The Oblique Bridges in Italy

Riccardo Gulli and Giovanni Mochi

Rome, May 1851. Around a table were seated the delegates of five States: The Hungarian-Austrian Emperor, The Duke of Parma and Piacenza, The Duke of Modena, The Grand Duke of Tuscany and representatives of the Papal State. The objective: to reach an agreement for the realization of the first rail link between northern and central Italy, crossing the Alps. Until that time only 300km of railway existed in Italy; small sections, separated one from the other and designed to connect the capital cities to the main ports: Turin with Genoa, Milan with Florence and Florence with Livorno.The papal government was planning connections between Bologna – Ancona and Ancona – Rome, whilst in the south, after the pioneering work on the Napoli – Portici line (1839), all further activity had ceased.

Figure 1. Railway system of the Italian States in 1848 (Berengo Gardin 1988)

The agreement signed in Rome provided the opportunity to achieve a breakthrough in the isolation of the single states and the chance to link Rome and Florence with Vienna and Northern Europe. In the following fifteen years, up until the end of 1866, 4000km of railway line was constructed, and by 1876 so much as to reach a total expanse of 7780 km. Despite the great efforts over these years Italy was not however able to attain the level of infrastructure of other European states that, over the same period, had reached a greatly superior level of development in their railway networks (Towards the end of the 1870's Germany had 29 000 km of line, France more than 22 000 km whilst the Austrian Hungarian Empire boasted of around 17 000 km of rail line).

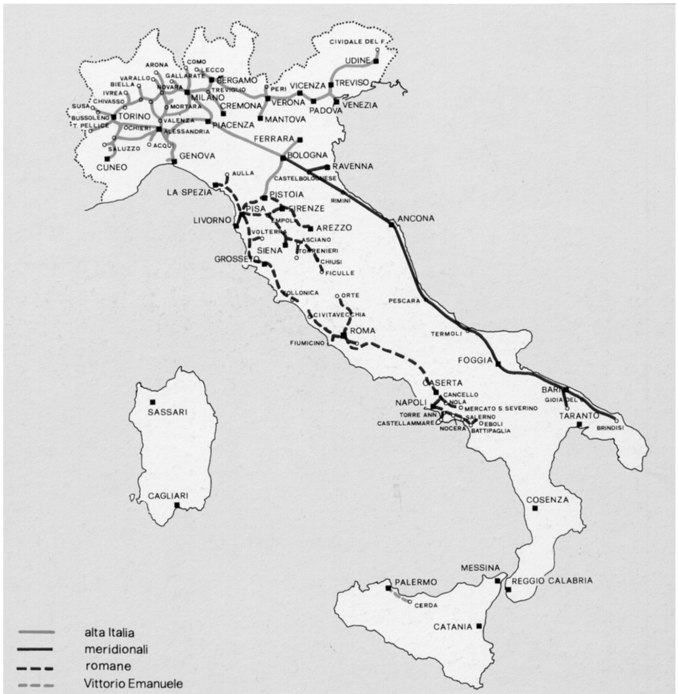

Figure 2. Italian railway system in 1865 after the Unity of Italy (Berengo Gardin 1988)

Italy's particular orography was, without a doubt, an immense barrier to the development of communications, however alongside this barrier there were other factors that served to slow down if not to prevent progress. Of prime importance was the fragmented political environment that however, as was earlier noted, was overcome in May 1851 at least as far as the trans - Apennine connection was concerned. In addition, the scarcity of raw materials, such as iron and coal, brought about a slowing down of growth in the railway industry. Lastly, but of equal importance compared to the factors listed above, one notes a lack of technological development in this specific industry, which was in turn a result of the poor diffusion of a polytechnic culture, particularly during the first half of the 19th Century. This relatively embryonic culture, closely tied to the presence of a central state, that necessarily exercised strategic control over territorial development, in Italy was not wanting in terms of scientific tradition or innovative thinking of international prominence. The principal explanation for the poor development of communications is to be found in the lack of schools that imparted instruction that could form the basis of a polytechnic culture. This was in turn linked to the absence of a central body responsible for overall planning of instruction.

In this respect it is noteworthy that in Italy as of 1851 there were only three schools in existence that issued diplomas for free engineering practice: Pavia (from 1803), Napoli (from 1810) and Rome (from 1817). In the formation of all of these institutes the influence of historical factors connected to the Napoleonic campaign seemed to be fundamental and as such these schools were derived from the model provided by *Ècole des Ponts et Chaussées* founded in 1747. However, even if in keeping with the French didactic model, these three schools were not able to overcome on their own the technological gap that existed alongside other national factors, directly linked to the extreme fragmentation of the Italian state. Disregarding northern Italy, where the existence of the Sabaudo State and above all the Austrian Hungarian Empire constituted two contexts in direct contrast with the rest of Europe, the state authorities operating in central and southern Italy were unable to maintain their own territories, let alone bring about the transformation and the organisation of these into modern states. Some relevant exceptions are to be found in events in the grand duchy of Tuscany and the modernisation works initiated within this territory by the Grand Duke Pietro Leopoldo d'Asburgo – Lorena in the 18^{th} century. Between the 18^{th} and the middle of the 19^{th} century working in the service of the grand duchies, were the so-called *"Acqua e strade",* individuals of undoubted merit, who realized reclamation and construction works of notable importance. Within this group, Leonardo Ximenes and Alessandro Manetti have been remembered. Leonardo Ximines was born in Trapani in 1716. He moved to Florence as a teacher for the children of the The Marquess Riccardi. Geographer, mathematician and hydraulic engineer he also established The San Giovannino Astronomic Observatory in Florence. He died in the capital of the duchy in 1782. Jesuit and therefore of the rationalist school as was Guarino Guarini, he worked in the area of hydraulic redevelopment and brought about the road connection from Florence to Abetone. Alessandro Manetti was born in Florence in 1787, he studied in Pisa and Paris and specialised in the construction of public works, working on sites in France, Belgium, Holland, and Prussia. He died in 1863. Manetti constructed various bridges some of which had decks suspended by metal tie beams. In the duchy of Lucca worked Lorenzo Nottolini (1787 – 1851), noted for the so-called Chain Bridge in the Bagni di Lucca region, which used decks suspended by metal chains, based directly on a similar English construction that Nottolini had expressly visited after receiving the commission for this work.

