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The Swiss covered bridges of eighteenth century A special case: The bridge of Schaffhausen

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In history of timber carpentries, great interest comes out of Swiss covered bridges from a technological as well as a structural point of view. Beyond the numerous testimonies of such still existing works, acquaintance of the most important realizations is offered by the consultation of handbooks on carpentry, like those of Krafft (1805) and Emy (1841), and by widespread works as Rondelet's treatise (Rondelet 1810).

The bridge object of the present study constitutes a singular case as it is reproduced by some treatise writers as a bridge realized in the city of Wettingen, on Limmat River, but in truth it was never constructed. It is instead only the first design, set aside later on, proposed by Hans Ulrich Grubenmann for Rein river crossing at Schaffhausen. The interest for such design is motivated by the extremely dared structural conception: the potentialities of the structural scheme composite with struts arranged in the vertical surfaces aside of the track, already adopted in many illustrious examples of the past, come exalted through the connection of such structures with those of a covering central skeleton, realizing an effective spatial scheme.

A calculation scheme, based on the reproductions of the original design, and on a precise reconstruction of technological solutions adopted at the end of eighteenth-century in Switzerland, has been conceived to verify the reliability of this design which, with a free span of about 120 m, represents the attainment of a limit never equaled.

STRUCTURAL EVOLUTION OF COVERED BRIDGES UNTIL THE EIGHTEENTH CENTURY

Covered bridges can surely be included between the most fascinating timber structures of the past, and in particular those constructed in Switzerland in the XVIII century. The desire of protecting the main timber structures from the atmospheric agents, especially in the alpine regions, pushed the constructors of timber bridges to adopt covering systems of wood tables or tiles, and often wood tables were placed side by side giving rise to partially or totally blind vertical walls, at the aim of protecting against wind action too.

Between the known ancient Swiss covered bridges, there is the Kapellbrücke in Lucerne, built in the beginning of thirteenth century, which has a total

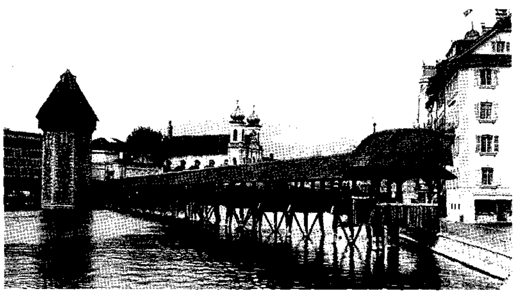

Figure 1
Kapellbrücke in Lucerne

length of 285 m, composed with spans of 7,65 m, and is supported by a simple beam structure, Figure 1.

This bridge, destroyed by a fire in 1993, has been then reconstructed in recent times.

A beautiful example of Italian covered bridges is the famous bridge of Bassano del Grappa (VI) of 1561, on Brenta River, built by Palladio (1508–1580), whose track is supported by an underlying structure. The spans, about 12,00 m long, show a trestle structure with inclined struts, Figure 2.

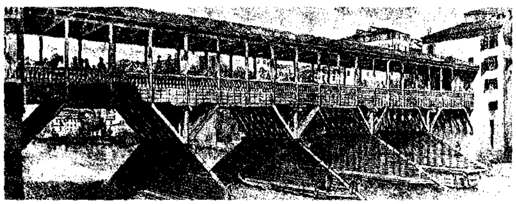

Figure 2
Bassano Bridge in a nineteenth century press

The bridge, destroyed in 1945, has been reconstructed identical to the original one in 1948.

However these support solutions with spans of modest length, don't represent, in the structural evolution of covered bridges, the most interesting examples, which can instead be ascribed to a different structural typology characterized by the presence of bearing elements disposed mainly above the track, besides those standing below.

Such typology can be interpreted like a different version of bridges «with lower deck», with bearing structures all disposed above the track, in contrast to bridges «with upper deck» in which the bearing structure is developed completely under the floor. The lower deck typology is that which Palladio develops and reproduces in book III of his treatise *The four books of Architecture*, published for the first time in 1570. Here various designs of bridges, based on the structural scheme of roof trusses, are proposed, all with an upper truss, Figure 3.

