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French bridge engineering in Andalusia (1810 – 1900)

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Abstract

French engineering has had a great influence in Spain since the time of The Enlightenment, when the construction of public works was organized by the state as in France, according a centralist model. Subsequently, throughout the 19th century, this presence intensified, there being a twofold increase in the transfer from France to Spain. In the field, Spanish engineers enthusiastically incorporated all of the scientific and technical knowledge created by their brilliant French colleagues (Navier, Vicat, Cauchy, Saint-Vénant, etc.). At the same time, the development of Spanish infrastructures (mainly railways) favoured the employment of French companies with their own engineers, who were directly in charge of building their constructions in Spain.

In Andalusia, the southern region of the country, the construction of public works inspired by the French was particularly significant, especially in the field of bridges. The first constructions were built at the time of the Napoleonic invasion and a bridge in the city of Granada dates from this period. A few decades later, French technicians were responsible for the arrival of the first suspension bridges, and there were also some significant creations from the period of experimentation in bridge design, such as the Polonceau system bridge built in Seville. In the second half of the century, powerful French companies (Fives-Lille, Daydé & Pillé) took over the deployment of the main railway lines in Andalusia. The difficult topography of the area forced the construction of numerous bridges and viaducts, many of them very complex. Necessity stimulated the ingenuity of the engineers who had implemented new models previously developed in France, in the region.

In the context of a transcendental period in the history of engineering, in which a profound evolution of forms and materials took place, these bridges in Andalusia were particularly important. Some of them were the first, and sometimes the only one of their kind in Spain. They made a significant contribution to the dissemination of new construction techniques and to the consolidation of the use of rational design methods. The large metal viaducts, in particular, are some of the most representative works on the peninsula, both for their scale and for the application of complex engineering solutions.

The aim of this article is to study this tradition of French bridge building in Andalusia, paying special attention to the design techniques and construction procedures. It also aims to raise awareness of the valuable engineering heritage that originated during this historical period.

Keywords

Bridges, engineering design, roads, railway, Andalusia, 19th century.

Introduction

This paper investigates the activity and impact of French bridge engineering in Andalusia, as it is one of the regions of Spain where it was active for the longest period and with the greatest intensity, and today there are representative examples of the process of the evolution of bridges in the 19th century which were built in Andalusian territory.

More specifically, this research aims to record the presence of French engineers in Andalusia during the 19th century, record their achievements and describe their activity from the point of view of construction history. The main aim is to identify and quantify the transmission of knowledge of bridge construction from France.

In terms of methodology, the research was mainly based on the study of primary sources, being the technical documents on the design and construction of the bridges. They have been located in different national and regional archives. Other primary sources, such as historical photographs and the press of the time, were also used. The article also draws on secondary sources. Among these, recent studies of the history of construction and architecture have been favoured. Finally, the data obtained from documentary sources have been verified by means of on-site surveys of the bridges.

Masonry bridges – The introduction of new Perronet's models

French engineering has had a great influence in Spain since the time of The Enlightenment. The construction of public works was reorganised by the State according to the French model. From the Renaissance onwards, large infrastructure projects were carried out by royal engineers (usually from Flanders or Italy), but smaller public works, such as most bridges, were largely financed by the municipalities and entrusted to highly-skilled architects.[1]

During the second half of the 18th century, a new dynasty from France promoted numerous measures for the modernisation of the country. One of the most important of these was the formation of a national network of roads, whose main routes began to be constructed in these years. Several important routes were established in Andalusia.

These works were carried out by army engineers, many of them recruited from abroad. One of the most prominent was Charles Lemaur, a French engineer who joined the Spanish service in 1750. For a quarter of a century he was the country's leading specialist in public works. Among other major projects, he was responsible for the complicated *Despeñaperros* pass on the road from Madrid to Andalusia. He also designed the route of the Royal Road from Malaga to Antequera.[2]

The new roads included numerous bridges, most of which were designed conservatively (Spanish bridges of this period were generally built with solid semicircular arches supported by very sturdy abutments). Neither Lemaur nor his Spanish colleagues dared to innovate in the design of these works. This was the opposite of what was happening in France, where the advances of Jean Rodolphe Perronet (introduction of flatter arches, shallower arch rings and thinner piers) were revolutionising bridge engineering.[3]

From 1799 onwards, the construction of public works became the responsibility of specialised civil engineers. Following the French model, a corps of civil servants, the *Ingenieros de Caminos*, was created.

Its head was Agustín de Betancourt, a brilliant Spanish civil engineer who had completed his training in France and England. Between 1784 and 1791, he lived in Paris, studying and working as a researcher at the *École de Ponts et Chausées* in Paris, where he became a collaborator of Perronet and Gaspard de Prony.[4] He also spent three years in London (1794-97), where he improved his knowledge of mechanical engineering and ironworks, among others in collaboration with ironmaster Henry Maudslay.[5]

On his return to Spain, Betancourt was put in charge of the training of future engineers. He set up an institution equivalent to the Paris School, in which French teachings played a major role.[6]

The new Spanish civil engineers who trained there were not slow to implement Perronet's designs in Spain. One of the most representative examples was the *Puente Verde* (Green Bridge) over the river Genil, built in the city of Granada (Fig.1). It is a lowered 15m single arch, whose shape seems to be inspired by the designs of Perronet (in particular in his *Pont de Saint-Maxence sur l'Oise*),[7] reproduced however on a smaller scale. It was erected in 1811, during the Peninsular War, on the initiative of the French General Sebastiani. Although its creator was the Spaniard Rafael Bauzá,[8] this bridge must be considered largely a product of French engineering. Bauzá, one of the first Spanish civil engineers and a disciple of Betancourt, was working for the Napoleonic administration of Spain at the time.

Figure 1: Puente Verde over the Genil river in Granada, 1811. Rafael Bauzá, engineer. Photo taken in 1885 by Rafael Garzón Rodríguez. Courtesy of Rafael Garzón Cubero.

Later, these low arch masonry bridges (specially the basket-handled type) were widely used in other roads of Andalusia.

Early suspension bridges

The victory over Napoleon ushered in a turbulent period in Spain. Serious difficulties, especially economic ones, characterised the last throes of absolutism in Spain. The construction of public works was paralysed for several decades, but from 1835 things began to change with the irreversible introduction of the liberal regime. In the field of public works, important advances were made in technical and legal regulation, but the deficiency of the national treasury (whose resources were mainly committed to the civil war unleashed by the supporters of the *Ancien Régime*) prevented new works from materialising. Nevertheless, with difficulty, some progress was made. And shortage favoured the introduction of some innovative designs, such as the suspension bridge.

The development of iron construction facilitated the appearance of this type of bridge in The West, although they had a long tradition in China (and were also known to some pre-Columbian civilisations in South America). In their modern version, they were initially made of chains of wrought iron elements. The American James Finley pioneered their use in the United States with the Chain Bridge at Falls of Schyullkill, north of Philadelphia, circa 1808.[9] The layout was immediately adopted with success in Great Britain, where the Menai and Conway (now Conwy) bridges were built in the 1820s by Thomas Telford.[10] At the same time, chain suspension bridges were also being built in Russia.[11]

After Telford, suspension bridges underwent a number of developments in the British Empire, but the momentum moved to the Continent, where France took the lead. Its theoretical definition, completed by Charles Navier in 1823, was decisive, but the most important factor was the introduction of cables as a support element, first realised by Henri Dufour and Marc Seguin on the *Saint-Antoine* bridge of Geneva.[12] In the following years, the wire cable bridge underwent an extraordinary development. French engineers and companies exported them to other countries such as Spain, where suspension bridges were introduced by the Seguin brothers' company. In 1837, the Spanish State agreed with Jules Seguin to build a dozen suspension bridges located in different parts of the country. Given the weakness of the national coffers, it was a good deal: Seguin's company assumed all the construction costs in exchange for the rights of way for fifty years.

The 1837 agreement included four bridges in Andalusia: one over the Guadalquivir River in Mengibar (province of Jaén), two in the city of Puerto Santa María (Cádiz) and another one over the Guadalquivir in Seville. In 1838, Jules Seguin presented technical documents for their construction, however, these projects were put on hold for several years. The general situation improved a few years later and from 1842 onwards, a company owned by the Seguin brothers could build four of the bridges contracted in others parts of the Peninsula.