The representatives of the five States signed, in May 1851, the agreement that would allow the realisation of the first Apennine crossing, after which however, the first signs of conflict started to show. Those representing Lorena had already in hand two studies for the connection on Tuscan soil running from Pistoia to Porretta (the first Pistoia-Porretta project dates 1842 and was the work of Tommaso Cini, whilst the same month of the agreement saw the development of the second proposal under the engineer Antonio Giuliani), but the representatives of Lombardy-Veneto raised doubts on the technical validity of the proposals and ordered the undertaking of a special commission into the study of the entire Piacenza-Bologna-Porretta line. The Railway Society of Lombardy and Central Italy, agent for the new rail network, in 1856 chose a young French engineer, Jean Louis Protche, for the project and to oversee the work. His solid grounding as a *politechnicien* and later as an engineer qualified at the *École des Ponts et Chaussées*, was sufficient to speak for the absolute technical validity of his selection. Jean Louis Protche was born in Metz in 1818 and at the time of the agreement between the five states (1851) had graduated from his technical studies with high honours. Called to Italy he based himself in Bologna from where, in the space of only 8 years, he oversaw the construction of the entire Piacenza to Pistoia line.

Antonio Cantalupi in his work *La construzione dei ponti e dei viadotti: trattato di architettura pratica* (Cantalupi 1884) claims that the first oblique bridge in Italy was constructed by the engineer Carlo Caimi in 1837 to cross *Il Naviglio Grande* between Boffalora and Magenta. Prior to this (1811) the same engineer had constructed, again with an oblique structure, a small bridge of modest dimensions over a canal on the outskirts of Binasco, along the Milan-Pavia railroad. With respect to the same bridge the work of Francesco Colombani *Sul taglio dei cunei nei ponti in sbieco* (Colombani 1838), is also noted. This structure, that at the time of printing was undergoing re-construction, was destroyed in the battle of Magenta of 4 June 1859, during the Italian Independence War, by Austrian sappers in retreat. Further details of the first oblique structures in Italy are to be found in the work of Cantalupi (Cantalupi 1884), who describes for example a bridge on the *Naviglio* close to Porta Venezia in Milan (realised by the engineer Giannella) and another constructed by the engineer Ribecchi over the Lambro river (along the Milan-Treviglio rail line) in 1844.

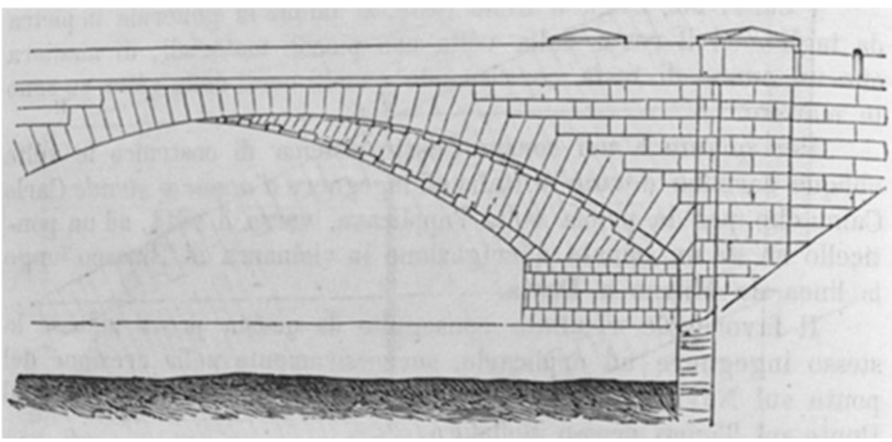

Figure 3. The bridge over Naviglio Grande near Boffalora (Cantalupi 1884)

The sighting of these first structures in Lombardy was to be expected, given that the Austrian region of Lombardy Veneto was the first to be provided with rail networks. It is also noteworthy that the first experts to become involved with stereotomy as applied to oblique bridges, came from the

Engineering School of Pavia, granted independence from the Faculty of Philosophy during the Napoleonic period, and that during the reign of Maria Teresa of Austria had already become distinguished as a principal centre in the training of engineers and architects in the Italian territory (the Austrian Empress in 1771, assigned to the Philosophy Faculty of The University of Pavia the chairs of Geometry, Elementary Algebra, General Physics, Advanced Algebra, Experimental Mechanics and Physics, under Alessandro Volta from 1778. In 1786 an imperial disposition singled out Pavia as the principal seat of engineering training in the Italian territory).

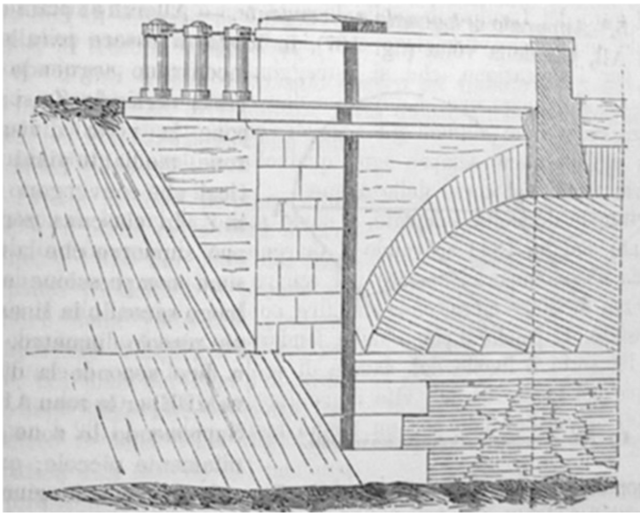

Figure 4. The bridge over Lambro near Treviglio (Cantalupi 1884)

