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RAILWAY MASONRY ARCH BRIDGE OF VENICE LAGOON: HISTORY, TECHNOLOGY AND STRUCTURAL BEHAVIOUR

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Abstract. *Many historical arch bridges are widespread in Italy. Usually they are part of roadway or railway net and nowadays the loading, carried by these structures, are higher than that considered for their design. The Infrastructure Authorities need to check the structural behaviour of these structure under current vehicular loading to evaluate the safety and durability of load bearing elements. A research about that topic was carried out on Venice –Mestre road masonry arch bridge[1]. The RFI (Railway Italian Net) decided to check trans-lagoon railway bridge which is in service since 1846, in cooperation with University IUAV of Venice and Strength of Material Laboratory (LaSC). The research program is wide and some results of the first investigation phase are reported in this paper. The procedure of analysis considers different aspect of this structure: history, technology, material, and dynamic behaviour under railway loading. A first dynamic testing was carried out on 220th arch to evaluate the structural condition under train crossing and to compare it with natural frequency of arch, evaluated by F.E. Method. This is a first analysis which will be carried on considering some of the 222 arches of the bridge. The research aim is to evaluate the structural behaviour of railway masonry arch bridge of Venice lagoon. The investigation started from the historical research about its construction and the technology used. The final goal is to formulate a numerical model which could be employed for evaluating its safety under modern loading.*

1 INTRODUCTION

The methodology applied to analyse the structure of Venice lagoon bridge starts from historical investigation about its construction. This bridge was an important infrastructural brickwork for Venice and its connection with mainland. The aim of this research is to understand how it was designed to determine the geometry of structural elements and the mechanical characteristics of materials used for its construction. These data are useful to model the structure by numerical methods and compare the results with experimental testing on present structure.

2 HISTORICAL INVESTIGATION

The first railway net arose in Unite Kingdom on 27th September 1825, connecting Stockton to Darlington. From this date the railway had been a great development firstly in Europe and then in the other continents (United States, 1831, Canada, 1836, Australia, 1854, Egypt and Argentina, 1857, South Africa, 1860, Japan, 1872). The railway net was realised for connecting the industrial centres to mine and port centres.

The railway net developed in many European countries as France (1832), Belgium (1835), Germany (1835) and Austria (1838). That railway net was composed of short railway sections. The railway net was sufficiently developed about 1870, at international level, and it was able to perform its economical and social functions for which it was created.

In Italy, the first railway section was constructed on 13th October 1839, connecting Napoli to Portici, under the Ferdinando II di Bordone Kingdom. This railway section was constructed by Bayard, a French company, and it was 7,25 km long.

2.1 The Milan – Venice railway section

Sebastiano Wagner and Francesco Varè proposed to create a railway section connecting Milan to Venice, through the "Lombardo – Veneto" region (1835), at that time, under the Austrian Kingdom government.

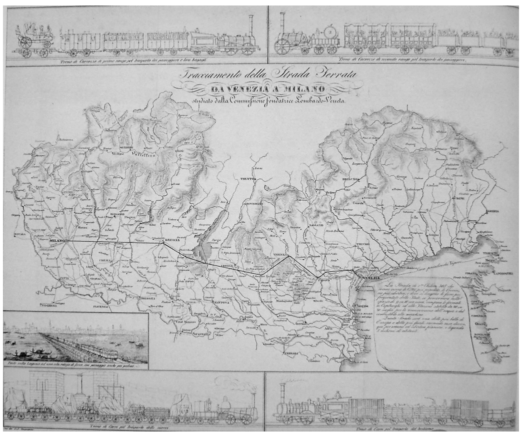

Figure 1: Milan – Venice railway route.