However, for the Andalusian bridges, the Spanish administration decided not to employ the Seguins. A project for the Mengibar bridge was commissioned to the Spanish engineer Eugenio Barrón, which was presented in 1842. He designed a single-span bridge of 120m, the deck of which was suspended by four 120mm diameter cables (two on each side) and vertical suspenders. These cables rested on mobile cast-iron cylinders placed on top of 11m high Ashlar pillars.[13] According to the structural calculations for this project, Barrón determined the length of the cables, their cross-section and the working stresses using the formulae developed by Navier in 1823.[14]

A year later, the French civil engineer Emile Gabriel Bertin was hired as general consultant to supervise the construction of the Andalusian suspension bridges.[15] As a main contribution, Bertin drew up official Technical Specifications for the construction of suspension bridges.[16] They prescribed a maximum working tension of 178 N/mm2 for the cables and insisted on a load test of the bridge, which had to be able to withstand an imposed load of 2.00 kN/m^2.

In December 1843, contractors were officially invited to tender for the work, prompting protests from Jules Seguin, who claimed authorship of the design..[17] His complaint was not heeded and the construction of the bridge was awarded to a Spanish company, with the French engineer Frederic Malboz, who had previously worked for the Seguins on their other Spanish bridges, as the main technical manager.

It was probably he who replaced the stone pillars supporting the cables with cast-iron columns. The idea had already been used by the Seguins in several of their Spanish bridges. Those of the Mengibar bridge, which were one of its main distinguishing features, seem to have been inspired by those of the formidable Saint-André de Cubzac bridge (France), built by the French engineers Vergès and Martin in 1839.[18] The Mengibar suspension bridge was finished in 1845 and remained in use until 1930 (Fig. 2). Following an accident that rendered its deck unusable, it was replaced by a new reinforced concrete bridge.

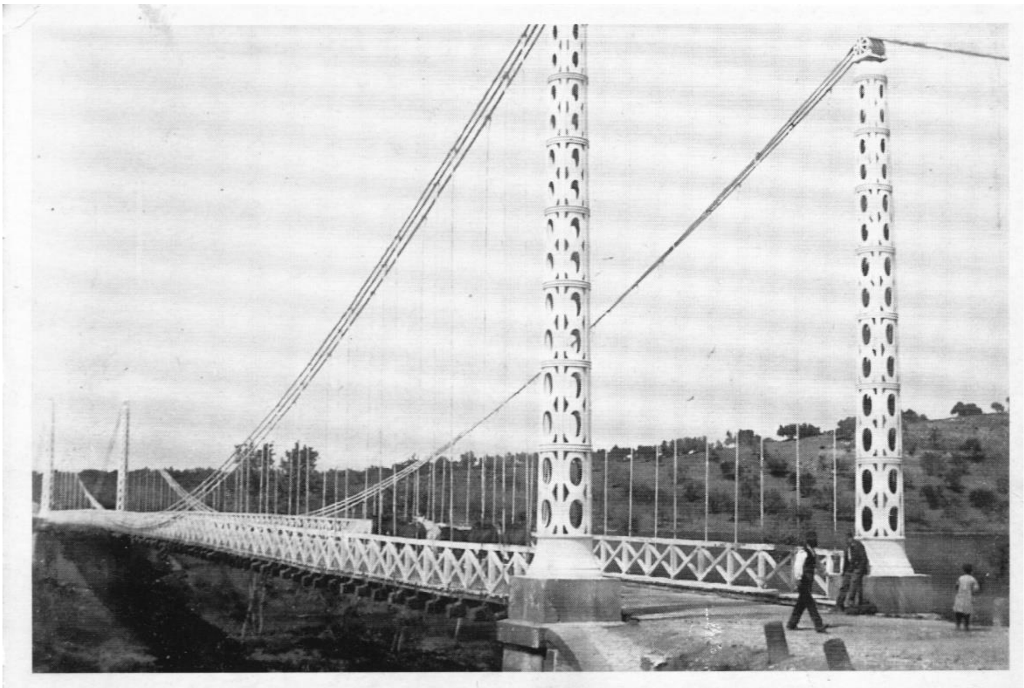


Figure 2: The Suspension bridge over the river Guadalquivir in Mengibar (Jaén), 1845. Photo taken at the beginning of the 20th century. Courtesy of Sebastián Barahona Vallecillo.

Emil Bertin was directly in charge of the second of the Andalusian suspension bridges, its construction taking place between 1844 and 1846, resulting in a 104m single-span bridge.[19] In this case, a more conservative solution was chosen, with the cables resting on masonry pillars (Fig. 3). This bridge stood until 1877.

Finally, the bridge over the San Pedro river, on the road from Madrid to Cádiz, was also built by French engineers. In this case it was Gustave Steinacher and Ferdinand Bernardot who won the contract in 1844. Smaller than its neighbouring San Alejandro (84m span), it had a similar configuration: a single span with cables strung from 10m high masonry pillars. It was in use from 1846 to 1896.[20]

Figure 3: San Alejandro suspension bridge in Puerto Real (Cadiz). Photograph taken around 1860 by Jean Laurent. Archivo Ruíz Vernacci, Spanish Ministry of Culture and Sports.

Cast-iron bridges

Along with suspension bridges, the other most common form of early metal bridge was that of arches made of cast iron. The earliest application took place in Great Britain (bridge over the River Severn in Coakbrookdale, 1779). Its creators (Pritchard, Darby and Wilkinson) used large curved pieces with bracing at the spandrels, a process analogous to timber construction.[21] From then on, more and more engineers were inspired to use cast iron in their bridges, always using the recognised structural form of the time: the arch. The ways in which this was achieved were varied. Thomas Telford designed a system of large cast-iron ribs for Buildwas Bridge (1796), but he left open spandrels for Mhythe Bridge (1826), connected by cast iron diamond sections. John Rennie built Southwark Bridge (1819), where the main arches were held in place by cast-iron wedges.[22]

Iron bridges soon spread to other European countries like France, where some remarkable examples were also erected on both of the same principles,[23] as seen in Great Britain, as well as some Prussian examples circa 1800.[24]

During this period of experimentation, the use of cast-iron tubes was considered as an alternative to arches formed from assembled parts. It was developed in theory and put into practice on several bridges in Germany (including the Braunschweig Brige over the Oker in Brunswick) by the scientist and engineer George F. Reinchenbach.[25] Very likely influenced by this, the French engineer Antoine-Remy Polonceau designed his famous *Pont du Carrousel* over The River Seine in Paris (Fig. 4). In the structural configuration designed by Polonceau, the main elements were the arches (five in each span) made of iron tubes with timber cores. The deck was supported by iron rings of variable diameter.