An interesting anticipation was that one of Leonardo from Vinci (1452–1519). In «folio 23», Code B he represents two bridges which can be classified as lower deck ones. In the first one, moreover, one observes how the principal structure,

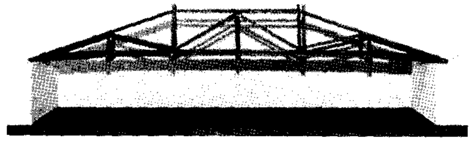

Figure 3
Timber model of the bridge on Cismone River

contained in the vertical surfaces aside the track, develops upon as well as below the floor, with inclined struts pushing on the banks, Figure 4.

Leonardo develops and synthesizes structural ideas already partially expressed in medieval age, as it is testified in «folio 20» of the Note-book of Villard de Honnecourt (XIII century) in which the author illustrates the modalities of building a bridge, based on the disposition of underlying inclined struts (Russo Ermolli 1995), Figure 5.

The employment in lower deck bridges of pushing structural elements, disposed also under the track, realizes a composite structural scheme which is

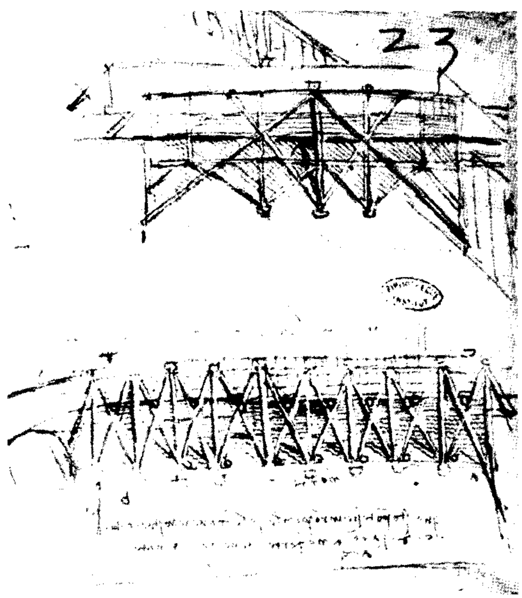

Figure 4
Leonardo's bridges in «folio 23, Code B»

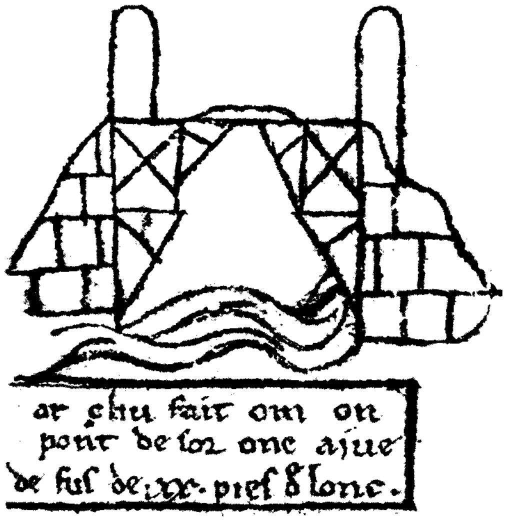

Figure 5
Bridge from the Note-book of Villard de Honnecourt

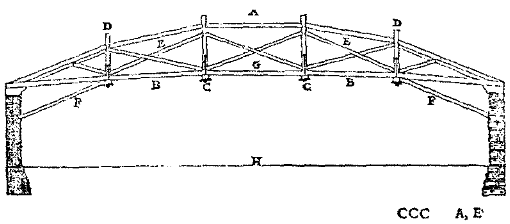

Figure 6
Palladio's «Second invention»