The “Privilegiata Strada Ferdinandea Lombardo – Veneta” (Ferdinadea Society) was established in 1837. This company was public and it was authorised by the Austrian Emperor. An engineer inspector was created to overview the construction and maintenance of the railway net. The first engineer inspector was Eng. Giovanni Milani, who was expert in railway construction because he had previous similar involvement in Austria and Germany. In the first half of 1839, Milani designed the Milan- Venice railway net; the project was approved and published in 1840. The railway route had to cross the main cities of north Italy: Padova, Vicenza, Verona and Brescia; it had to be 305 km long (fig. 1).

2.2 The railway bridge of Venice lagoon

The construction of the railway section, from Milan to Venice, imposed a problem concerning the connection of Venice to mainland.

This road connection was firstly proposed by Marco Foscarini Doge in 1763 to restore the economical fortunes of Venice, which were declining at that time. The first project was presented (1823) by Luigi Casarini: an embankment 4852 m long connecting Venice to Campalto. The embankment had to be high enough to resist at lagoon higher tide to guarantee the wagons and people transit. He placed a big round platform in the middle of the embankment for the rest of pedestrians. Some arches were placed along the embankment to guarantee the boats crossing. Casarini’s project had been pioneering and the following projects took it as a starting point, as Giuseppe Picotti did in 1830.

The main planning restrictions about a the construction of a trans-lagoon bridge had been:

1. the safety of Venice from enemy attacks;
2. the safety of lagoon natural life system.

The first railway project had been proposed (1830) by Eng. Baccanello and contractor Biondetti – Crovato. In this project the railway had to arrive at San Giorgio island, along Giudecca island. The bridge structure had been made of stone and timber. The idea was daring and the proposed structure was not suitable for railway.

The first proposal for a railway bridge connecting Venice to mainland was carried out on 26th May 1836. Five different railway route had been proposed; the adopted way was that starting from the south side of Marghera’s blockhouse and arriving at St. Lucia lagoon bight. The final bridge realisation was done by the contribution of three designers: Tommaso Meduna, Giovanni Milani and Andrea Noale.

A first project of railway bridge was designed by Meduna (fig. 2). He proposed a structure of 234 masonry arches shared in 6 “stadii”; each “stadio” was composed of 39 masonry arches. The middle squares had a width double of bridge width. This bridge had one rail and it had to be 3477 m long. The structures which were underwater, had to be realised in stone to prevent water corrosion; the bearing structure (bridge piers) had have to be built on wood pile work 3.5 – 5 m long. This project was rejected by the Courtly War Council because it preferred a timber structure with drawbridges which could be burned or demolished in wartime.

Figure 2: The bridge designed by Tommaso Meduna (print FS Record Office, Venice).

The second project was done by Milani, who was entrusted with Milan – Venice railway and Venice lagoon bridge project. His project proposed a route parallel to San Secondo canal to not modify the hydraulic regime of lagoon. The bridge is defined by 6 "stadii" divided in two part with a main middle square; each "stadio" is composed of 42 masonry arches, shared in 6 parts, each composed of 7 arches, by a double pier. Milani proposed a masonry bridge because it would be more safe and stable. A swing bridge made of timber had have to be realised at Venice side for military scope. Milani bridge had to be 3547 m long.

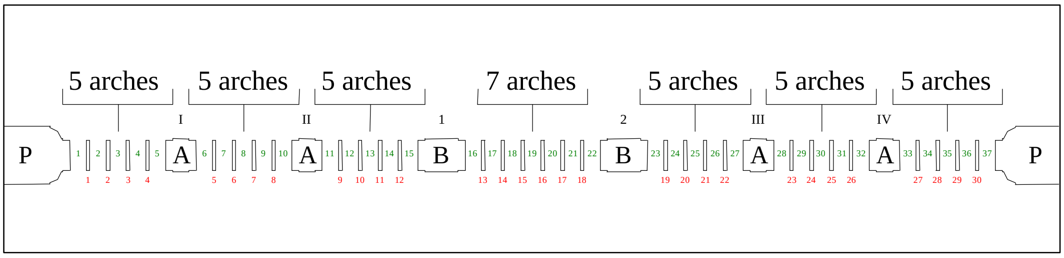

Figure 3: The modulus "stadio" in trans-lagoon Venice masonry arch bridge.