Representative of this school were Antonio Bordoni and Francesco Colombani who, as Antonio Becchi maintains:

> [Bordoni and Colombani] represent a singular exception in the Italian panorama in terms of the study of vaults and stereotomy
>
> (Becchi, Foce 2002, p.76)

Bordoni published, in 1826, a short work *Nota di stereotomia sopra i cunei dei ponti in isbieco,* in which his interest for theoretical discussion, and geometry in particular, is accompanied by practical recommendations for the selection of shape of the voussoirs that made up the vaults of these bridges. However, it would be his student from the University of Parma, Francesco Colombani, who distinguished himself for the originality of his proposals and profound understanding of the subject. Becchi (Becchi, Foce 2002) notes that at the time of publication of Colombani's work, there were no French texts that dealt with oblique bridges, whilst only a handful of English authors had published studies on the subject.

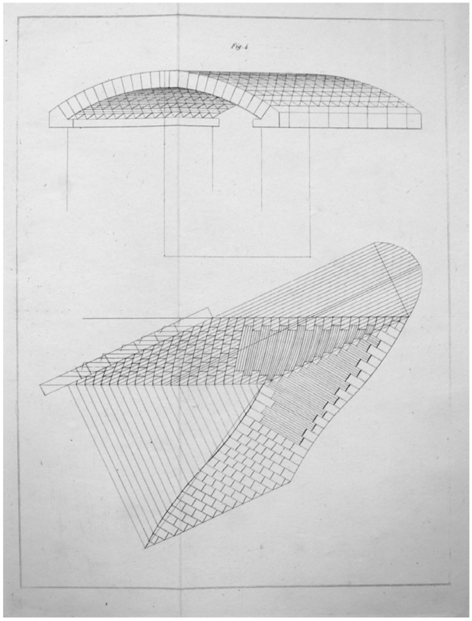

Figure 5. The helicoidal device (Colombani 1838)

Following the systemization of geometry made possible by the work of Gaspard Monge, the issue of stone vaulted construction lost its prominence as a independent discipline that had distinguished it in France between the 16th and the 18th century, and it came to form part of the teaching of descriptive geometry at the École Polytecnique. The exact geometric description of stereotomic operations, that eliminated any ambiguities resulting from incomplete methods of spatial representation, would have permitted from 1800 onwards a comprehensive and definitive progression in stone construction, if there had been studies of applied mechanics relevant to these wonderful structures. However, no scientist had as yet ventured into this area. The two disciplines, mechanics and descriptive geometry, were still dealt with separately as of the beginning of the 19th century (Becchi, Foce 2002) (Mochi 2002). On the other hand problems connected with the construction of *ponts biais* were, at that time, still in the early stages, but became of real importance some years later. At the end of the 18th Century there were in fact few bridges that exhibited oblique adaptations in keeping with the natural flow of water-courses. Becchi (Becchi, Foce 2002 p.70) cites the example of the Trilport bridge over the Marna, designed by Hupeau and de Chézy between 1756 and 1760, a structure of noteworthy obliqueness.

However, the development of infrastructure proceeded at a great pace in England towards the end of the 18th century, development that had as a consequence the construction of numerous oblique bridges. Amongst the English texts, that preceded analogous and specific French contributions on the subject, one notes those of Peter Nicholson (1828), John M. Hart (1836) and George W. Buck

(1839) (Becchi, Foce 2002, pp. 73-74). Buck became one of the most frequently quoted authors and builders, held to be a great authority in the construction of structures using the so -called helicoidal method. On many occasions Joseph Alphonse Adhémar in his work on stereotomy applied to bridges (Adhémar 1856), made reference to the writings and experience of Buck, and the widespread nature of precisely that construction method leads one to conclude that he was one of the greatest experts on an international level (Mochi 2002).

Colombani expressly cites the work of J.M. Hurt, who had first appeared two years earlier, as proof of the fact that he as a diligent Italian, was well versed in international technical and scientific debate. This was due to the fact that, after his studies at Pavia, Colombani had attended *l'École des Ponts et Chaussées* and had attained professional experience in France on the rail sites of the Paris – Saint Germain line, work which was headed by Lamé and Clapeyron.

On the same site also worked Lefort, the first French author to publish a dissertation on oblique bridges entitled *Études relatives à la construction des ponts biais* (1939) (Becchi, Foce, p.77). Even if this work came later than other technical English publications, with Lefort's first paper, the French treatment of the subject immediately stood out from that produced across the Channel. If English engineers appeared to be more interested in practical solutions to defined problems, the French, with a feel for the overall economic dimensions of construction, set themselves apart for their immensely more speculative approach. The overall dimensions of issues connected with the construction of an oblique bridge are analysed in all respects, theoretical, technical, mechanical and geometrical, even if the treatment of mechanical aspects reflects, quite notably, the somewhat sketchy approach already taken by Gaspard Monge. In Levort's work, his exposure to contrasting schools reveals itself in the emphasis that the author places on the superiority of the orthogonal method over the helicoidal. The second is considered definitely more economical, but less suitable in guaranteeing a stable end result and came to be called the English method, given its widespread use in this country. The first method is indicated as the only that be used to avoid the appearance of the so-called *void-thrust,* originally due to undesirable shifts in the vaults, shifts that are so severe as to cause collapse in cases of extreme obliquity.

However, the conclusion drawn by Lefort, which was shared by all successive authors, had already been anticipated in Colombani's work. In his short essay, the author offers a useful summary of acquired knowledge on the subject up until that moment. He begins by sighting the work of his teacher Professor Bordoni, whose exposure however had been limited to vaults with slight obliquity. For these structures one would apply a prescribed method designed for straight barrel vaults with the only difference being that the voussoirs did not appear with rectangular but rather parallelogram shaped sides.

