginatobel design of having the supporting arch wall not connected to the deck at the supports. In this way the arch is left free to rotate on the hinges.

3.2 Hinges

The hinge design was a controversial issue. They are difficult to analyse, they need to strong enough to carry the entire bridge load (at the springing points) and need to be flexible to rotate. [2] Reports how Roš, a fellow engineer and friend, was hired as a consultant to the consol and required extra reinforcing steel in the hinges.

The following figures 4 and 5 show cross sections of both the hinges used, at the crown and spring point.

Fig 4 Hinge at springing point. Taken from [2]

Fig 5 Hinge at crown

One can see how Malliart has made use of cork plates to allow movement. If he were to have left the gaps as open movement joints they would be prone to clog, and therefore be useless is function, providing no movement. The steel is designed to take all the forces, and as it is ductile, it is possible for small movements to occur without damage to the structure. Concrete is a brittle material and very poor in tension.

Two approach designs were submitted for tender:

Fig. 6 Alternative approach designs. [3]

The more traditional masonry approach was priced at Fr. 144,000, and the continuation of concrete columns at Fr. 135,000. The masonry arches look very out of place with the rest of the structure, being in slender concrete. The concrete continuation definitely looks much more fitting with the overall scheme and aesthetically pleasing.

4 Aesthetics

No one can deny the beauty of this bridge. It setting most defiantly helps. Spanning the valley, surrounded by green alpine trees with clouds flowing over the top of the mountain it creates a picturesque scene. The grey/white of the concrete shines through the foliage drawing attention to the rightly so awarded “most beautiful bridge in the world” [4].

Following Fritz Leonhardt 10 steps to being beautiful Salginatobel fulfils its function. Clearly the arch provides support to the thin deck, and the valley walls provide
substantial foundation for the arch. The mountain walls provide the necessary horizontal and vertical support needed for an arch. The structure defiantly shows the observer how it works.

This is not a complex structure, and the simplicity of the bridge is one of its greatest appeals. David Billington reported that “discipline of structural efficiency is the primary basis for creation” [5]. This is mirrored brilliantly in Malliart’s bridge, it was the nature of the arch structure which lead to the design and complemented through the most efficient dimensions creating the overall structure.

The proportions of the bridge follow the efficiency of the structure. The arch walls widen at the centre where maximum bending occurs. The columns are spaced at uniform distances and “look” the correct size. They are neither giant, drawing unduly attention, nor are they match-stick in appearance, looking insubstantial to the structure.

Malliart actually widened the columns to appear more in proportion with the deck. Structurally they only need to be as thick as their centre cross section. This was just one of Malliart’s clever refinements. As the columns do not extend to the valley floor, only to the arch, the spacing has been keep uniform, rather than shortening the span at abutments as in many viaducts.

The bridge deck is constant and creates a sharp shadow accentuating the slenderness.

The surroundings has already been touched upon, but the suitability of Salginatobel to its surroundings cannot be appreciated until other choices are considered. A suspension or cantilever bridge would look imposing and heavy within the scenic landscape. The thin deck and arch of Salginatobel appear to flow out of the mountain wall as though part of the landscape itself. Leonhardt commented that a bridge should be incorporated into nature.

When the bridge was built in 1929 masonry walls were popular for arch bridges among other façade detailing. [5] Using just the concrete as a finish was radically different from the current trend but proved to be a success; the white standing out from the green of the trees and complementing the snow in the winter.

It should be noted that your viewpoint of the bridge changes its appearance. From far away, the slenderness is apparent and concrete gives the all white clean look. From the viewing platform below the bridge, and also up close, the greyness of the concrete and also the layers in which it has been poured, are noticeable. However matched against the rocky walls of the valley it fits in and makes one appreciate that all the concrete for the bridge was mixed by hand and wheel-barrowed into place! This adds to the character of the bridge.

Overall the bridge looks beautiful and it follows that it obeys Leonhardt’s rules. Beauty does not come with a price and it is surprising that this bridge that has drawn so much attention from round the globe serves two, low populated villages as a simple valley crossing.

5 Construction

The bridge was constructed using centring. The erected scaffolding looks impressive on its own.
The wooden scaffolding was constructed over the summer of 1929 by six men. It was proposed to be finished late summer, so concrete pouring could begin in the relative temperate summer/autumn period, but an accident to one of the scaffolders (he fell 35m and survived!) set back the finished date till late October so concreting did not begin until the following year. The scaffolding cost an additional 45,000 to the project budget, making it a third of the total costs. It was constructed by the highly regarded [5] Richard Coray. The design of the formwork must have taken into account that the wood would move somewhat with the weight of the concrete and so would have been a heavily engineered structure itself. (Rough scaling, 15m rise on scaffold. 13m on final bridge)

The arch walls increase in length but decrease in thickness from the springing points to the centre. This is because the greatest moment is experienced at the quarter-span points. The arch walls join to the deck from the quarter point. Reference [3] talks how Malliart calculated the most efficient design to increase the length of the gap in between the arch and deck further into the bridge, keeping the arch and deck separate for all but the centre key and hinge. Clearly, from a construction point of view, the formwork to create such a gap (around 10-30mm) is very timely and expensive and so Malliart choose the cheaper option, even though this contradicts his design that uses least materials.