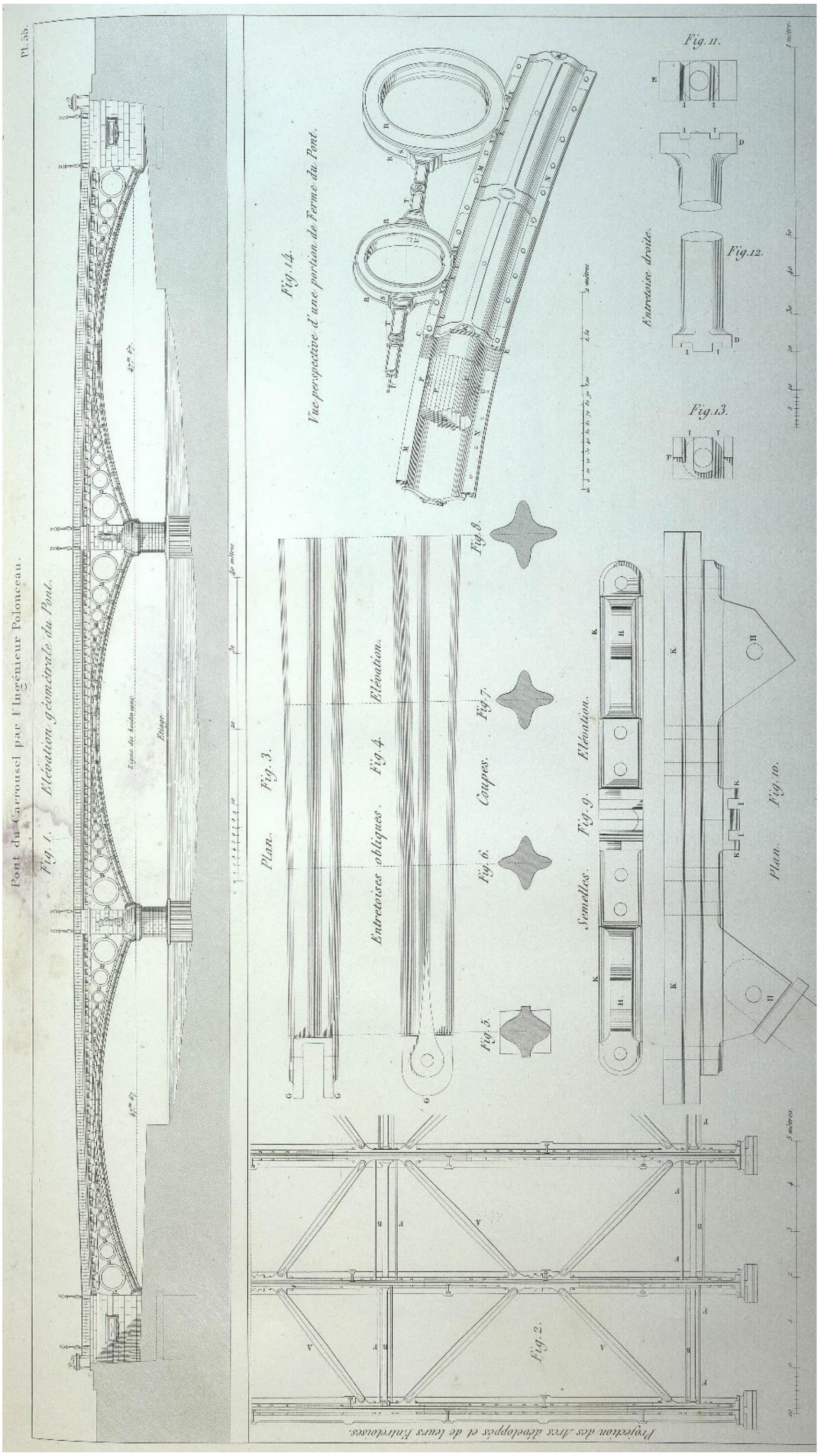


Figure 4: Carrousel bridge at Paris, built by A.R. Polonceau in 1834.[26] A description is included in Charles Ecks' book Traité de l' application du Fer. University of Granada. Royal Hospital Library

The successful technical resolution of the work prompted its creator to propose the use of the system in other places.[27] It was, above all, its aesthetically pleasing appearance that blended in to the city of Paris, where its monumental character was immediately recognised, leading to its most significant and unique application, which has survived to the present day: the *Isabella II* or *Triana* bridge in Seville (Fig. 5).

Figure 5: Triana bridge over the Guadalquivir river in Seville. Photograph taken around 1872 by Jean Laurent. Archivo Ruíz Vernacci, Spanish Ministry of Culture and Sports.

At the beginning of the 19th century the city of Seville was divided by the Guadalquivir River. The only connection between the two banks was an ancestral pontoon of boats. From 1825, the city council had been trying to put an end to this anachronism by building a permanent bridge, but it was complicated given the width of the river (130m) and the difficulty of establishing stable foundations in the river bed.

For more than a decade, its construction was the subject of controversy. Several solutions were proposed, including the aforementioned suspension bridge by Jules Seguin, which did not succeed.

In 1844, the French engineers Steinacher and Bernardot (builders of the San Pedro suspension bridge) managed to convince the city council to build a permanent iron bridge. They proposed the Carrousel Bridge in Paris as the ideal form, which had already been built for more than a decade without the slightest problem.[28] On December 19 1844, Spain's Queen Isabella II approved the construction of 'a firm iron bridge on stone piers and abutments'. The technical specifications said that it was to consist of three arches, with a total span of 130m.[29] Along with the geometric definition, this document included requirements for cast-iron working stresses: 23 MPa maximum tension and 376 MPa maximum compression.

The work was awarded at the beginning of 1845 to the 'Seville Bridge Company', formed by the French engineers Steinacher and Bernardot as technical partners, and the Spanish banker Francisco Javier Albert as financial partner. The terms of the contract literally stated that the bridge was to be built 'in the likeness of the one in Paris called the Carroussel', although a little shorter (three spans of 43m compared to 48m for the original). So Steinacher and Bernardot designed an almost exact replica.[30]

Work began in 1845. A year later, the foundations for the supports were completed, under the direction of Steinacher. It was built with wooden enclosures driven into the riverbed, which were filled with concrete. In 1847, however, disagreements arose between the technical partners and the main financier, which led to their separation. From then on, the Spanish engineer Canuto Corroza, who was responsible for the construction of the bridge's superstructure, took over the work. The work lasted until 1852, when the bridge was inaugurated.

With some repairs, the bridge survived in its original structural configuration until 1975. In order to ensure its survival as an emblematic monument of the city, it had to undergo a major restoration. Its appearance was maintained, but a new resistant structure had to be added.

Wrought-iron plate-girder bridges

In the second third of the 19th century, the introduction of railways gave rise to the extraordinary development of bridge building. The greatest advances were made in Great Britain, where the flat beam, in its three early basic forms: lattice, truss and plate girder, made its great breakthrough in modern bridge building.

The triangular girder was invented by the English entrepreneur and engineer Alfred H. Neville. He used it to build several bridges in Italy, Belgium and Austria in the 1850s.[31] Much more widespread, however, was a triangular frame truss patented by James Warren and Willoughby Theobald Monzoni in England in 1848. Considered the most economical and efficient beam for spans of considerable size, it was extensively used in Great Britain and its colonies. Its main proponent was Thomas William Kennard, the builder of the Sursutee Bridge for the East Indian Railway and, most notably, the Crumlin Bridge for the Newport, Abergavenny and Hereford Railway (South Wales),[32] yet the triangular beam had no application in Spain.

The British and Irish railways would also see the appearance of lattice girder bridges, which would spread throughout Europe in the middle of the century. However, its expansion was temporarily interrupted by the sudden appearance of the tubular bridge.

Between 1846 and 1850, the engineers Robert Stephenson and William Fairbairn and the mathematician Eaton Hodkingson devised an original beam system of bridges based on wrought iron box girders, which was first applied to the railway bridges over the River Conwy and the Britannia Bridge over the Menai Straits. The latter was a particularly revolutionary work, which not only advanced the use of wrought-iron plates as a construction material but was also of great importance for the study of the structural behaviour of multi-span beams with intermediate supports.

However, the rapidly developed wrought-iron box pattern was not widely used, although small tubular beams, such as those used in the Torksey and Spey bridges were widely applied.[33] Truss bridges were also popular in the 1850s and 1860s, but later they virtually disappeared as truss bridges became more widespread.

In fact, they were soon to be found in France, where in 1852 the engineer Eugène Flachat built the Asnières Bridge with tubular girders for the Saint-Germain railway. Three years later he built the Longon Bridge over the Garonne and his colleague Debauge the Moissac bridge over the river Tarn, the first two French plate girder bridges, both on the Chemin de Fer du Midi.[34]

The construction of railways was the main reason for the dissemination of these bridges. In Spain, the construction of railway lines was monopolised by foreign companies. Initially, British engineers and contractors came to Spain in large numbers to work on the design and construction of railway lines. They had the double advantage of technological and financial supremacy, but they soon realised the risks involved in building railways in Spain, whose complicated orography meant that the cost of establishing and maintaining the lines would be very high and that it would be very difficult to recover monies invested from the scant traffic it could provide as an underdeveloped country. Robert Stephenson's rejection of the construction of the Royal North North Line is paradigmatic.[35] Many British engineers went to Spain to work as engineers (such as Frederick Thomas Turner on the Córdoba-Málaga Railway,[36] and Henry Francis Ross for the Utrera to Morón and Osuna line),[37] but British companies generally preferred to concentrate on other parts of the world, such as South America. It was not until the last years of the century that a British consortium obtained an important concession to built and manage an important line in Andalusia.[38]

However, in France, where Henri-Saint-Simon's ideas were very influential, the peninsula became a prime target for the creation of a common railway area between France, Spain and Portugal.[39] On the other hand, due to the lack of a strong financial structure, the Spanish market was open to booming foreign capitalists, in particular, the emerging French groups (Rotschild, Pereire) transferred to the Iberian Peninsula the economic struggle they were waging in France and contested the nascent railway business in Spain. French companies were prepared to take risks whereas British entrepreneurs demanded guaranteed profitability, which eventually led them to withdraw from the Spanish railway market.[40]

Thus, in the decade after 1855, the main lines were built, financed and managed mainly by French investors. These entrusted their materialisation to French construction companies, with French engineers taking all of the jobs in the company that required technical competence.[41]

In this way, the influence of French engineering in Spain intensified with the arrival of the railway, but initially was not so in the case of the Córdoba-Seville line, one of the most important lines of Andalusia, whose concession was given in 1853 by the Spanish Government to a consortium of British and French investors, led by Henry O'Sea.[42] Its contractor was a French company, Savalette, which worked in partnership with the English engineer Joseph Lane Manby. This could have had a major influence on the path of the line, particularly in the decision to build all its bridges with iron plate girders, a design that had been developed in Britain. The line included up to four bridges like this, the most important being the Guadalquivir bridge at Lora del Río (Fig. 6).[43]

In 1857, before the bridges had been built, the Seville-Cordoba railway was incorporated into the Pereire brothers' conglomerate. Once it was fully integrated into the French orbit, engineers from the neighbouring country took charge of its final completion.