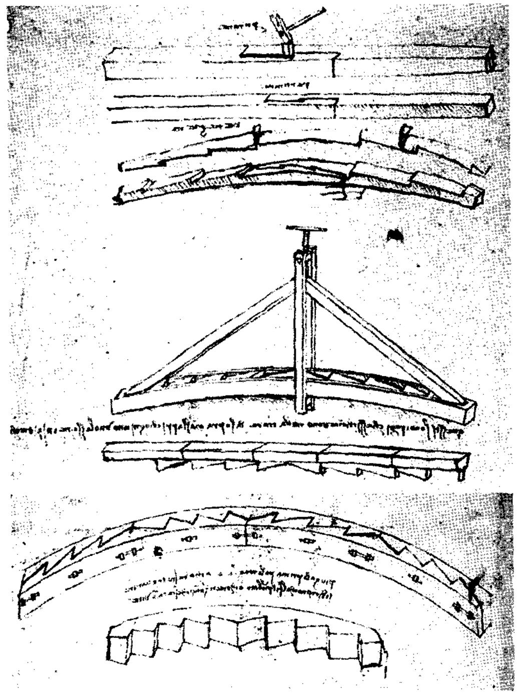

Figure 7
Atlantic Code. Folio 33 v. b and Folio 344 v. a

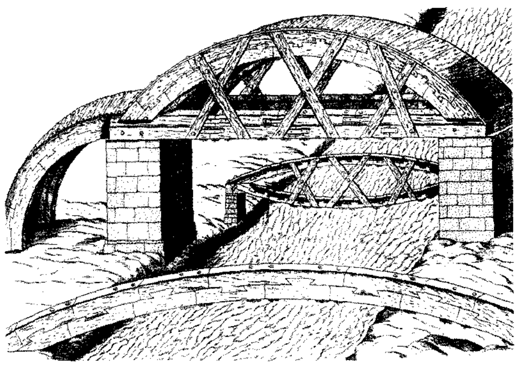

Figure 8
Drawing of a bridge from Veranzio's «Machinae novae»

obscurely present also in the «second invention» of Palladio, Figure 6.

This solution aims at transforming one simply supported structure in a complex of pushing type. Such structural behavior is a clear anticipation of the timber arch, whose structural effectiveness already had been understood, but whose practical realization was delayed by technological difficulties. Attempts to connect timber elements, making them behave like a single structural system, resembling an arch, had been proposed by Leonardo in the Atlantic Code, Figure 7, and by Veranzio (1551–1617) in his work «Machinae novae» of 1595, Figure 8.

The constructive problem of making timber arches of great span was resolved by Swiss carpenters in the

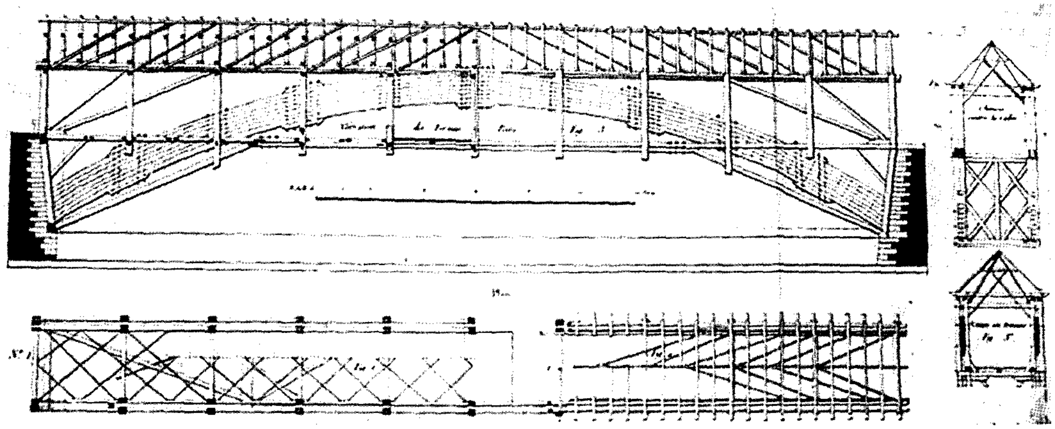

Figure 9
Wettingen Bridge (1765) from Table 28 of Krafft's Treatise (Krafft 1805)

eighteenth century, employing timber table notched and bent, held with iron bolts placed in correspondence of hanging double posts, Figure 9.