5.1 Cantilever construction

Where the arch walls connect with the deck the familiar cross section of a hollow box is created. Cantilever construction makes use of the hollow box, starting at a pier or abutment sections are cast in situ or precast segments rose into place and then connected back using steel tension wires. This technique is now widely used, but would have been unsuitable for Salginatobel for many reasons. Cantilever construction uses a lot of tension wires to hold up the bridge during construction. Once the bridge is completed, and either side connected, the tension wires no longer perform a purpose. This is a very wasteful and expensive process and the council, and Malliart himself, were looking for an economical option. Also cantilever construction requires a balance of two sides over a pier, although ballast could have been used to start the cantilever at the abutments and to perform this method of construction. Alternatively a pier could have been erected mid-span in the valley, creating two 45m spans. The depth to the valley floor at Salginatobel is 80m, which would make the pier substantial in size. This would be costly in time and money, but also would look out of place in such a steep valley (as in fig. 10)

Temporary supports could have been utilised to support the bridge during construction and allowing the pier to be of a more slender construction.

Fig. 10 Possible alternative using a pier mid-span.

5.2 Centring

In modern day centring performed on such grand formwork is uncommon by not unheard of. Formwork is incredibly expensive, due to the materials and expertise required and because of stringent safety checks. In many projects it would also be a massive inconvenience to block up the area below, for example on a motorway crossing. The cost of the Salginatobel formwork today would defiantly exceed the Fr. 45,000 in relative terms. The thin arch plate was cast continually and symmetrically from both sides in 40 hours; an amazing feat [6].

It is likely that once the arch plate was cast more formwork would have been erected to cast the supporting columns and arch wall. The approach road and associated columns may have been cast first so the deck over the arch could be construction symmetrically from either side, so the arch doesn’t experience non-uniform loading when it is not at full strength. Concrete takes a time to “cure” before it reaches full strength. Temperature and moisture content are the main factors. If the temperature is too hot, i.e. in the height of summer, then concrete reaches stiffness earlier. However, the stiffness reached is not it’s highest possible value. There is also a high chance of cracking. Concrete should be kept cool and moist whilst curing to reach its optimum strength. As the formwork for Salginatobel was not finished till late October, the weather would have become too cold to mix concrete and so the concrete was started in the spring of 1930.

The deck is a continuous beam over the columns supports with hinges at each end, and at point 5 and 7 (Mentioned in Bridge Components), the edge of the arch and mid-span of the arch. It is likely in-situ centring continued for this. Formwork is erected and the deck cast above.

If it was possible to cast in one go, like the arch, then this would surpass the need for any construction joints. In modern construction is it very possible for concrete to be held up and casting stopped. In Switzerland they may have had a more efficient system (like they do for most things!) but this would still require a lot of effort to pour as one. Construction joints may have been formed, so the deck needn’t be poured as one. Also the support columns and deck would have been poured incrementally in conjunction.
Fig. 11 Showing how columns and deck would be built in conjunction.

The deck would be taken out to a fifth span in between supports which is where the joint would occur. This point is used because dead weight bending moment is approximately zero here. The formwork is tied to the first casting to avoid differential movement. Concrete is then poured from the next section towards the joint. If poured from the joint then increased strain is experienced in the joint and cracking would likely occur.

To build the bridge, the way it was back in 1929, today would not happen: the scaffolding would be so incredibly expensive and dangerous.

5.3 Pre-cast

Pre-cast steel and concrete sections span about 40m. It may be possible to construct an arch out 3 pre-cast sections, and then craned out. However the joints would most likely be around the quarter span point, which receives the greatest bending moments. If it were feasible to pre-cast larger segments then a three-pinned-arch could be created to mirror the current bridge. Casting a section over 40m is not impossible, but finding the space and then transportation is the difficult part.

5.4 Casting girder

A casting girder could be used as an alternative. This is often used when a deck is high up, and centring cannot be used, and the spans are medium to long, i.e. greater than 40m.

The casting girder acts as temporary formwork. Only a few companies in the world own girders of this length so this process is very expensive. They are typically around 50m in length, so a temporary support would be required. These require solid reinforced foundations as the support has to take some bending moment. This cannot be re-used so is a very costly and wasteful process.