The choice of plate girder bridges was maintained, a decision that may have been influenced by the fact that Crédit Mobilier was also the owner of the *Chemin de Fer du Midi*, where the first French full girder bridges had been built by Flachat and Debauge.

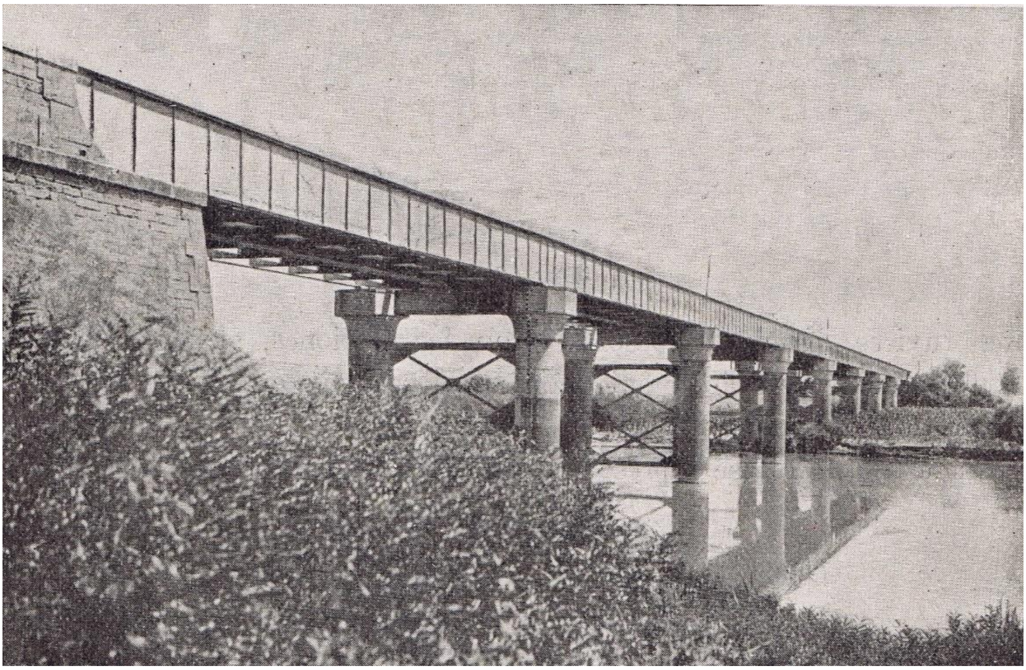


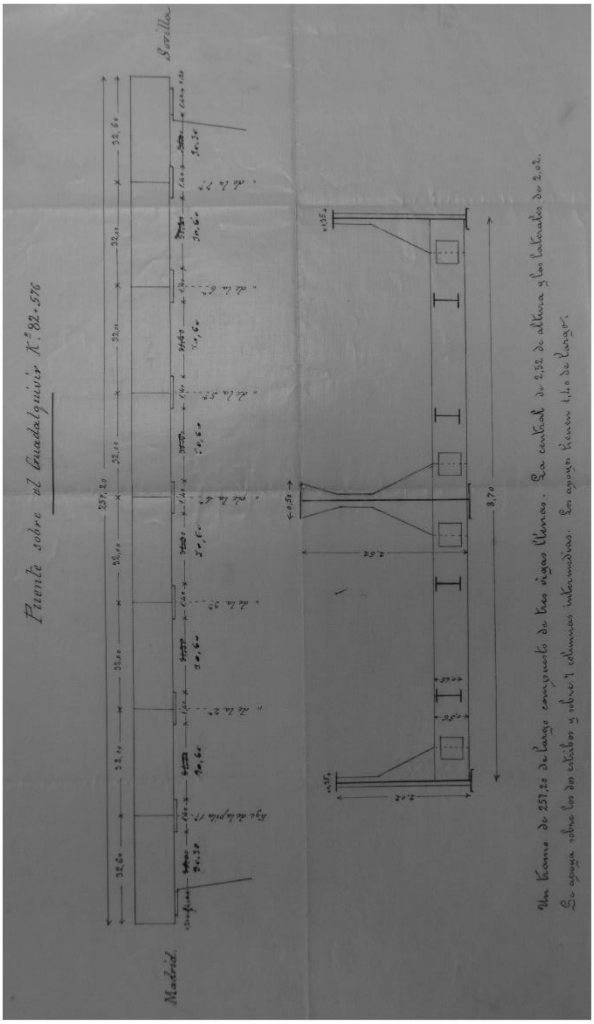
Figure 6: Lora del Río railway iron bridge over Guadalquivir river.[44] *University of Granada, Polytechnic Library.*

The construction of the Lora del Río bridge was charged to the *Ponts et Chausées* engineer Etiénne Napoleon Lionnet, who himself had worked on the construction of another very similar plate girder bridge, the Mâcon bridge over the Saône (Paris-Lyon railway).[45]

The superstructure of the bridge consisted of three wrought-iron universal beams (the central one was larger than the lateral ones), forming a large continuous beam divided into eight 32m spans and supported by masonry abutments and cylindrical cast iron columns filled with concrete (Fig. 7).

French engineers Pierre Rapin and C. Julliany leaded the set up of the metal part, which was built on an auxiliary wooden structure (Fig. 8). This bridge remained standing until 1923. New masonry piers were built and Linville truss girders were installed to replace the original ones.[46]

Apart from those on the Cordoba-Seville line, only two other plate girder bridges more (on the Madrid-Alicante line) were built in Spain. Lattice bridges soon prevailed. However, ten years later, the Spanish Technical Administration adopted plate girder as the standard for road iron bridges and a dozen or so were built throughout the country. There was an undeniable British design to these second generation bridges. In fact, some of them were built in English factories and then transported to Spain.[47]



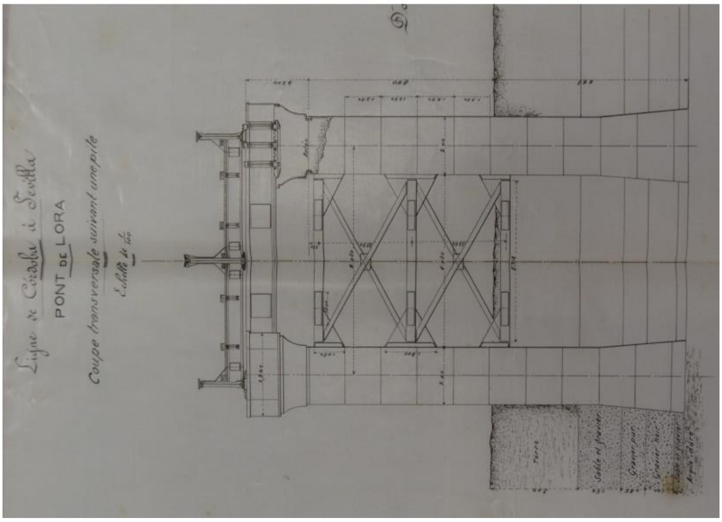


Figure 7: Lora del Río bridge over the Guadalquivir river. Drawings for construction. Archivo Histórico Ferroviario (Spanish National Railway Archive, Madrid).