Such building system, which allowed exceeding spans of 30 m easily, first developed side by side and therefore substituted the composite structural scheme with inclined struts. Both constructive typologies were skillfully used by carpenters of Grubenmann family. In particular the three brothers Jacob (1694–1758), Johannes (1707–1771) and Hans Ulrich (1709–1783), born in Teufen in Appenzell Canton, built the most pregnant examples of eighteenth — century timber architecture in Switzerland and their work was held in so great consideration near the contemporaries and the nineteenth— century researchers to give place also to legends (Blaser 1982).

Between the existing bridges built by Grubenmann brothers, the following ones can be remembered:

— the most ancient bridge built by Johannes, the Rümlangbrücke near Oberglatt, dated 1766–1767,with arch typology and a span of about 28 m;
— the Kubelbrücke, near Herisau and Stein, built by Hans Ulrich in 1778, with multiple hanging trusses without nails or iron dogs and a span of about 30 m.

However the bridges which gave greater notoriety to Grubenmann family unfortunately had been destroyed during the Napoleonic wars, by French troops, in 1799. They are:

— the Schaffhausen bridge on Reno river, built in 1755–1758 by Hans Ulrich, with two spans of 52,00 and 58,80 m, constructed in fir with composite truss frames and inclined struts, Figure 10.
— the Wettingen bridge on Limmat river, built by Hans Ulrich in 1765, with a span of about 61 m, constructed with two sturdy arches constituted by notched and bolted overlapping beams, Figure 9.

A proof of the importance attached by contemporaries to these Grubenmann's bridges is the presentation of their plan, sections and prospects, made at the «Academie Royale d'Architecture», in 1771 by J. P. Blondel, who, it must be remembered, has been an active collaborator of the Enlightenment «encyclopedia» writers (Navone 2002).

But the work which for its boldness by far exceeds the quoted examples, constituting the apex in timber carpentry art, is represented by the first design Hans Ulrich Grubenmann made for Reno river crossing at Schaffhausen with only one span, a design never

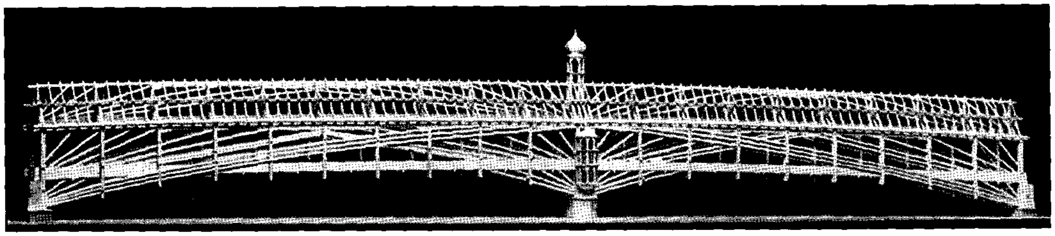

Figure 10
Model of Schaffhausen bridge with two spans (Steinmann, 1984)

realized. To its place it was constructed instead a bridge with two spans, Figure 10.