Further on Colombani cites the case of oblique English vaults created using the helicoidal method, which could also be used in the case of more pronounced obliquity, but which did not however guarantee stability (Colombani 1838, pp. 3-4). A third construction method, between these two, was that that came to be used on the bridge over the Naviglio Grande near Boffalora, at the time still in construction. This method, somewhat uncommon, can be seen as complementary to that analysed by Bordoni, in as much as it followed that the geometry of the facades is no longer the voussoir head, but it is the other two sides that are come to be formed perpendicularly to the frontal curves, whilst the heads are perpendicular to the vault axis.

At the root of these rules, as with those so-called orthogonal, that he introduced after having dealt with the others and that he claimed was that which, alone, could guarantee perfect vault stability, there were certain convictions that from the outset formed part of the body of knowledge of those building in stone. These were that stability was guaranteed by avoiding acute angles in the voussoirs and by maintaining the perpendicularity of the radial joints with respect to the curvature of the intrados. Other than these rules there was another that had to be observed for oblique bridges. This was to eliminate or at least to lessen the so-called *void-thrust*. From the total or partial conformity of the construction method to these rules followed a judgement of greater or lesser suitability that also encompassed structural stability. But as can be clearly appreciated the problem was raised, and resolved, strictly in geometrical terms.

Great importance was placed on pinpointing the direction of the so - called *void-thrust*, whose effects were shown, according to some authors, in compression of the acute parts and with an over - spilling of the bridgehead from its designated base. To avoid this it was necessary to make the oblique vault “behave” as much as possible as a straight vault, that is to direct the force onto the abutments in a perpendicular direction to these. Unanimously the authors agreed that this could be achieved by giving the voussoirs precise geometric configurations that they favoured in order of increasing importance: the parallelism of the voussoir heads with the frontal arch of the vault, the perpendicularity between the longitudinal joints of the voussoirs and the base of the frontal arch and, finally, the parallelism of these joints to the direction of the abutments.

The method studied by Colombani satisfied these three further conditions and the author supported it with key geometrical and analytical mathematical demonstrations, but considerable and noticeable problems in the cut of the voussoirs, which were all different, and the presence of uneven joints wiped out the brilliance of his theoretical solution in its practical applications.

Giovanni Codazza (1844), in his work *Nozioni teorico – practiche sul taglio delle pietre e sulle centine delle volte*, even if he doesn’t explore in depth the subject of oblique bridges, pays credit to the great theoretical value of Colombani’s work. He even goes as far as to call the orthogonal method the Italian method described in the first instance by Francesco Colombani, and contrasts it to the English method (helicoidal) and the French (which according to the author is a mixed method with the bridgeheads formed in an other way from the central part of the vault, which is treated as a straight vault). Codazza, who came from Pavia as did the two previous Italian authors, highlighted, with significant emphasis, Colombani's role in the study of oblique bridges, also in virtue of the fact that he made known in Italy the helicoidal method, which was widely used in England.

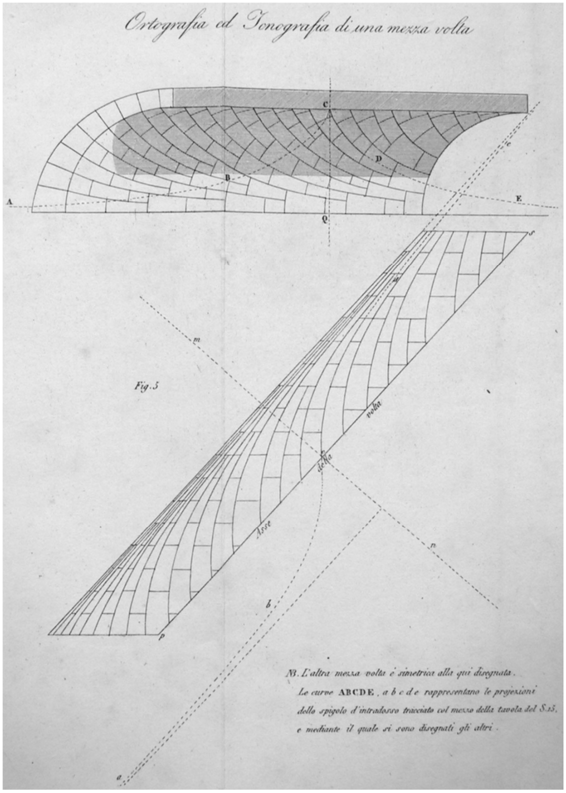

Figure 6. The device invented by Colombani (Colombani 1838)

And in effect the bridges over the Naviglio and the Lambro, of which we have spoken above, seem to reflect this method. Following Colombani's work there do not appear to have been many leaps forward in understanding and use of oblique bridges in Italy. If one excludes the work of Codazza, one needs to wait until the work of Curioni (1875), Cantalupi (1884) and that of Canevazzi (1884), in order to find complete and up to date treatment of the subject. In terms of construction, and before encountering the events on the Porrettana and the work of Protche, it can be said that there is no research that would allow us to further pinpoint oblique structures in Italy during the first half of the 19th century. Whilst in France and in England the development of the rail network constituted an occasion for constant reflection and constructive experimentation, the fragmented Italian environment hindered the development of the rail network, delayed the spread of specific knowledge of the subject and as such, most probably, also the construction of these types of bridges.

One additional example is remembered, that of the Mosca Bridge, in Turin, constructed according to the plans of the engineer Carlo Bernando Mosca, between 1823 and 1828. This elegant construction can be numbered alongside the best French and European structures and was overseen by a learned technician who, after formative training in the two celebrated French Écoles from which he graduated with the highest results, worked in France until 1815 to then take up the direction of prestigious projects in the Sabaudo State. The bridge over the Dora Riparia was however negatively referred to by Buck as reflecting a weak grasp of current knowledge of bridge vault design. He believed that, due to the incidence between the road axis and the water flow, the turinese project should have been realised with an oblique vault. However, Mosca did not opt for the solution of an oblique bridge, but modified the geometry of the fixed piers, disregarding the basic premise of parallelism with the direction of current. One can disregard the possibility of a lack of knowledge of the solutions already realised in England; it seems likely that Mosca's choice was the result of considerations that a pronounced span (a single span of around 120 metres), relative to a reduced transversal dimension (around 14 metres), would have required an extremely daring solution, with an uncertain outcome. This suggested that oblique bridges did not as yet constitute, at least in Italy, a tried and tested construction and structural typology, a typology to which, even in the future, one would turn to with certain reservations.