In 1840, Milani withdrew from the assignment for disagreement with the Ferdinandea Society and Luigi Duodo and Tommaso Meduna were called to review the Milani's project. The preliminary contract by tender was stipulated with Antonio Busetto building contractors on 7th April 1841; the supervision of works was assigned to Eng. Andrea Noale. This last one modified the bridge project building a bridge 3602 m long, constituted by the sequence of a 6 "stadii" (222 arches), each composed of 37 masonry arches. The "stadio" is defined by 5 masonry arches repeated for 3 times, a central system of 7 masonry arches and again 5 masonry arches repeated for 3 times (fig. 3). The new project was approved in 1842, and the starting works had been started. At that time Eng. Duodo commission finished and Milani took his place with Eng. Noale at supervision of work.

The final architectural and structural bridge configuration is the fruit of three capable engineers, that well knew the masonry arch construction technique and the lagoon site (fig. 4). The bridge is still called Austrian railway bridge but it was built by Italian engineers and building contractors. Its construction took 4 and a half years time; 1000 employers with different tasks worked at its construction each day; 46 boats were used to carry materials and 14 cargo boats transported Istria stone daily. The last arch was finished on 27th October 1845 and its inauguration was done on 11th January 1846.

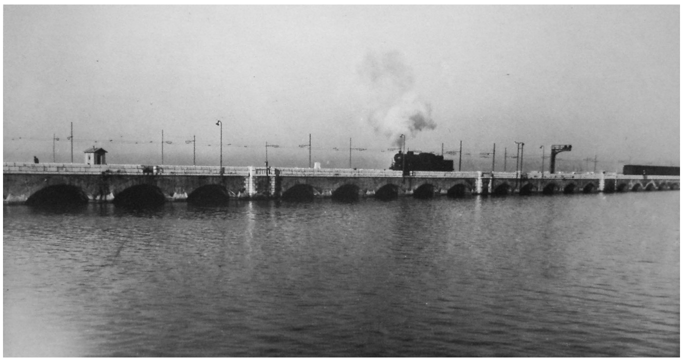

Figure 4: The masonry arch bridge of Venice lagoon under service loading (photo, FS Record Office, Venice).

2.3 The present structure of the bridge

The present structure of the old Venice lagoon bridge (line A, fig. 5) is not more visible. It is included between the roadway bridge and the new railway bridge.

The roadway bridge was built according to Eng. Eugenio Miozzi' project (line B). He designed a bridge similar to the railway one and its inauguration was done on 25th April 1933; its construction took 21 months time. This bridge is made of masonry (arches structures) and stone (abutments), whereas the piers are made of reinforced concrete piles. It was firstly called "Littorio" Bridge but its name was changed after the end of 2nd World War in "Freedom" Bridge. It is placed on the south side of the railway bridge.

The new railway (line D) was built parallel to the old masonry arch bridge. Its construction started in 1965 and finished in 1973. This structure is made of reinforced concrete for foundation and upper structures. The deck is constituted by pre-stressed reinforced concrete beams connected in situ by transversal steel cables and casting concrete. This bridge was built to increase the railway net capacity and to carry on a restoration on the old bridge, which had been in service for 131 years. The restoration works consisted of stopping the water infiltrations by cement injections from the extrados and a waterproof sheet application; the rails were substituted with new ones due to new train transit.

The old railway bridge was partially enlarged in the first half of XX century. The enlargement concerned the last "stadio", close to Venice, to extend the arrival platforms of S. Lucia station (line C). The enlargement structure follows the original one except for the arches depth: 20 m in the last 5 arches toward Venice and 17 m for the other 32 arches. The structure seems the same but important data were collected during the bridge inspection, especially concerning the piers.