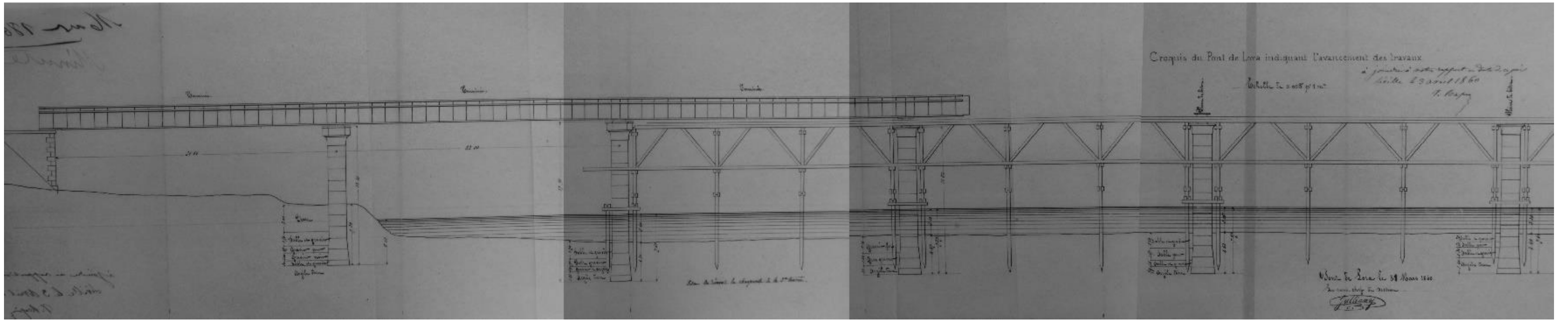


Figure 8: Lora del Río bridge. Site plan showing the state of the works in April 1860 (detail). Archivo Histórico Ferroviario (Spanish National Railway Archive, Madrid).

Lattice bridges

The most commonly used configuration for iron bridges in the 19th century was the lattice girder. These bridges were formed with two girders of parallel chords, containing a lattice of diagonally intersecting flat bars. This design, created in 1820 by the American engineer Ithiel Town, was originally intended for timber.[48] A number of mostly overbridges were built for the Irish and British railways in the 1840s and 1850s,[49] but the design was immediately reformulated with laminated iron elements, achieving an extraordinary popularity due to its simplicity and reliability. It was in Ireland in the 1840s that the metal version was largely used in railway bridges, and it soon spread to the Continent, being rapidly adopted in France, Germany and Austria.[50]

In the mid-19th century, timber Town beams were known in Spain and even had some applications there, but their real major use was with railway communications, where French construction companies played the most important role. In Andalusia, the first metal lattices were those of the railway line from Córdoba to Málaga. This infrastructure was built between 1860 and 1865 by the French company *Vitali, Picard et Compagnie*, whose main civil engineer was Jean Charles Dupuy. Spanish engineers De Mesa and Arriete also worked on the design of the line. Fifteen bridges of various sizes and three large viaducts had to be built along the complicated route. All of them were built using lattice iron girder (Fig. 9).

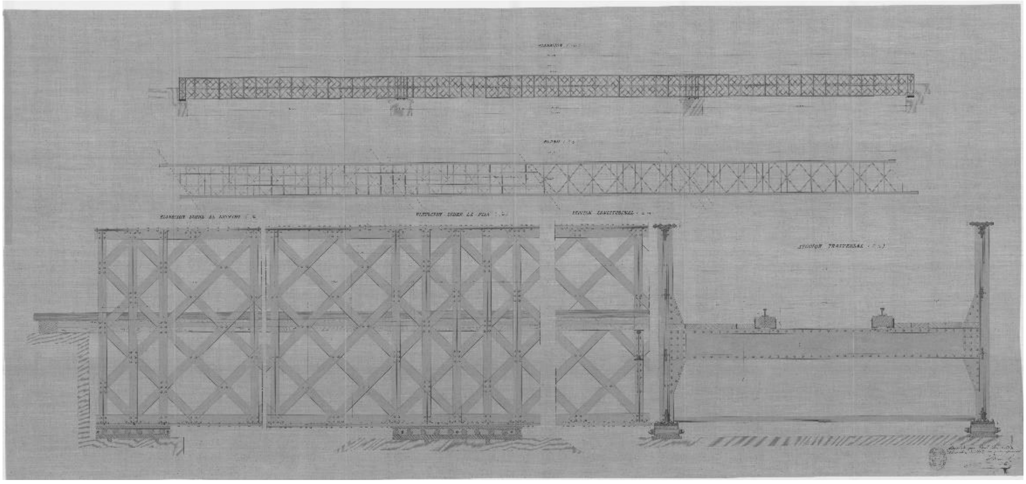


Figure 9: Drawings of Las Mellizas bridge (100m span), Málaga-Cordoba Railway.[51] *1862. Archivo General de la Administración.*

The largest construction was a 200m long, four-span viaduct across the Guadalquivir River near the city of Cordoba (Fig. 10). Its piers were twin cast-iron cylinders, sunk 6m into the ground using compressed air caissons.[52] Such a foundation system had just been developed in France by Fleur Saint-Denis on the Rhine bridge at Kehl (1859).[53] It was one of its first applications in Spain.

Another construction novelty that was put into practice on this and most of the other bridges on the line was the placement of the metal part by launching. Contemporaries of the construction of the viaduct were impressed by the sight of the viaduct completely built and laid out on the track before being pushed into its final position by winches,[54] whereby the usual method of erection the bridges was the use scaffolding or other falsework (Fig. 11).

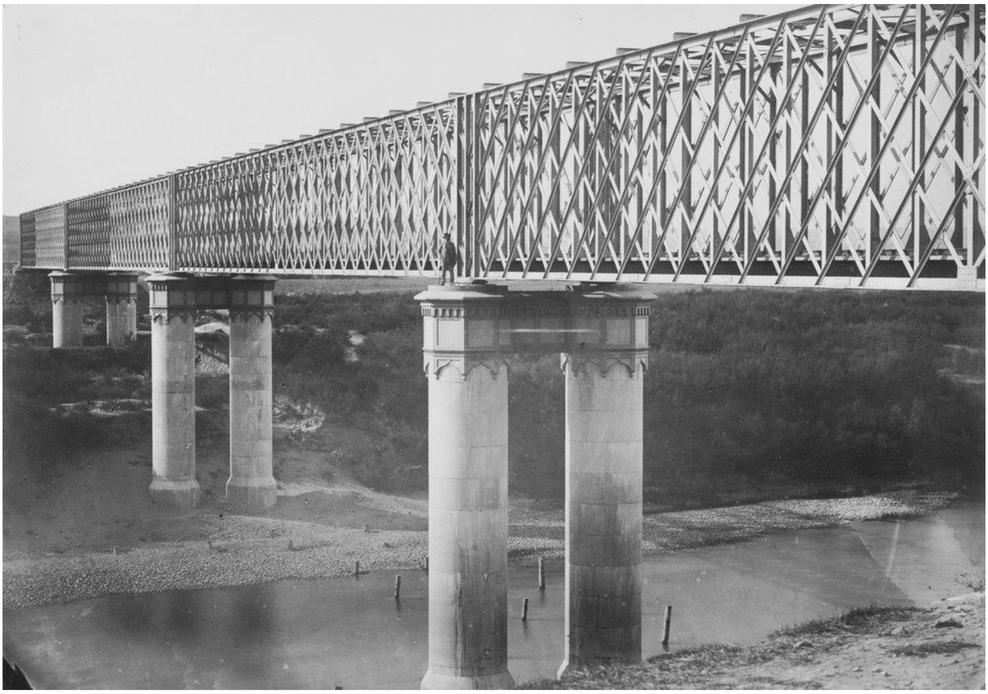


Figure 10: Guadalquivir viaduct in the Málaga-Córdoba Railway. Photo taken by José Spreafico in 1867.[55] *Patrimonio Nacional, Real Biblioteca.*