Bologna, 1856. Jean Luois Protche bases himself in the city in which he will work until the end of his career and from where he will take on important posts such as that of director and, successively, president of the Academy of Fine Arts. From Bologna he oversees the realisation of the Porrettana, the name given to the rail line running from Bologna to Pistoia. Up until 1859 he will work on the section between Piacenza and Bologna and on the construction of the first part of the Bologna railway station. In the meantime he perfects the section of the line that will for the first time cross the Apennines. The difficulties to be overcome are enormous: narrow valleys, steep drops, and unstable terrain. The solutions put into practice by Protche are utterly innovative and effective and amongst these can be numbered a helical shaped tunnel that allowed the descent into Pistoia. The project envisaged three branches that would be simultaneously constructed: the Bologna – Vergato line (inaugurated in 1862), the Vergato-Pracchia line (opened in 1863) and the last section between Pracchia – Pistoia (inaugurated in 1864), in total 99 km of track. The whole line included 35 bridges and viaducts and 49 tunnels. The last section alone running between Pracchia to Pistoia (14km) covers a difference in height of 500ml.

In the section that climbs from Bologna to Pracchia the line can be characterised as following the valley floor and ascending whilst the section from Ponte della Venturina to Pracchia, shows a much greater meandering progression. The bridges and the viaducts were constructed both in stone and metal and at various points made use of oblique stone structures. In its entirety one can speak of the most remarkable engineering work in the field of infrastructure in Italy. Furthermore, this project came into being as the country moved towards the creation of a nation state, which also offered the opportunity for technical modernisation in the railway sector. Some of the oblique bridges were truly imposing and were great construction and design undertakings of which one finds only partial note in the texts of the1800's.

Figure 7. Jean Louis Protche (in the middle of the picture, set down) with the technicians who work together with him on the realization of the *Porrettana* railway

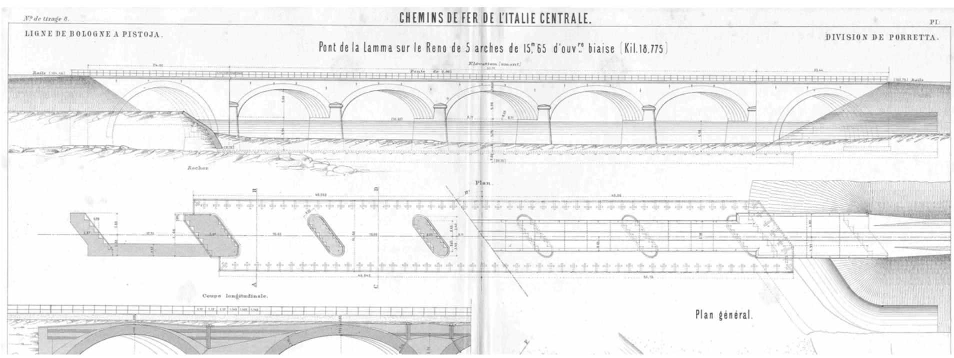

Figure 8. Jean Louis Protche, plan of the bridge in Lama di Reno (Protche, 1864)

In fact, Cantalupi (1884) speaks of only one bridge on the Pracchia-Pistoia line, constructed with the technique of offset straight vaults. This mode of construction, not as yet dealt with in the previous parts of this paper, originated from works in the 1800's, and was considered in the same way as structures made from offset straight arches from which it had derived. It was a stopgap solution due to the loss of intrados continuity that was entailed. However, where accentuated obliquity existed and a tight ratio between the span and length of the vaults, the helicoidal method, as has been previously noted for the Mosca bridge in Turin, showed itself to be somewhat unreliable in terms of stability. For this reason the solution realised by Protche, not only on one bridge, but also on diverse structures of the Porrettana, became almost the obligatory choice, also due to the overall economy of its construction. These structures were able to be realised as mobile ribs, then moved towards the vault axis at the end of construction of the single buttresses that, being placed perpendicularly to the piers and the abutments, completely eliminated the problem of *void-thrust*.

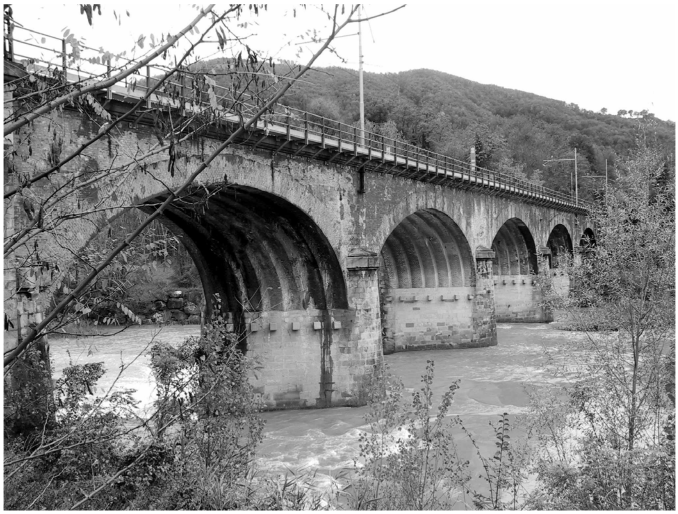

Figure 9. View of the bridge in Lama di Reno on the *Porrettana* railway

Figure 10. Oblique bridge near Vergato on the *Porrettana* railway

The Porrettana was the rail line with the greatest concentration of oblique structures ever realised in Italy and has a place, therefore, amongst the monuments of the national engineering culture. Other than bridges with straight vaults and with offset straight arches there were also various bridges constructed with the helicoidal method with variable degrees of obliquity. All of these works bore the signature of the young engineer Protche, called to Italy to fill a technological gap that previously only the work of Francesco Colombani had been able to fill (it is worth noting that within the group of Protche's young collaborators the engineer Giuseppe Mengoni, was also working. A native of Fontanelice in the province of Bologna, he is remembered by historians as the designer of the Galleria Vittorio Emanuele II in Milan).