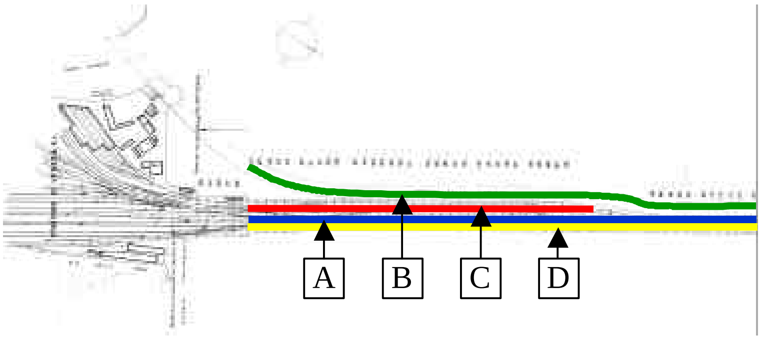

Figure 5: The railway and roadway bridges close to Venice.

3 TECHNOLOGY AND MATERIALS OF THE BRIDGE

The railway bridge is composed of a set of masonry arches, which abutments are based on three different type of piers: small, medium (type A) and big (type B) pier (fig. 3). The bearing structure is constituted by a masonry barrel vault with variable cross section.

3.1 The load bearing structure

The arch span is 10 m and its rise is 1.73 m. The curvature radius is 8.08 m, at intrados and the arch thickness is 0.94 m at abutments, 0.80 at ¼ of span and 0.65 m at crown. The backfill is made of heterogeneous materials, as sand, stone and brick in small pieces, and it is covered by a waterproof sheet made of lime and pieces of brick conglomerate. Another multilayer backfill is placed under these first two layers. It is made of a first layer of stone blocks, broken bricks and sandbank earth; over this the ballast and finally the rail track. The backfill materials are restrained in the spandrel walls made of masonry and stone for the upper part. Some transversal ties along the masonry arch and stone block at crown could be seen in the Noale's drawing, but a a second drawing these element are not visible any more (fig. 6).

A


B


Figure 6: The bridge arch in a drawing of 1842 (A) and in a drawing of 1844 (B).
(Private collection Q. Ferron, Lonigo - Vicenza)

The abutments are made of Istrian stone. Each abutment is constituted by a block of stone, which sedimentation layer are perpendicular to the thrust line. Following this stone disposition, the thrust could be carried by abutment and transferred to pier.

The piers have different dimensions but, generally, their cross section is variable. Close to abutments, there is a stone ring 0.25 m thick, then the first part of pier is 2.17 m wide and 1 m deep, made of squared stone blocks with thin hydraulic mortar joints; the inner side is filled with incoherent material. The second and deeper part of pier is made with the same technology but the external stone block are not squared and it is 2.77 m wide and 1.33m deep. The biggest piers are built at same manner but they have a cavity inside the cross section. This cavity had done to put gunpowder for demolishing the bridge during enemy attack.

3.2 The foundation structure

The pier bases on foundation which is typical of Venetian technology. It is made by a lot of larch pile 4.5 m deep, close each other; over the pile heads, there is a double planking made of timber elements, which are layered in two direction. The pier stars from that point. The foundation soil is layered and, generally, the layers are made of sand, mud and clay. Nevertheless, a layer of clay with good mechanical characteristics should be found deeply; this layer is called “caranto”. The best foundation technology is the Venetian one for the lagoon soil.

3.3 The structural material

The mechanical characteristics could not be evaluate directly on the structure.