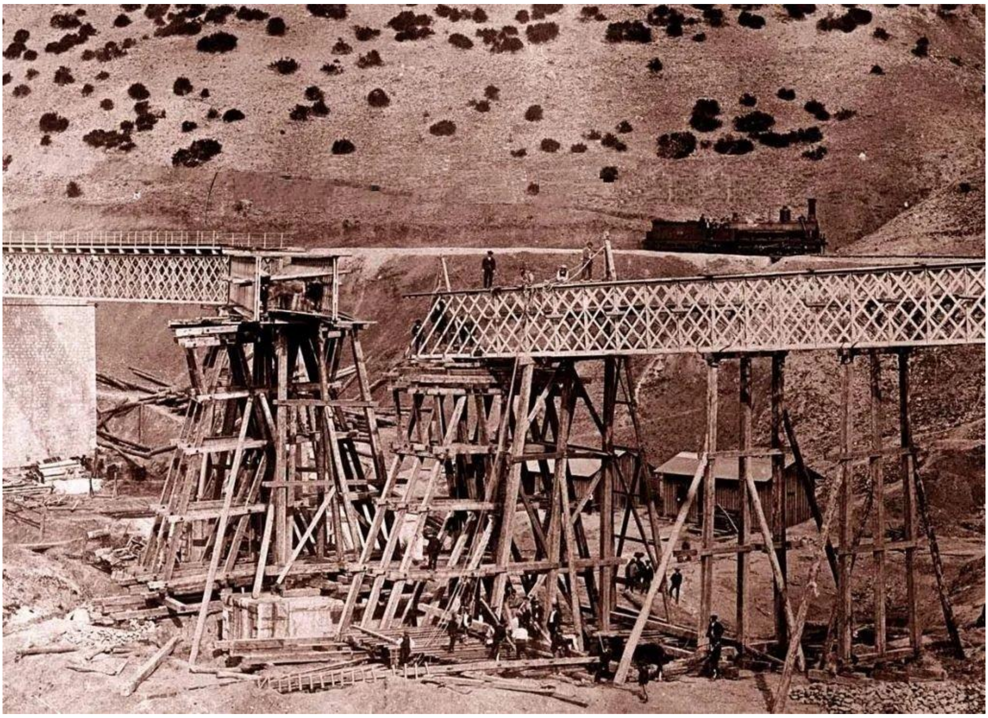


Figure 11: Construction of the Chorro viaduct on the Málaga-Córdoba railway. Photo taken by José Spreafico around 1865 with the kind permission of the Fernández Rivero Collection of Antique Photography. https://cfrivero.blog/

Five years after its inauguration (1865) a branch line to the city of Granada was added. Its technical manager was the French engineer Jean Charles Dupuy, this time acting alone. Dupuy added half a dozen metal lattice girder bridges. Among them was the *Río Frío* viaduct (near Granada), with a length of 120m (spans 35m, 50m, 35m), which was built at a height of 46m on characteristic masonry piers that gradually decreased in section with height (Fig. 12). This bridge was used for more than a century. In 1982 it was replaced by a modern viaduct that was built next to it.[56] In this way it has been able to survive, being the only extant railway lattice in Andalusia.

Figure 12: Río Frío Viaduct near the city of Loja, the present day. Designed and built by Jean Dupuy in 1873. Photo: the authors.

Apart from the introduction of the new forms and procedures of execution, the bridges of the Malaga-Cordoba Railway already show a rational organisation of that engineering design, similar to modern postulates. Technical projects were drawn up for all the bridges, including overall and detailed drawings, as well as calculations justifying the dimensions of all the elements of the structure.

French engineers made bridge design more scientific by introducing improvements such as geotechnical studies to aid in the design of the foundations (Fig.13).

There was registered another transcendent innovation in the design of these bridges. In the first half of the century, the theory of elasticity and the general theory of the strength of materials were established in France, owing to some brilliant mathematicians and engineers (as Navier, Cauchy, Lamé and Clapeyron).[57] In Britain, Fairbairn and Hodgkinson contributed important empirical findings. This knowledge, which made it possible to design structures in a rational way, was later refined by British and German engineers.[58]

In Spain, public works were organised according to the French model, the influence of the neighbouring country being decisive. The teaching of the subject at the School of Civil Engineering was mainly based on French construction theory. With the arrival of the railways, this influence increased. The French engineers who came to build the new lines introduced their design and construction methods, which were directly transmitted to the Spanish technicians. For example, the design bending moments of the railway bridges were determined using Clapeyron's theory, and of course, the formula established by Navier in 1833 was applied to calculate the strength of the iron beams.

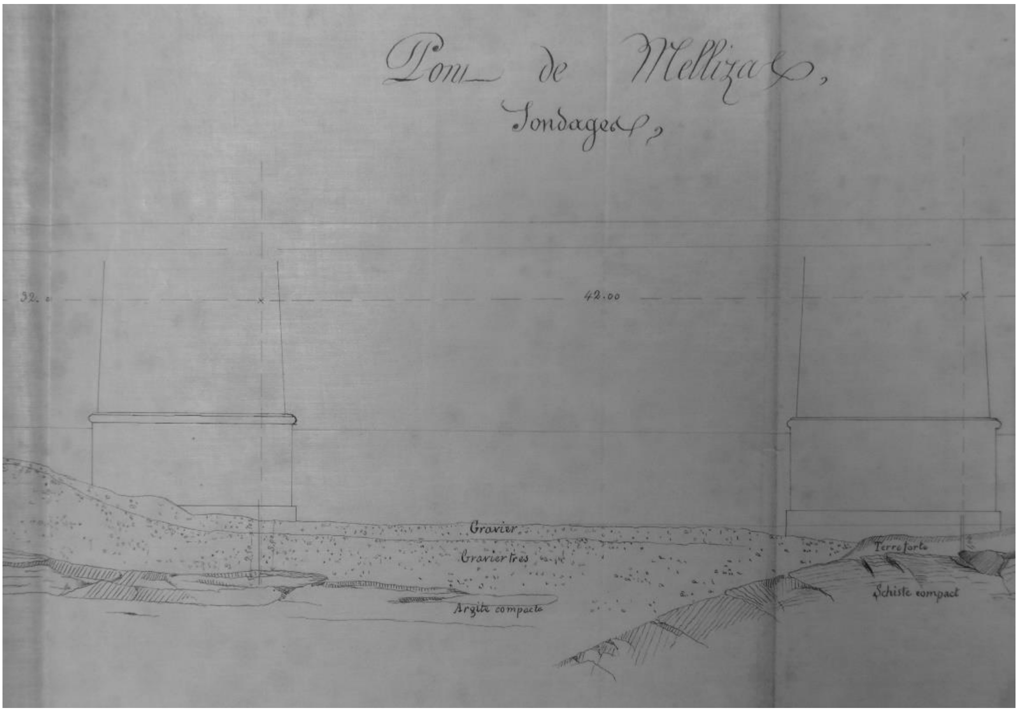


Figure 13: Study of the ground by means of boreholes, for the foundations of Las Mellizas bridge, 1860.[59] *Archivo Histórico Ferroviario (Spanish National Railway Archive, Madrid).*

Iron truss bridges

The lattice girders played a major role in the implementation of the first railway lines in Europe. But the evolution of metal bridges did not stop with them and they soon gave way to better formulae, obtained from triangular trusses. The most widely used models were developed early in America, where the Howe, Pratt and Linville systems had been in regular use since the 1850s.[60] On this side of the Atlantic emerged proposals such as the Warren girder. However, it would take several decades for the dominance of lattice girders to be superseded.

From 1865 onwards, triangular beams underwent a dizzying expansion, in which French Engineering played an important role. Gustave Eiffel opened up the path significantly with bridges such as *Rouzat*.[61] This new type of bridge was introduced in Spain mainly by French construction companies. The mining boom (in eastern Andalusia important iron deposits were being exploited at the end of the 19th century) led to the construction of new railway lines, which were again mainly contracted to French companies. Indeed, of the three major new lines built in Andalusia, two were the work of French engineers. The only line awarded to a British company during this period was the Granada-Murcia Railway. However, its iron bridges were given to a Belgian subcontractor, so they were not built to British standards. Due to the complicated topography of the region, these railway lines shared as a distinctive feature an extraordinary set of bridges, both in quality and quantity.

In the last quarter of the 19th century, three major railways were built in south-eastern Spain. In two of them, the participation of French engineering was decisive.

The Linares-Puente Genil line ran along the northern edge of the Betic mountain ranges. Unable to ignore the topographical difficulties, its route included fourteen large bridges, four of which were more than 200m in length.[62] The government awarded this line to the Spanish company The Andalusian Railway, which signed a contract for the construction of all the bridges with the entreprise Daydé et Pillé. All the bridges were manufactured at the company's factory in Creil (Oise), then transported to Spain and finally assembled on site. The French engineers Alesandri and Delaperrière were technically responsible for their design and construction.