Historical news and sources

Steinmann (1984) reports that in 1775 Schaffhausen Town Council commissioned to Grubenmann master-carpenter the design of a timber bridge on Reno river, substituting the masonry one collapsed. The first design contemplated only one span of 120 m, which compelled the Communal Administrators to distrust that it could be built. A legend wants that when Grubenmann showed to the Councilmen the timber model of the bridge, they derided the design. He, in order to convince them, did not produce calculations demonstrating its feasibility, but stood up on the model (Blaser 1982). In that age in fact designers, and in particular carpenters, still based themselves on traditions and intuitions in dimensioning their structures. So Grubenmann was forced to elaborate a new design, in which the track was supported by the masonry existing pile at the center of the river bed. Such design was shown to Authorities in 1756, accompanied by a new timber model, a copy of which is reproduced in Figure 10. A drawing of this really built bridge is brought back by Krafft in his treatise (Krafft 1805), but it had already been published in Basel in 1803 in the work «Plan, Durckscknitt und Aufriss der drey merkwürdigsten höllzernen Brücken in der Schweiz» by Christian de Mechel, who had reproduced it in an etching of 1802. A previous table with the drawings of the Schaffhausen bridge was due to Christoph Jezeler, «Stadbaumeister» of Schaffhausen from 1766 and 1769 (Navone 2002). Rondelet, in the first edition of his treatise (Rondelet 1810), gives the description of Krafft, who erroneously dated the construction of the bridge to 1770–1771, and reproduces its drawing in Table 143.

Krafft and Rondelet both report that Grubenmann had designed a bridge with only one span, but was forced to make it rest on the existing central pier. They affirm, but this is another legend, that, once construction was completed, the bridge did not rest on the central pier, but it balanced with a gap of 18 inches above the pier. Only after some years, when the relaxation of whole structure was completed, the bridge leant on the central pier. Such circumstance is rightly contested by Emy in his treatise:

> Si è preteso che Grubenmann, per dimostrare la potenza dell'arte sua, avesse costrutto questo ponte in guisa che non posava sulla pila di mezzo, e che i magistrati esigettero che vi si facesse poggiar sopra usandovi delle zeppe: ciò che troviamo poco probabile perciocché non essendo il ponte in linea retta, ma formando angolo e cadendo il centro di gravità fuori della linea che unisce gli assi delle due testate, lo si avrebbe esposto ad un movimento di torsione proveniente dal suo peso (Emy [1841] 1856).

Also the most famous survey of Schaffhausen bridge first design is due Christian de Mechel who, in 1802, reproduced it in a etching by plan, longitudinal and cross sections, identifying it erroneously with the design of a bridge on Limmat river at Wettingen, destroyed, like that one of

Schaffhausen, in 1799, by French troops. This error of attribution was repeated by Rondelet, who in his treatise, in the paragraph entitled Wettingen Bridge, reports integrally the description of the first design of

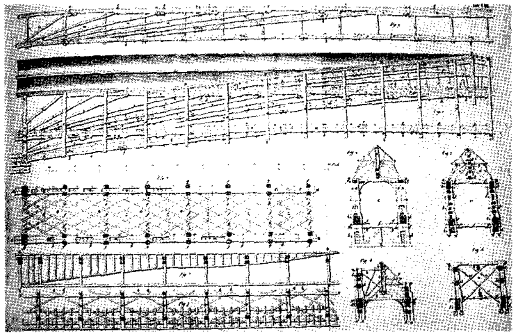

Figure 11
Plate 103 of sixth edition of Rondelet's treatise (Rondelet [1810] 1833)

Schaffhausen Bridge, given by Christian de Mechel, and reproduces it in Plate 103, (Rondelet [1810] 1833), Figure 11.

The same error is repeated by Emy ([1841] 1856) who reports its description with reference to his Table 134. In truth, the covered bridge really realized at Wettingen by Grubenmann brothers is that one with an arch structure brought back in Figure 9, destroyed in 1799. The contract for its construction was stipulated between Abbot Caspar Burgisser of the Cistercians Wettingen Abbey and Hans Ulrich Grubenmann in 1764. To its construction, which lasted from 1765 to the end of 1766 took part also Johannes Grubenman and two sons (Kottmann 1958). In the same site, in 1818–1820, was built a new bridge with two spans of 36 and 19 m, resting on a masonry central pier; the larger span, which is a covered one, is still existing.

Description of the structure

The description of Schaffhausen bridge first design, which has been taken as reference, is that one of Christian de Mechel, brought back by Rondelet ([1810] 1833); the survey has been Table 103, Figure 11.