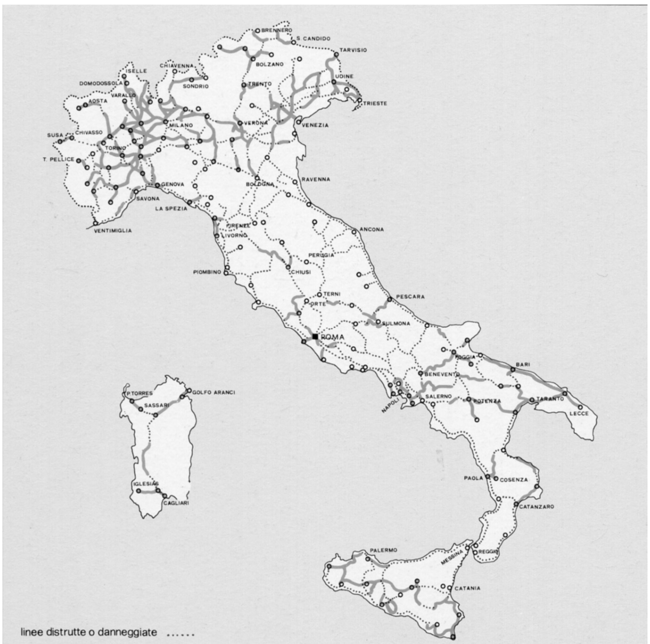

Figure 11. The condition of the italian railway system after the World War Second (Berengo Gardin 1988)

The Gothic Line, along which the nazi army had attempted to concentrate their defensive action against the advances of the Anglo-American forces that re-emerged in Italy during the Second World War, cut in two the Porrettana Line. The longest established rail crossing of the Apennines was of vital importance to the conflicting forces for which it heavily paid the consequences. Between the winter of 1944 and the spring of 1945, all of the bridges on the Porrettana were blown up by the Germans in retreat. The amazing structures constructed by Protche all disappeared, but on the abutments and the piers left standing, between 1945 and 1949 all of the vaults came to be reconstructed, unfortunately not always in keeping with the original solutions. Amongst these, worthy of special note for their scale and construction specifications are:the bridge in the Lama di

Reno region with seven archways spanning from 16 metres and a obliquity of 37 degrees; the bridge with one archway spanning 30m and a obliquity of 48 degrees built in the Pian di Reno region; the three structures of Calvenzano and Vergato near the valley and near the mountains, made of many reduced curved archways and of notable obliquity and last of all the one span bridge in the Sette Ponti region. The original structures were built between 1860 and 1862, but at the time of re-construction only the first came to be re-built in stone, following the model of the original bridge with offset straight arche. The other structures were rebuilt retaining the original intrados typology, but using castings in cement conglomerate with weak or no metal reinforcement.

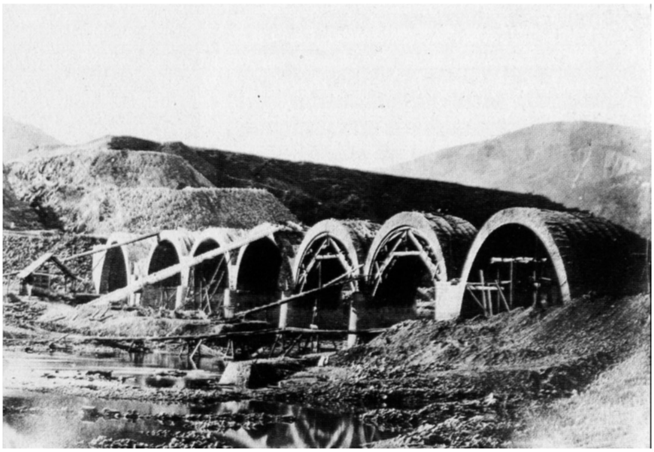

Figure 12. Rebuilding of the oblique bridge in Lama di Reno after the destruction in 1945