The other major railway in southeastern Spain was the Linares-Almeria line, completed in 1899. In this case it was a consortium of French capital that was behind its construction, which was subcontracted to the powerful construction company Fives-Lille. Its route was even more complicated, as it had to cross the great mountain range in the south of the Iberian Peninsula. Thus, the 250 km length of the line included twenty five bridges, six of which were over 300m long (among them the 560m long *El Hacho* viaduct, which was the longest metal bridge built in Spain).[63]

As with the other line, the bridges were manufactured in France and then transported to Spain. They were designed in the technical department of the Fives-Lille company, with all the projects bearing the signature of its general manager, Edmond Duval. In Spain, the company had outstanding technicians on the ground, who played a decisive role, first in its preliminary design and later in its materialisation. The famed French engineer Paul Sejourné played a major role in fitting the bridges into the infrastructure, although the main responsibility for its specific design lay with the French-Polish engineer Stanislaw Bazinsky.

The bridges of both lines were all built with truss iron girders (the sole exception was the *Rambla de las Adelfas* bridge, a masonry viaduct in seven arches with 12m spans). In the *Linares-Almería* railway, X trusses were the solution for simple spans; however, the double-order trellis girder was the common model for the *Puente Genil* line (Fig. 14).

Both solutions were used interchangeably for the multi-span bridges on the *Linares-Puente Genil* railway, the most significant construction being the 206m length (central span 74m) *Guadajoz* viaduct. Its main beams rest on two 28m high wrought-iron towers. This splendid work has managed to survive to the present day (Fig. 15).

The large bridges on the Linares-Almería line were built with Linville type trellis trusses. Among them, the exceptional *Salado* viaduct, made of three 105m long decks resting on 90m high monumental ashlar piers stands out (Fig. 16). It was designed by the civil engineers of the company Fives Lille: Baznsk and the Spaniards Otaño, Acedo and Moreno Ossorio. The Swiss engineer Schüle, as consultant, supervised the structural calculations and the Frenchman Guerin oversaw the launching of the main beams and deck by pushing them into position.[64]

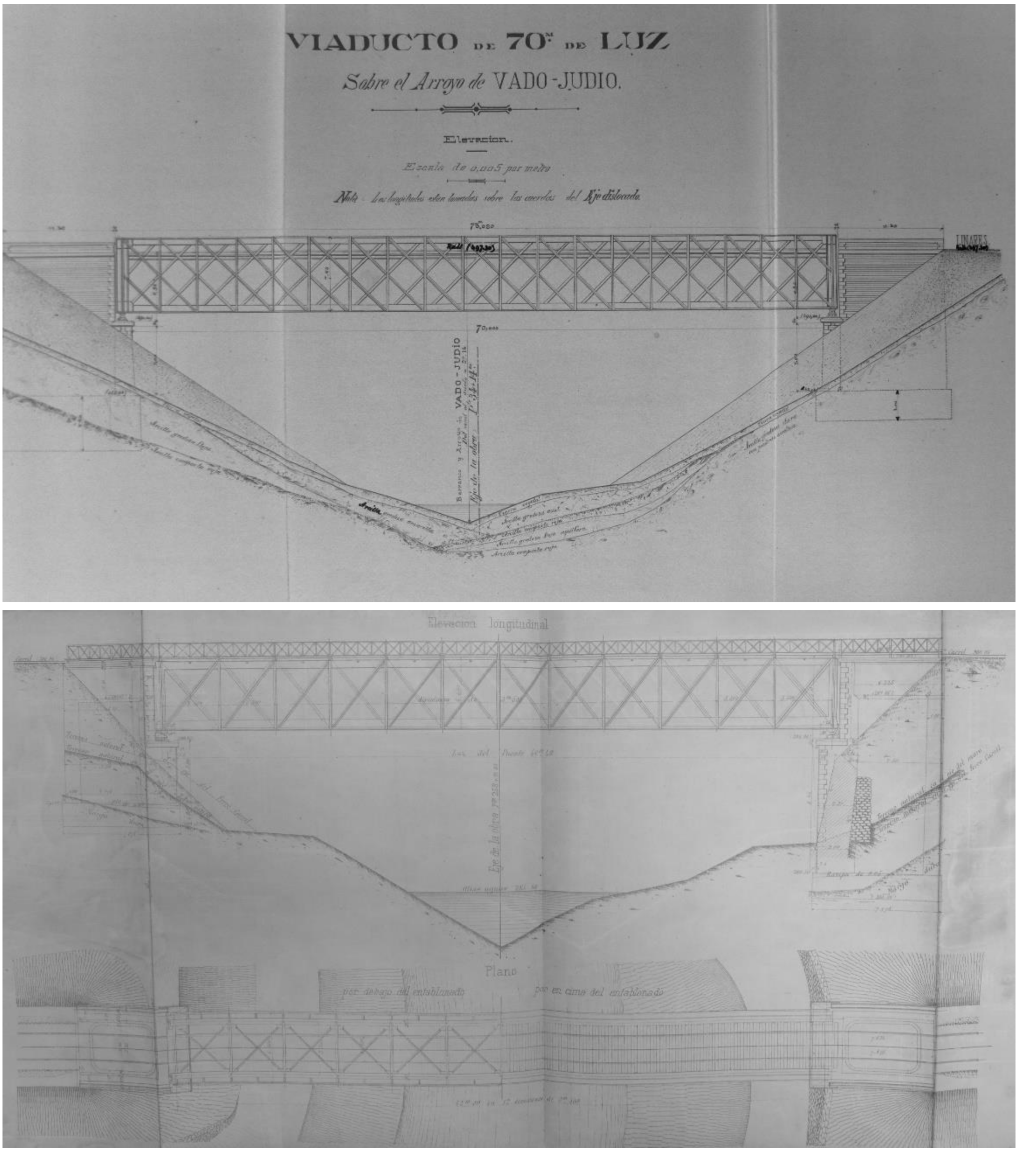


Figure 14: Simple span bridges.[65] *Above: Barranco del Matadero, 1892, Linares-Almería Railway.*[66] *Below: Vado Judío, 1890, Linares-Puente Genil Railway.*[67] *Archivo Histórico Ferroviario (Spanish National Railway Archive, Madrid).*

Extraordinary construction methods had to be used to build this bridge. For example, because of its height, it was not possible to use scaffolding to build the piers. A vertical shaft or chimney was built inside the bridge, through which materials were lifted and workers moved by a lift.[68]

The projects for the bridges on these two lines already showed a mature structural design, which is used in the detailed determination of the calculated stresses, taking into account the different loads and implementing concepts such as the influence lines (Fig. 17).

Figure 15: Guadajoz Viaduct, at the present day. Designed and built by Ch. Alessandri and A. Delaperrière, 1893. Photo: the authors.

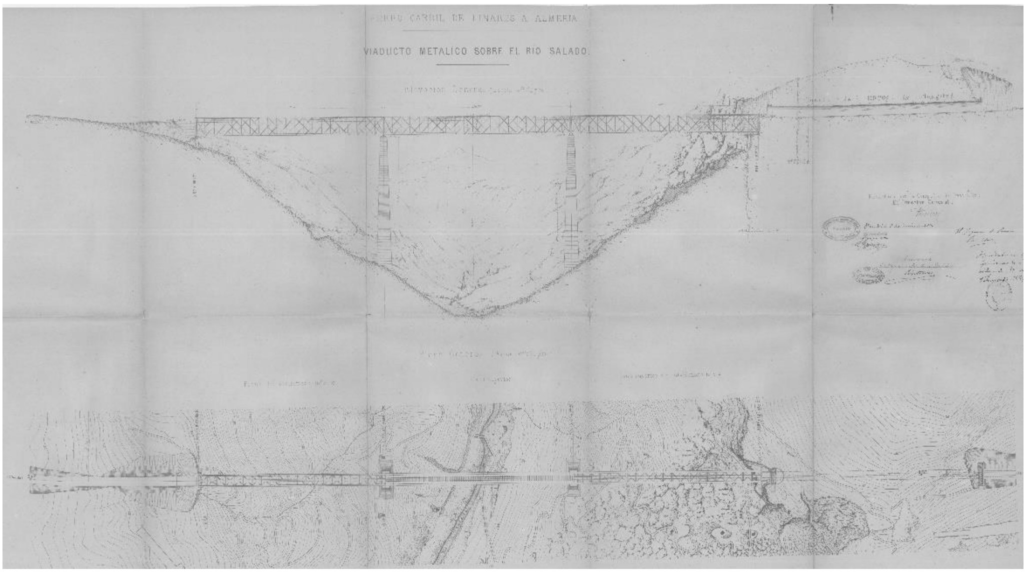


Figure 16: Elevation and ground plan of the Salado bridge, Linares-Almería railway.[69] Designed and built by Fives-Lille company, 1899. Archivo Histórico Ferroviario (Spanish National Railway Archive, Madrid).