The bridge has one free span of 118,80 m, with track clean width of 5,00 m. The inner height, under the covering structure intrados is of 5,50 m. The covering, with a variable profile, is of a mansard-roof type. In analogy with the existing documentation of other contemporary covered bridges, it has been assumed that the cover mantle was realized with wood tiles and that the sidewalls were completely closed by timber tables. Moreover the presence of five openings for each side has been considered, illuminating the middle of the bridge. In conclusion the building aspect could have been like that shown in Figure 12.

This prospect shows the exceptional slenderness of this construction, which can be synthetically expressed by the ratio between the height at middle point and the length of the span, and is equal to 1/11, in contrast with that one of some contemporary covered bridges with values variable between 1/3 and 1/7.

The designed structure is contained in the vertical surfaces aside the track and is of composite type, formed by trusses with inclined struts, disposed above and below the deck. All the structural elements in vertical plans are fixed by sturdy double hanging posts, at a mutual distance of approximately 5,20 m. These posts embrace and support the track main beam of cross-sectional dimensions 0,26 × 0,95 m, the covering structure impost beam, of maximum cross dimensions 0,60 3 1,45 m, the rafter, of 0,50 × 0.55 m, and all the inclined struts, of variable cross-sectional dimensions from a minimum of 0,26 × 0,26 m to a maximum of 0,70 × 0,80 m.

About connections in these structural elements, Christian de Mechel says:

> Le grandi travi . . . ed i grandi puntoni . . . sono formati . . . da molti pezzi innestati alle loro estremità e commessi a denti nella loro lunghezza, serrati l'uno contro l'altro da cunei, e legati insieme con ferri a vite e dadi (Rondelet [1810] 1833).

The double hanging posts are constituted by couple of symmetrical elements, regarding the vertical plan, at a mutual distance of 0,30 m and of variable cross-sectional dimensions along the height: in the lower part they are 0,60 × 0,38 m, in the intermediate part 0,45 × 0,38 m, and in the upper part 0,30 × 0,38 m.

The covering structure is articulated on a central backbone, contained in the bridge symmetrical plan, constituted by a lower longitudinal beam of constant cross-sectional dimensions of 0,34 × 0,60 m, and an upper one of variable cross dimensions from 0,30 × 0,28 m to 0,85 × 0,28 m, connected by double hanging posts composed by two parallel elements of 0,28 × 0,14 m, placed at the same mutual distance of

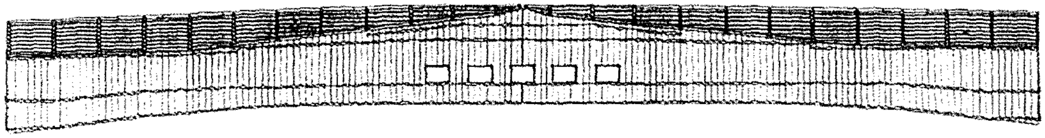

Figure 12
Reconstruction of the prospect of Schaffhausen Bridge first design

the main double hanging posts. In the vertical surface between upper and lower beams numerous inclined struts are arranged, with a cross section of 0,26 × 0,26 m. From the central backbone many inclined joists depart which, with variable cross-section and inclination, support the covering structure conforming timber elements. Such joists, together with the beams of cross-sectional connection, re-united at the top of the double hanging posts using metallic aids, make the covering structure a solidly jointed part of the bridge main structure.

The presence of a backbone is characteristic of the most important carpentry works of the Grubenmann family, already experimented in building churches coverings, like in the Evangelic Church of Grub, where the roof trusses, placed at very small intervals, form a single spatial structure because of the presence of a longitudinal polygonal skeleton (Killer 1988).

The secondary structure of the bridge deck is constituted by connecting crosspieces of cross-sectional dimensions 0,35 × 0,45 m, rigidly jointed to the double hanging posts also with iron strips and bolts.

The combination of all the described elements, defines a spatial entity with a box-like behavior, which as been understood by Christian de Mechel who tries a static interpretation based on the mutual support of the main elements of the structure (Rondelet [1810] 1833).