Clay brick		**Historical masonry**					
		Mortar joint thickness 10mm			Mortar joint thickness 13mm		
f_b MPa	E_b GPa	f_{mr} MPa	ε_r ‰	$E_{0,2}$ GPa	fm MPa	ε_r ‰	$E_{0,2}$ GPa
16	6,5	3,2	9-7	1,6	1,9	10-7	1
22	8,1	4,4	8-6	2,2	2,6	9-6	1,3
28	9,8	5,6	7-5	2,8	3,4	8-5	1,7

f_b brick compressive strength; E_b brick Young modulus; f_{mr} masonry ultimate compressive strength; ε_{mr} masonry ultimate compressive strain; $E_{0.2}$ masonry Young modulus

Table 1. Mechanical characteristics of historical masonry in Venice.

Material	Density [kg/m^3]	Compressive strength [N/mm^2]	Tensile strength [N/mm^2]	Shear Strength [N/mm^2]	Flexural Strength [N/mm^2]	Young modulus [GPa]
Istrian stone	2770	135 // 160 ±	5	10÷50	12.5	40÷60
Larch timber	580÷850	53 // 10 ±	85	--	96	14

// parallel to fiber axis; ± perpendicular to fiber axis;

Table 2. Mechanical characteristics of Istrian stone and larch timber.

Therefore, the authors had referred to some studies concerning the mechanical characterisation of Venetian historical masonry[2] (tab. 1) to characterise the bridge masonry. The data about Istrian stone and larch timber are carried out from historical handbooks (tab.

2). In particular, the larch timber had been considered the best timber for construction by numerous architects in the past[2].

4 STRUCTURAL EVALUATION OF THE BRIDGE

The evaluation of the trans-lagoon railway bridge has stared from the historical analysis of some handbooks, which were widespread at construction time.

The theory on masonry arch stability before XVII century were based on geometrical rules carried out from construction of such type of structure. An extended description of this arch theory is reported in Benvenuto (1991)[3]. The bridge was built between 1842 and 1846 so that more attention has been put on the handbooks or publications for railway arch bridge published in XIX century and after. The main handbook[4] is that of Perronet, who proposed to reduce the pier thickness in multi-arch bridge, due to that the thrust at abutments is almost vertical. His design rules were applied also in the following centuries. Many treatises[2, 5, 6, 7] have been analysed and the some structural elements have been evaluated using the formula reported by each author (tab. 3), assuming a masonry arch equal to the trans-lagoon bridge arch.

Author	Year	Arch thickness at crown [m]	Arch thickness at abutment [m]	Abutment thickness [m]	Pier thickness [m]
Venice bridge	1842-1846	0.65	0.94	> 2.17	2.17
Perronet	XVIII sec.	0.89			1.62
Rondelet	1827-1832	0.97	1.95		
Cantalupi	1857	1.42		3.70	1.72
Scheffler	1864	0.89	0.92	> 2.17	min 1.16
Breymann	1885	0.89÷0.97	1.95		

Table 3. Structural dimension of trans-lagoon bridge arch for the main authors of XIX century.

The dimensions established using Scheffler'rules look to be the best fit to the bridge recorded dimensions. It is possible that Milani knew Scheffler's theory because he had been in Austria and Germany before he designed the bridge, so that he kept some information about the theory for railway bridge construction. The arch span was imposed by military prescriptions. The bridge arch seems to be right designed and its structural dimensions are comparable with Scheffler's data.

A safety evaluation was carried on evaluating the thrust line due to dead and live loading.

4.1 Thrust line by Mery method

A single arch was considered for this analysis. The load analysis was divided in dead load and live load. The dead load was evaluated considering the materials used for its construction as masonry (1800 kg/m^3), stone (2770 kg/m^3), backfill (2000 kg/m^3) and ballast (1550 kg/m^3). The dead load (kg/m) has a distribution which could be represented by a quadratic equation for half an arch,1 m deep.