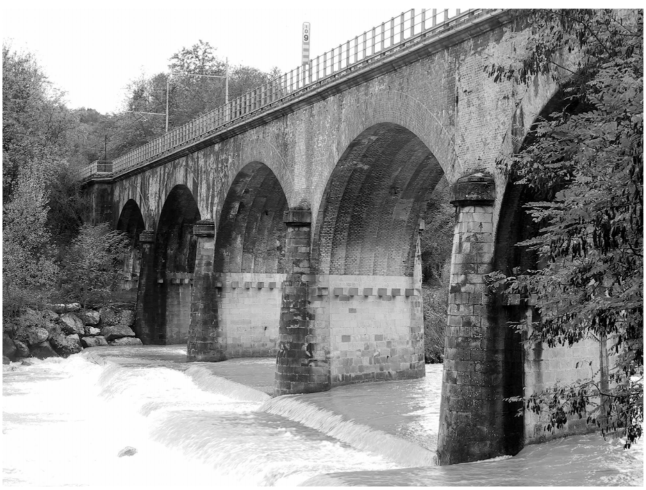

Figure 13. The bridge in Lama di Reno after sixty years since the rebuilding

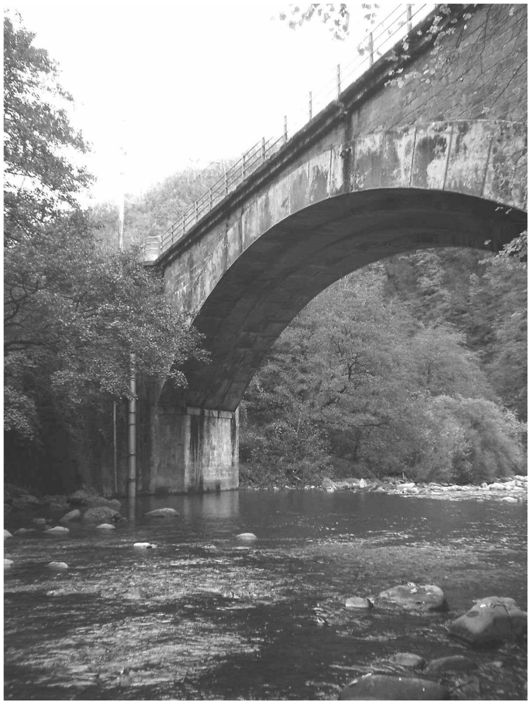

Figure 14. Porrettana railway. Single arch bridge in Pian di Reno

In 1875 Giovanni Curioni published his *L'arte del fabbricare*. It was the first text that came to be published in Italy after Codazza's and in which is a section dedicated to oblique bridges. Its textbook style tone does not allow theoretical descriptions (Ramazzotti 1984); but lends itself to a description of operative and construction phases, adding nothing to that which one could already read in preceding studies or contemporary French works. However, the author's contributions should be considered against the general context in which it was written. Italy was witnessing an expansion in the rail network that, at the time of publication of Curioni's text, extended for around 8 000 km, 90% of which had been built in the preceding 25 years.

And in effect, Curioni emphasizes the extent to which the construction of oblique bridges was becoming a solution in increasing demand relative to the great development of the rail network. To the engineers of this period, theoretical questions concerning the conformity of certain methods to stereotomic rules were perhaps of little interest; of equal importance was the efficacy and simplicity of these methods. Curioni in his work pays greatest attention to the helicoidal method, and is quickly dismissive of others, given that, on his own admission, this is the only that can be conveniently used. The description of phases of work and problems is extensive and detailed, with particular attention given to the discussion of particular solutions, with constructive details and rich in suggestions for problem solving in specific instances.

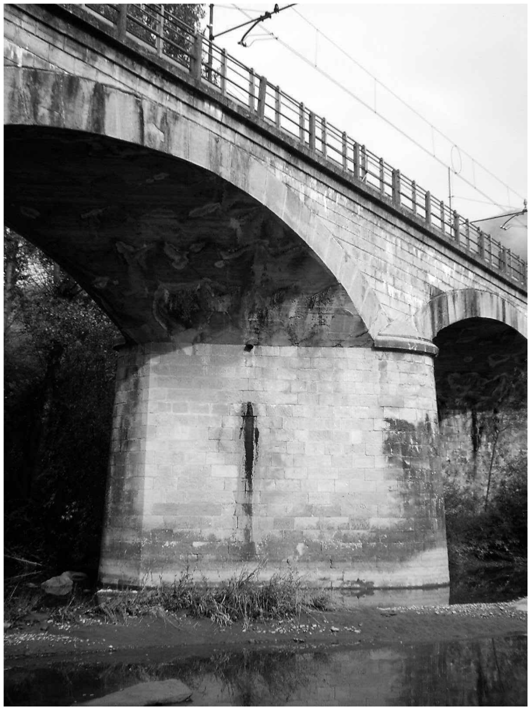

Figure 15. Bridge near Vergato on Porrettana railway. Detail of oblique vault rebuilt with concrete.

The problem was therefore changing in its very nature. One was no longer dealing with debate over a technical question or, if you like, research into the most optimal solution. The technical Italian environment already appeared to have made its choice. Vaults for oblique bridges would be constructed using the helicoidal method. Theoretical discussions were put aside; it appeared that all was headed towards the provision of risolutive starting points for particular cases, cases with which the engineer had most to do with on a day-to-day basis. During this transition, one detects a feature that will come to increasingly characterise modern construction. Strongly tied to economic principles and to increasingly more rigid prescriptive rules, modern constructive techniques would offer little room for experimentation and for the definition of new solutions that were radically different from the standard that had long been used. The manuals did not offer wide -ranging theoretical treatments, but conformist solutions, summary tables, and formulas that could be quickly applied.

Curioni was a teacher at the *regia Scuola di specializzazione per ingegneri* of Turin and most probably was writing with teaching aims in mind, intending his writing for future technicians. Antonio Cantalupi was however working on the front line. A civil engineer at the time of writing *La costruzione dei ponti e dei viadotti* (1884) he had already accumulated ten years of a career behind him. His work is of less interest in the section that deals with general classification, however when he deals with the specifics of accomplished solutions, he offers a panorama of projects based on the use of oblique solutions: Protche on the Porrettana and Bermani on the Udine, Pontebba in Ospedaletto, Caimi in Boffalora and Ribecchi on the Lambro. The text has therefore more of the tone of a well reasoned summary of all that had been achieved in bridge making and, in the part that interests us, the chapter on oblique bridges, exhibits a certain bias towards the French context. The ideas presented are the fruit of critical scrutiny that by this time the contemporary culture had put into practice and in particular offer interesting starting points to an understanding of the phenomenon of oblique construction.