Such box-like behavior is exalted by the presence of the timber sidewalls coverings, and of course is subordinate to the hypothesis that the covering structure is rigidly jointed to the side one, and can be taught as a part of the resistant scheme. This circumstance is realized when the timber elements in the horizontal plane at the level of covering impost form a quite indeformable frame.

Structural verification

The spatial structural scheme of Schaffhausen Bridge, based on the drawings of Christian de Mechel, is constituted by one-dimensional elements with joints reproducing the described connections. The three-dimensional sight of the reconstructed scheme is brought up in Figure 13 where the outer cover is only partially reproduced in order to allow viewing the structure devised by Grubenmann.

The analysis has been led in linear elastic range.[1]

Enforced laws oblige to take into account, in bridge dimensioning, the possible presence of very large accidental loads which, therefore, constitute one remarkable share of total loads to be computed. For eighteenth-century timber bridges, built in Swiss valleys, it can be thought that the most important loads are dead ones, especially in presence of structures with an extremely closely-traced texture of beams with large cross-sectional dimensions, and also of timber coverings of sidewalls and topping.

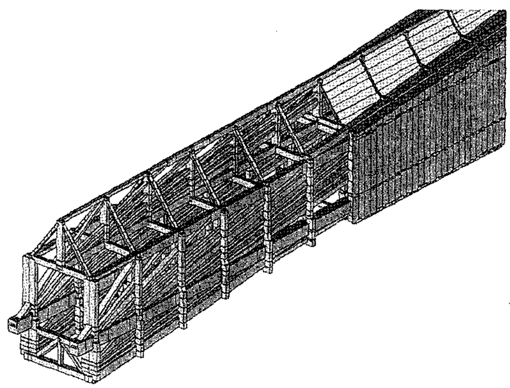

Figure 13
Rendering of the devised structural scheme

Knowing the employed wood essence is therefore determinant at the aim of right appraisal of dead-loads. Blaser (1982) says that the most used essences were oak and fir, as larch, technically more favorable, would have turned out excessive expensive. In lack of indications about the essences which Grubenmann meant to use in building his first designed bridge, and being based on the circumstance that the second bridge was built in fir, the employment of this essence has been assumed, with a density of 450 kg/m^2. In making calculations a value of 500 kg/m^2 has been adopted in order to take account of the great amount of iron fittings forecasted to strengthen the joints.

The overload on the track has been deduced by Rondelet's considerations about calculation of bridges assigned to heavy coaches passing:

> Supponendo il ponte destinato al passaggio di grosse vetture, il maggior peso che possa aver da portare la parte di mezzo, prendendo 6 piedi per lo spazio fra ciascuna armatura, non potrebbe essere più di 20.000 libbre. Questo carico equivale per ciascun armatura allo sforzo di un peso di 10.000 libbre situato sul mezzo (Rondelet [1810] 1833).

An overload of 2,35 kN/m^2 on the whole track length can therefore be deduced, even if this value is lower than actual standards.

The evaluation of overloads on covering structures due to snow effect has been carried out in compliance with the enforced Italian laws, using a referring value of q_{sk} = 0,90 kN/m^2 brought back in Euro Code 1 (2–3).[2]

Wind action is very relevant for a bridge with a closed cross section and making assignment on Euro Code 1 (2–4),[3] it as been evaluated as q_s = 6 kN/m^2.

Numerical analysis has given following values of maximum normal stress in the leeward vertical surface, which is the most stressed:

— in upper longitudinal beam, near the third inclined strut upper end σ ~ 17 MPa
— in lower longitudinal beam, in the maximum positive bending moment section σ ~ 13 MPa
— in the third inclined strut σ ~ 19 MPa

Corresponding diagrams of normal stress and bending moment are reported in Figure 14.