The live load is represented by two train type D4 (locomotive and 20 wagons, 4 axis per wagon of 22.5 t) on the arch at the same time. This is the worst loading condition. The point loads were distributed on the arch span and a dynamic coefficient (1.16) was applied to take in account dynamic force induced by train transit, following Italian railway code[8]. The live load is equal to 2000 kg/m. Following Mery method and assuming that the horizontal thrust at crown is applied at the extrados of middle third of arch thickness, the thrust line due to dead and live loading is inside the middle third arch thickness. The masonry arch is safe and there is not tensile stress in its cross sections. The maximum compressive stress is 1.14 N/mm^2, at crown due to the imposed as limit condition; this value is 2.8 times lower than the minimum compressive strength of historical masonry in Venice (tab. 1).

4.2 Dynamic analysis

A dynamic analysis was carried out following the experience of Bintrim and al [9, 10]. During dynamic testing, accelerations of three points along the 220th arch intrados were recorded, during train crossing. The piezoelectric accelerometers were stuck to masonry by plasticine and steel plate, at crown and hunches. An signal amplifier received the accelerometers output and transferred this amplified to a PC with modal test program. The recorded data are accelerations vs time. The data were translated in frequency by FFT (fig. 7). The frequency of railway bridge arch under train transit is about 41 Hz.

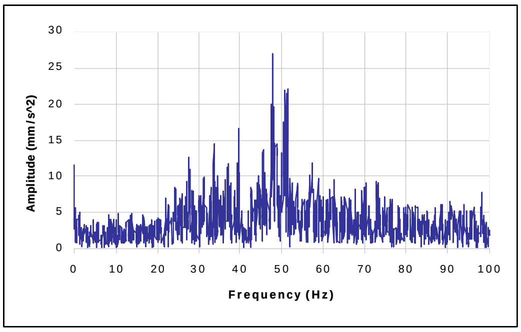

Figure 7: Amplitude vs frequency of 220° arch under train crossing (9.3.2004 at 11.13 am).

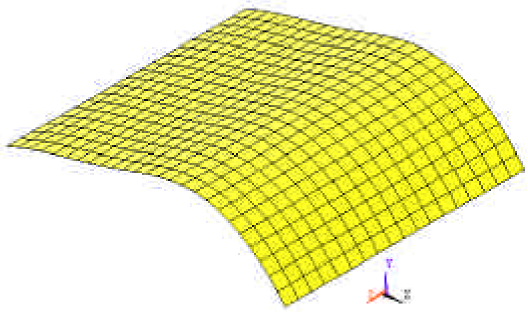

Figure 8: First modal shape of masonry vault

Masonry Young modulus[N/mm^2]	1st mode Frequency [Hz]	2nd mode Frequency [Hz]	3rd mode Frequency [Hz]	4th mode Frequency [Hz]
1600	4.96	8.26	8.53	9.19
2200	5.81	9.69	10.00	10.77
2800	6.56	10.93	11.28	12.16

Table 4. Results of F.E. model of a trans-lagoon bridge arch.

A numerical analysis using F.E. Method was carried out for evaluating the natural frequencies and the corresponding mode shape. This model is a simplified one to evaluate firstly the natural modal mode of a single arch. The mechanical properties were assumed following table 1, whereas the mass density was modified to take the dead and live loading into account (mass density is 6348 kg/m^3). The barrel vault was modelled following the actual geometry using shell elements with bending and membrane capabilities (fig. 8). Numerical results are reported in table 4.

5 CONCLUSIONS

- The first investigation on railway arch bridge of Venice lagoon showed that the bridge was well built using high quality technology and materials and the engineers that built it well knew the railway design rules and the lagoon environment.
- The mechanical properties of materials could be assumed by testing, but if it is not possible some experimental results could be kept as reference data. The authors hope to do some NDT tests to check these data.
- The research has to be carried on analysing the arches at halfway through the bridge, before, during and after train crossing, so that to evaluate the natural frequencies. These data should be useful to calibrate the model by structural identification.
- The results of F.E.M. model shows that the natural frequencies are far from the frequency induced by train crossing, at arch close to Venice station. This data have to be checked also in other arches, especially at bridge halfway.
- The F.E.M. model has to be developed to simulate a “stadio” and the whole structure.

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