5.5 Launching girder

Alternative to the casting girder is the launching girder, which may be more suitable for the Salginatobel crossing as the girder is placed above the deck. Both pre-cast and in-situ is possible in this form of construction. Some girders reach 80m, and there is a possibility that one maybe able to span the whole Salginatobel valley. This is unlikely, so a pier or temporary support could be utilised.

One of the main disadvantages with both the casting girder and the launching girder is that for cast in-situ concrete the concrete needs to be pumped along way which often results in a inferior concrete, as it can separate or “bleed”. Pre-cast units result in higher quality but transport to site is expensive and hazardous. The Salginatobel valley is situated in the mountains and would be very difficult to deliver parts to site, let alone a 50/80m girder!

All the concrete for the Salginatobel bridge was hand mixed near to site, and then wheel-barrowed into place which is a fantastic performance but crazy to duplicate today.

5.6 Incremental launching

Setting up a factory type site next to the valley and performing incremental launching could be a possibility for constructing the Salginatobel Bridge today. Pre-cast transportation costs and difficulties can be avoided. Sectioned can be cast and pushed out making space for more to be cast and set. A steel nose is added to the end to reduce hogging moments. No scaffolding or false-work under the bridge in the valley would be required for this process. Just the one set of formwork could be used reducing costs further.

An arch bridge could be created, mimicking the original bridge as long as the curve was kept constant, however it would be easier to construct straight. The bridge would be of high quality due to the factory conditions. A span to depth ratio of 1:15 is normally required and kept constant. This would make the bridge around 6 metres deep, and defiantly this would not have the same aesthetic appeal as the current bridge.

Strict control is required of the formwork, and the whole set up requires a lot of room. The mountain plateaus either side of the bridge, so this would be possible.

Heavy pre-stressing would be needed throughout the whole bridge, much more than would be required in the finished bridge, because every-section experiences the maximum hogging and sagging moments. Tendons would be needed at the top and bottom of the section to take this hogging and sagging, and once the bridge is completed further tendons are required to take service loading. This is wasteful and expensive.

To launch the bridge, the section must be either pushed or pulled. Pushing is the easier option, but not as safe as pulling. VSL developed a system which could be utilised. Using stainless steel sheets, in conjunction with teflon, and a cable the sections are pulled towards the jack near the support and out into the valley span. Also pulling from the lower ground, i.e. on the Schuders side, would be safer than pulling from the higher ground and risking the bridge sliding.

5.7 Suspended Cantilever
It is possible to combine suspended cantilever construction with launching, to reduce the hogging moment. Arches still seem most favourable for valley crossings, and this is most commonly constructed with centring. Some bridges make use of launching girders over columns, supported on an arch. It is even possible to supported a section of an arch using cables, while it is suspended like a cantilever over a valley.

Fig. 12 Using cable stay to support an arch during construction.

This would be a good solution to building the bridge today, and it would relieve the need for centring. However the cost of the cables and the towers that support them are large. Cable-stay bridges are very cost effective because the method of construction remains as part of the bridge structure.

5.8 Malliart’s Construction

Malliart’s Construction is so material efficient, aesthetically pleasing and cost effective, that it seems unlikely to be able to build a bridge to revile it today. Even with the humungous advance in methods and technology, most methods of construction lead to a vast waste of materials. A cable-stay bridge does do this, but would likely look out of place in the Salginatobel valley.

6 Loading

The British Standards for Bridge loading are possibly the most conservative in the world. When Malliart designed Salginatobel it is unlikely he designed for 40 tonne trucks to come bombarding down his bridge (the equivalent loading of the British Standards!).

Bridges need to be checked for ultimate limit state (ULS), to check that the material can resist the bending moments and shear force from the loading. This is to prevent collapse.

Serviceability also needs to be checked, making sure the bridge doesn’t deflect too much, or if creep has an effect.

6.1 Loads

1. Dead Load; This is the structure of the bridge, in this case the reinforced concrete. Except in construction it is always present, but different factors can be applied depending on whether the load is relieving, i.e. reducing bending moment in the structure at some point.

2. Super-imposed dead; This is any dead weight not performing a structural function, such as road surfacing, lighting and railings. This are present most of the time, but not always, so can be apply in different combinations to achieve the worst case.

3. Live Traffic; British Standards have two forms of traffic loading, HA and HB. HA is for general traffic and HB is for abnormally large vehicles. Various other loadings can be applied, such as skidding and braking loads. Abnormally large vehicles, such as mobile cranes, were not around when the Salginatobel was built. With more demands from the construction industry, among others, vehicles are getting bigger and bigger, increasing the loads that bridges have to take. HB loading is considered over a 3.5m width. Salginatobel is 3.5m centre to centre of the parapets, plus it is unlikely for such a large abnormal truck to be up the mountain.