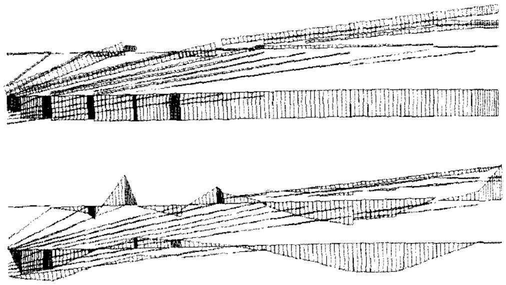

Figure 14
Normal stress and bending moment diagrams for the leeward surface

In the symmetry surface, maximum stress values are:

— in upper longitudinal beam, near the last inclined strut upper end σ ~19 MPa;
— in lower longitudinal beam, in the maximum positive bending moment section σ ~13 MPa;
— in the last inclined strut σ ~16 MPa.

Corresponding diagrams of normal stress and bending moment are reported in Figure 15.

A verification made using maximum allowable stress criterion shows that obtained values of normal stress are larger than the admissible value in bending parallel to longitudinal fiber, which is 11,00 MPa. Nonetheless with reference to known values of rupture for fir wood with a density of 450 kg/m^2, which waver about 70 MPa (Giordano 1999), it can be concluded that bridge structure,

Figure 15
Normal stress and bending moment diagrams for the symmetry surface

even if strongly stressed, is very far from local collapse. Moreover maximum inflection measured in middle section is about 0,69 m, which corresponds to a ratio of 1/170 to the span, and therefore only little above the admissible value of 0,59 m, corresponding to 1/200.

CONCLUDING REMARKS

Structural analysis shows that the first solution proposed by Hans Ulrich Grubenmann to build Schaffhausen Bridge, is a quite right one. In fact, safety conception about timber structures, as developed in the second half of twentieth-century, was not even guessed, at Grubenmann's times, by people operating in building field, especially for what concerns aleatoriety of rupture limit strength of wood. This lack of notions was sometimes overcome by great experience in choosing timber logs more secure in relation to their specific structural arrangement.

So the high exercise normal stress values measured wouldn't compromise the full utilization of the bridge. Also Christian von Mechel reports, in his just quoted writing of 1803, that evaluation of wood strength, must be commensurate to its weight, as he says could be deduced by Busson's works, exposed to Paris Royal Science Society in 1739 (Rondelet [1810] 1833).

The most interesting aspect of the studied structure is due to its spatial behavior, surely guessed by Grubenmann. In fact he brings about a large stiffness increase inserting a truss along bridge axis, which supports the covering system, and is rigidly connected to side surfaces structures, and also making the timber coverings of side surfaces and top, as well as the cross structures of the track, have cooperating structural parts. This behavior has been verified confronting structural analysis results of bridge spatial schemes with and without timber coverings on side surfaces and on the top. The presence of the timber shell causes a maximum stress reduction of about 15% in side frames and about 40% in central backbone structures. Also maximum inflection value shows a considerable reduction of about 30%.

Moreover it is interesting to observe that the arrangement of timber structural elements in side walls, characterized by a gathering of inclined struts near the banks with their inclination growing from middle axis towards side leanings, induces in side frames the arch behavior. In fact inclined struts and upper beams at the covering impost form an arch which takes compressive stresses due to superimposed loads and brings them at the ends of the lower beam, which behaves like a true tie-beam, supporting the considerable pull. As the arch is quite flat, bending effects are preeminent in all structural elements.

Even if it has never been built, this bridge represents an extremely dared structure and testifies the high level of Swiss carpentry art at the end of eighteen-century. It is significant the great admiration for this bridge shown by treatise writers of nineteen-century: Rondelet ed Emy, who both believed it was a really built bridge at Wettingen, report it as one of the most significant example of timber carpentry and mourn over its destruction with passionate tones.

NOTES

1. The software used is Nolian program by Softing.
2. *Basi di calcolo ed azioni sulle strutture*, 2–3 Azioni sulle strutture, carichi da neve. UNI ENV 1991. 2–3 October 1996.
3. *Basi di calcolo ed azioni sulle strutture*. Parte 2–4. Azioni sulle strutture, azione del vento. UNI ENV 1991. 2–4 March 1997.

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