From the beginning of technical production – scientific on this subject, an absolutely fundamental role had been played by the so-called *void-thrust*. Ground for conflict between scholars in the field of mechanics and geometry, its undefined character stirred up scientific controversy in France based on conflicting ways of analysing masonry construction (Becchi, Foce 2002), but it is indisputable that studies and hypotheses during the course of 19th Century were based on the certainty of its effects. This is not only because the oblique bridges were an innovation confined to the 1800's; in fact obliquely vaulted structures had been built at least from the late Middle Ages onwards. Cantalupi himself refers to the existence of Milanese bridges on the Navigli, still present at the end of the 19th Century, which had been built from the 1400's onwards. The need for solid and robust structures, called for by dynamic loads and therefore subjected to conditions of stress for which the effects were not clearly known, brought to light the need to find efficacious and long lasting solutions. An oblique vault built with a straight method necessarily has a section of single arches that make up the entire cylindrical expanse, which have an effect on the two oblique bridgeheads. These effects thrust the frontal vault to overspill or tip over from its designated base. All of this can be accepted as an objective experimental outcome, a point of departure for proposals intent on eliminating such an effect. The described outcome is produced as much as vaulted structure has been thought of as a succession of single sections of straight vaults, but what effect would occur in the extreme case of a single arch made up of voussoirs expressly shaped to form a helicoidal unit then subjected only to vertical force? The geometrists were able to clearly define the positions of the joints of this construction, relying on standard stereotomics that, as was still accepted at the beginning of the 19th Century, would have guaranteed stability: perpendicularity with the intrados and the absence of acute corners. The mechanics, on the other hand, became confused by the loss of bio dimensionality of the model. The union of geometrical and mechanical expertise, unattained by any of the authors, neither French, nor English, nor Italian who had ventured into the field of *ponts biais*, had not permitted a comprehensively and scientifically valid treatment of the subject. If one compares progress in this field in the second half of the 1800's, with that achieved in the field of mechanics, one comes to see that stereotomic principles were completely lacking in solid foundations. On the other hand, however, it was not known how to counterpoise a valid organic theory and for this reason the last studies on oblique constructions were rich with discussions of specific cases and mediate solutions: the pragmatic had taken over from the theoretical.

If Cantalupi continued to refer to the importance of the *void-thrust* in discussions on the efficacy of various methods, the same author reports news on oblique vaults constructed with straight methods, which had not created any problems in stability even when used on railway bridges. He cites Éveillè who, in a 1856 note, maintains that he had constructed bridges with as much as 70 degrees of obliquity using straight methods and also Gauthey who generally suggested only using angles up to 67 degrees. Solutions to improve performance could in any case be put into place at the time of construction. These experimented with the insertion of metal tie beams, vaults made of conglomerates, and braces to link up the voussoirs. Some engineers, and amongst these Bermani working in Ospedaletto, went so far as to design special voussoirs used on two courses near to each other, so that they sided with the adjoining arches. The section dedicated to vaults made with hydraulic cement seems to be unique to his text. In order to eliminate the costs and the difficulties connected to the use of freestone the author recommends making use of the cohesive properties of hydraulic binders. These, that could bind bricks or even small stones, transformed the vault into one entity, which was sufficient unified to prevent the formation of lesions caused by the *void-thrust*. Cantalupi cites three cases, all French, the Mayou bridge in Baiona, consisting of three acrches with 18 m span, height of 1.85 ml, 55 degrees of obliquity, made only of stone and hydraulic mortar; the Montaudran and Croix-Daurade bridges, both near Tolosa, for which the vaults, which are straight, are in brick walls with extremely strong mortar, notwithstanding a notable obliquity: 61 degrees for the first and 70 degrees for the second (Cantalupi 1884, pp. 435-436).

Cantalupi seems not to have noted that this citation of his played a central role in the controversy that had erupted in France on the practical management of *void-thrust* and that, in the ultimate analysis was the font of criticism of its existence. The debate in reference had involved two principal protagonists, Levy and La Gournerie. One can refer to the text cited by Antonio Becchi (Becchi, Foce 2002) for the details of the matter, however Cantalupi seems by this stage implicitly convinced, and with him perhaps the entire technical community, that the stereotomic method for oblique bridges was perhaps not to be considered relevant to the real nature of the problems in question. To address these a global treatment, which would study mechanical function, would become necessary.

This maturation of the technical and scientific environment, at least in terms of dissociation from certain peremptory stances taken in the past, also showed itself felt in more progressive academic circles. In the depths of the history section of the Central Library of the Faculty of Engineering of Bologna are conserved two manuscripts that constitute the transcripts of lectures that Professor Silvio Canevazzi gave at the *regia Scuola d'Applicazione* for engineers. The first is dated 1884 whilst the second can be traced back to 1895. The professor, a central figure in the Italian scientific and technical panorama over the century, dealing with the theme of oblique bridges in his course *Ponti e Costruzioni Idrauliche,* no longer raises the problem of the *void-thrust* as an essential question and fundamental part of theory and operational practice. Relying on the controversial experiment conducted by La Gourniere in 1874 (Becchi, Foce 2002), he aligned himself with those who claimed that the impact was directed parallel to the facades and that, therefore, the *void-thrust* did not exist (the experiment involved the construction of a model of a vault to scale held up by supports made of continuous jackscrews. Acting on the jackscrews connected to an intermediate arch, positioned parallel to the oblique facades, La Gourniere established that the parts of that arch dropped down only following the movement of the supports. From this result he deduced that there wasn't a connection between the arches and therefore that the pressure curve must have been contained within the arch parallel to the facades).

The question of methods continued to be discussed following the subdivision of typology already fully noted, however it is the helicoidal method that is the most widely dealt with, as according to the author it is this method, and not the orthogonal, that allows a better direction of force towards the imposts. The problem therefore comes to be greatly simplified, also as far as verification, in as much as it can be treated similarly to that for straight arches, with the only proviso that being to substitute for the minor span that of the oblique frontal section.

As with Cantalupi's work, Canevazzi also focused on particular cases drawn from specific sites, proof of the fact that by this stage theoretical aspects aroused less interest compared to real construction cases.

Only in the collection of his lectures from1895, together with stone, wooden and iron bridges, appear those made with reinforced cement, but these receive only passing mention as the scientific community had not as yet passed a unanimous judgement on the efficacy of this material. However, a few years on from this point, Canevazzi would become one of the most prominent figures in the study of this innovative construction method. In this field he would find an able collaborator in his student Attilio Muggia, he who had edited his first collection of lectures from 1884 on oblique bridges.

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