4. Wind; Wind is intermittent, and generally short term, but it can appear at any time and it often causes most problems during construction when a structure is not completed, and it’s full strength is not achieved. In the Salginatobel valley wind would be an increased problem as the valley shape causes gusting, increasing wind flow. If a bridge has a particularly low or high natural frequency then wind can become an increased problem also.

5. Temperature. Temperature affects materials as it can change their volume, creating large stresses to build up within a structure. As discussed before the Salginatobel Bridge is a three-pinned-arch and so is free to rotate eliminating these forces. Stresses can also build up from the constant warming and cooling effects of temperature change, causing fatigue and in concrete leading to cracking. The arch is separate from the deck at the supports, so these fatigue mechanism is avoided such as in the bridge at Zuoz (1903).

6.2 Factors of safety

Once loads have been defined, then they are applied in different combinations and with different factors to calculate the worst possible load the bridge may have to resist. Factors are applied for the load ($\gamma_f$), and also for possible inaccuracies in analysis ($\gamma_{f3}$).

In concrete the current factor for the analysis method ($\gamma_{f3}$) is 1.10 for elastic analysis and 1.15 for plastic analysis.

6.3 Load Combinations

There are five different load combinations, and each needs to be checked for ULS and SLS.

1. All permanents loads and primary live loads. This includes all dead weight (including super-imposed) and HA/HB loading. HA/HB loading will be discussed later.

2. Everything from combination 1, plus wind load and possible temporary loads. As centring is used, I will assume there are no extra loads on the bridge during construction (except wind).
3. Combination 1, plus temperature, and possible temporary loads. As temperature does not effect Salginatobel this loading will be the same as combination 1.

4. All permanent loads and secondary live loads such as skidding and collision loads. Centrifugal loads need not be considered as the bridge is straight. Also associated live loads.

5. All permanent loads, plus loads due to friction at supports.

6.4 Dead Weight

The total dead load for the bridge is reported as 9.5 tonnes/m. This includes superimposed dead weight of the road surface.

6.5 Live Weight

Bridge carriageways are divided into notional lanes. If it is less than 4.6m wide it is divided by 3 to give the number of lanes. In Salginatobel case it has one notional lane (3/3=1). HA loading is then spread over this notional lane in a uniformly distributed manner. A knife edge load (KEL) is also placed in a maximum impact position.

The un-factored load is calculated from a graph, table or formula, whichever is easiest. Using the table found in the load for a 90m span loaded length is 17.8kN/m. The KEL is defined as 120KN.

Full HA is normally applied to two notional lanes, and other lanes loaded with 1/3 of the full HA. In Salginatobel calculations would be performed with full HA loading over the one lane.

HB loading is applied over a 3.5m width. As mentioned before Salginatobel deck is just shy of 3.5m, and realistically abnormally large trucks would not be expected to cross the bridge, so it will not be calculated for.

6.6 Loading the deck.

As the bridge is symmetrical through the arch, loading one half of the bridge would suffice, especially as there is a hinge in the middle. The following diagram shows how the different loads would be applied.

6.7 Loading the Arch

Arches are used as it is possible to construct an arch with dimensions resulting in zero bending moment.

Calculating the forces on an arch are shown below.

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Fig. 13 Combination 1 loading on beam.
Dead weight is approximate to 41kN/m and applying factors of 1.15 gives 48kN/m. Live load is 17.8 and applying factors of 1.3 and 1.1 gives 25.5kN/m. Applying the moments is now shown below: Horizontal forces are then 5509kN.

The worst case however comes from loading the bridge on one side. This leads to the following deformation. Placing two KEL loads at quarter span, leads to the most adverse effect.

Malliart made the arch supporting walls deepest at quarter span because of this maximum moment occurring here. The hollow box section is of sufficient dimensions to resist this.

7 The Future

The bridge currently is only one lane wide. It is unlikely the population of the surrounding villages is likely to reach such a level that requires widening the bridge to encase more lanes, or whether a new bridge would be needed to be built.

In any case The Salginatobel Bridge still remains a marvellous bridge, in looks, structural performance and cost.
References


[3] http://www.jstor.org/view/00379808/ap030103 /03a00060/11?frame=noframe&userID=8a26c029@bath.ac.uk/01cee4406900501bca917&dpi=3&config=jstor

[4] “Almost ten years later, after a worldwide survey, the renowned British trade journal "Bridge - design & engineering" voted the Salginatobel Bridge the most beautiful bridge of the century”
http://www.schierstourismus.ch/salgina/esalgina.htm


[6] “The most delicate phase was casting the thin arch plate, which had to be done absolutely symmetrically from both sides without interruption. After 40 hours of strenuous work, it was completed.”
http://www.schierstourismus.ch/salgina/esalgina.htm