The great viaducts of the Andalusian railways had a different impact. The Linares-Puente Genil line was a little-known infrastructure at the time (and remains so to this day), probably because its construction was carried out satisfactorily. On the other hand, the Linares-Almería line was very problematic (the concessionaire and its contractor Fives-Lille, went to trial). The route had to be changed and, as it is already known, very large viaducts had to be built, using complex technical solutions that were to be considered milestones in Spanish civil engineering. Its construction was set in detail in several articles published in the *Revista de Obras Públicas* (channel of communication of the Spanish Civil engineers) and other contemporary Spanish technical journals (Fig. 18).

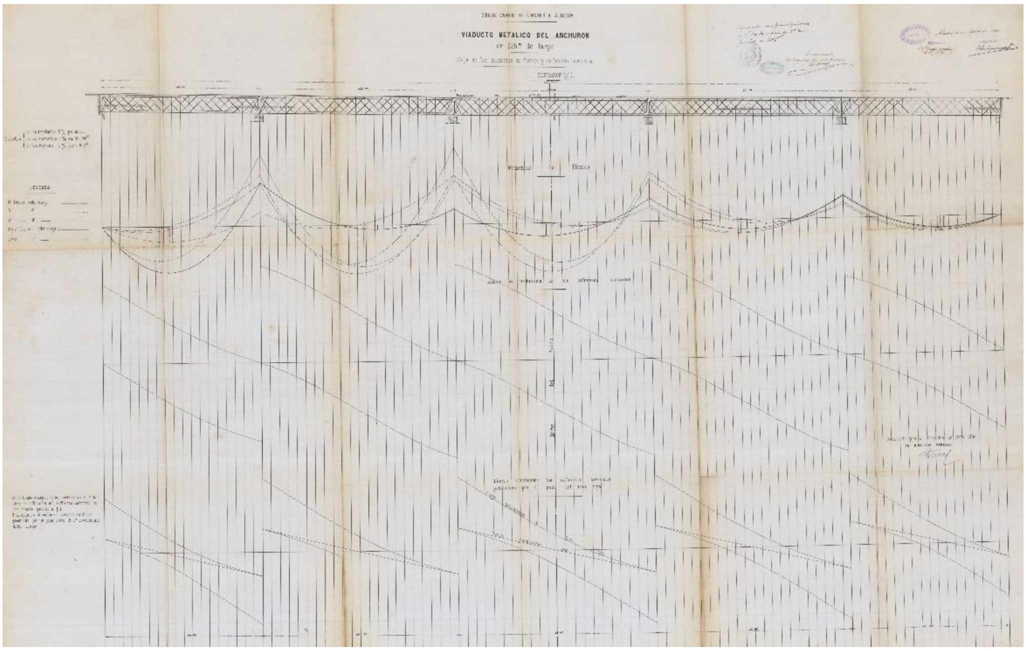


Figure 17: Bending moments and shear force diagrams for the Anchurón Bridge (255m span), Linares-Almería Railway.[70] *1894. Archivo General de la Administración*

Indeed, the successful conclusion of the works was celebrated in the national press, as can be seen in the report on the inauguration published in *La Ilustración Española y Americana*, the main Spanish illustrated magazine of the 19th century (Fig. 19). Since then, they have been widely recognised as outstanding elements of Spanish engineering and architectural heritage, although this was not enough to prevent them from undergoing major alterations in the 1970s to keep them in use. However, the bridges on the Linares-Puente Genil line, without railway traffic since 1984, have been preserved practically intact.

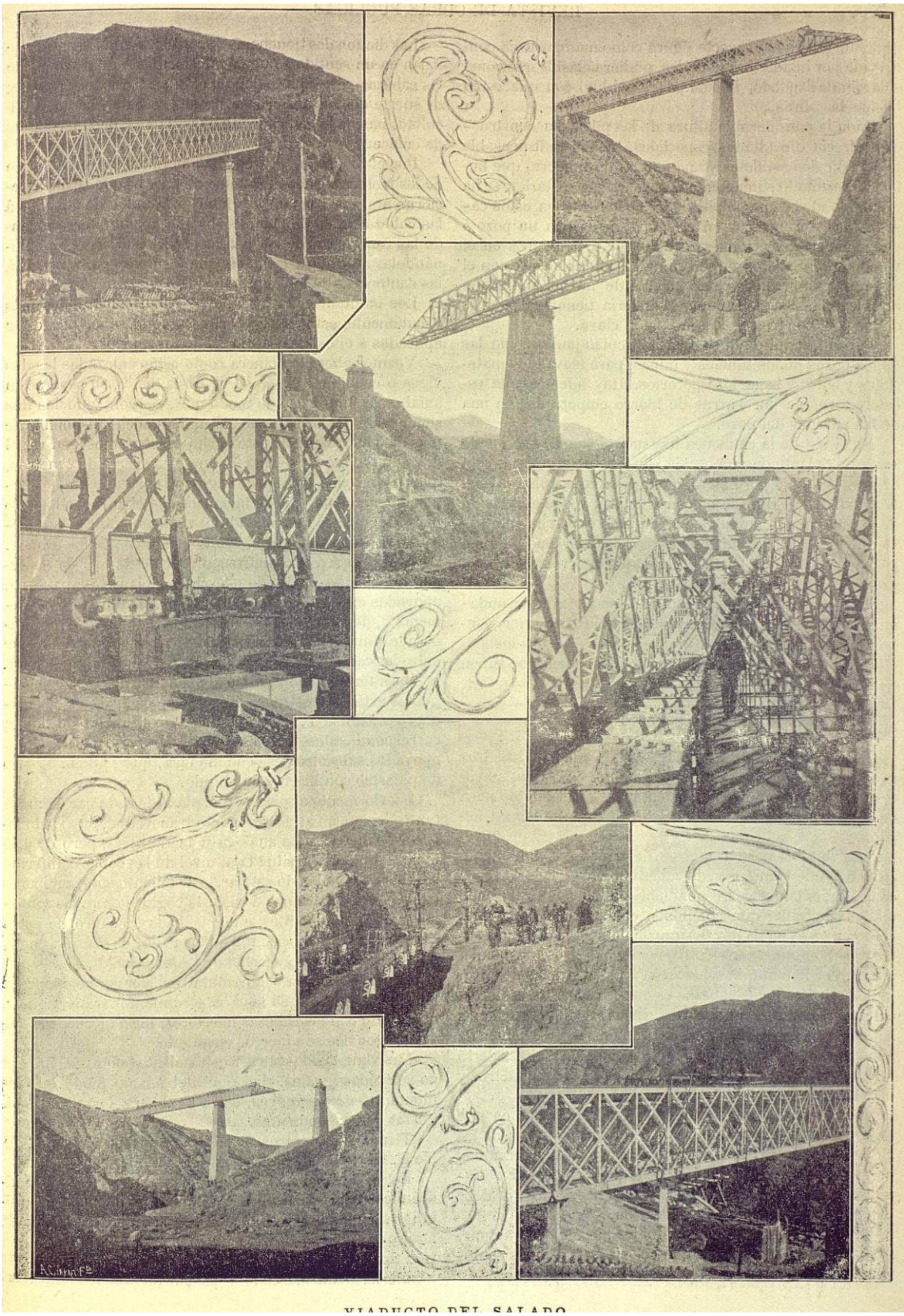


Figure 18: Photographic report regarding the construction of the Salado Viaduct included in the Spanish Journal of Public Works.[71] *University of Granada, Royal Hospital Library.*

Figure 19: Inauguration of the Salado Viaduct.[72] *Biblioteca Nacional de España (Spanish National Library).*

Conclusions

This article has highlighted the importance of French engineering in the evolution of modern bridges in Spain. The number and diversity of bridges built in its southernmost region is particularly representative of this phenomenon.

From the time of The Enlightenment, a large number of French engineers worked in Andalusia. This research has accredited their presence, and the bridges they built have been identified.

French engineers, either alone or in collaboration with Spanish technicians, were behind the construction of a large and diverse group of bridges in Andalusia. Through it we can see the evolution of the design of these works during the 19th century.

The transfer of knowledge has been recorded in this paper. New structural design theories and innovative construction procedures were applied for the first time in Spain, and, as the text has shown, the work of the French engineers helped to consolidate the modern organisation of the bridge project.

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