Color and Aesthetics in the Oporto São João Bridge

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Abstract. The São João Oporto Railway Bridge (1991) represents Prof. Edgar Cardoso (1913-2000) top achievement in long career, as one of the foremost Portuguese bridge designers. This structural concrete railway bridge had several constraints that were overcome: geometrical, environmental and technological. This study presents a unique design solution where a magnificent π-shaped 1029.00 m long portal spans 66.50m above the Douro river stormy waters. The aesthetics, construction and economic aspects are also considered. All details were considered, i.e., an adequate painted concrete surface to enhance sustainability (long-term duration in an aggressive environment) and visibility (a discrete, yet correct color) to create an *oeuvre d'art.,* for the people education and use.

1 INTRODUTION

After the 1877 Maria Pia iron arch railway bridge, designed by Gustave Eiffel, the 1886 Luiz I twin deck roadway iron arch bridge, designed by Theophile Seyrig (a former partner of G. Eiffel) and, the 1963 Arrábida and 1973 Mosteirô reinforced concrete highway bridges, designed by Prof. Edgar Cardoso, see Figures 1, 2 and 3, the Oporto Railway Bridge (1991) has recently completed 22 years of continuous and intensive use under growing traffic conditions, see Figures 4 and 5. This railway bridge linking the cities of Oporto (north bank) and Gaia (south bank) still represents a unique challenge to structural bridge designers. The magnificent π-shaped 1028.65m long portal span fording the Douro river, 66.5m above the stormy waters, represents the ultimate achievement ofn Prof. Edgar Cardoso, one of the foremost Portuguese bridge designers, author of more than 500 bridge designs in Portugal and overseas, L .L. Soares [12].

In the North of Portugal, crossing the steep river Douro granite v-shaped valley, major construction challenges were overcome during the last 150 years. In 1875, the Royal Portuguese Railroad Company organized a major European design competition for the Douro river railway bridge linking the cities of Oporto (north bank) and Gaia(south bank). The winner was the 43-year old French engineer Gustave Eiffel.

In that year, two major contracts were won by the Maison Gustave Eiffel & Co. of Levallois-Perret, Paris, almost simultaneously: (a) the 2.700.000 gold francs Nyugati railway station in Pest (Budapest), Hungary; and, (b) the 965.000 gold francs Oporto railway bridge, in Portugal. This price was 46% less than the second placed competitor, the well-known Fives-Lille Co. with a value of 1.410.000 gold francs, which made the choice obvious. These two major public works allowed Gustave Eiffel to establish a solid reputation as a major leading designer–builder entrepreneur.

The Oporto bridge solution presented to the selection committee consisted of a single steel twin-hinged arch, with a maximum span of 160.00m and the total height of 62.40m, H. Loyrette [8]. The bridge has a total length of 352.75m, the straight trellis girder is supported by piers whose height varies accordingly with the ground surface. The single line rail girder deck is divided into three portions: (1) the Gaia bank flanking the arch (south deck), 169.87m long, supported on the masonry end abutment, two ground based iron piers, and two piers fixed on the arch extrados; (2) the 51.88m long rail deck integral with the crowning arch central region; and, (3) the 132.50m long Oporto bank flanking deck with support conditions similar to the other side, see Figure 1. In this construction project, G. Eiffel noticed that two major problems would arise: (1) the trellis girder wasn't continuous along its total length, which made it unsatisfactory for train emergency stops on the bridge; and, (2) there was the real danger of train derailment, as the bridge had no accident stop barriers. In 1881, with the Gabarit viaduct, in the French Massive Central, G. Eiffel improved the steel arch bridge design with the observations made after the Maria Pia bridge. The railway trellis girder was made continuous from one abutment to the other and the rail track was placed 1.66m below the upper flange girders plate to encase the train during a major train derailment situation.

From 1902 onwards the progressive renovation of the Oporto-Lisbon one-track train line into a twin-track line created major traffic constraints on the use of the Maria Pia railway bridge. An initial maximum speed of 20 km/h was further reduced to 10 km/h, when a night freight train derailed just after the Gaia abutment. Furthermore, only 38.0 kN/m uniformly distributed load was allowed as well as a maximum 160.0 kN concentrated load per axle. In the early 1980's, the Portuguese Government under a major transport renewal plan decided to build a new railway bridge to improve the great Oporto metropolitan transit network and to ease the north-south communications link. The maximum speed was raised and specified to 120 km/h, a greater 250.0 kNconcentrated load per axle and 80.0 kN/m uniformed distributed load were also stipulated. The estimated daily traffic volume over the river Douro was 400 daily trains.

2 BRIDGE DESIGNERS - MASTERBUILDERS

For ages, masterworks were a result of the individual skills of a master builder able to develop empirical complex designs and construction solutions in masonry (stone, bricks) that still wonder the designers. Currently, the client expresses is ideas and wishes so the architect can imagine a possible solution, the structural engineer proposes a skeleton to resist the expected probable loading conditions, and the contractor tires to materialize both concepts into a real object that is an approximate solution to the initial ideas. Seldom end results correspond both to the original architect's dreams or the client's original needs (M. Salvadori [15, 16], Levy & Salvadori [17]).

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Figure 1. The 1877 Maria Pia railway bridge by G. Eiffel.

Figure 2. The 1963 Arrabida highway bridge by E. Cardoso.

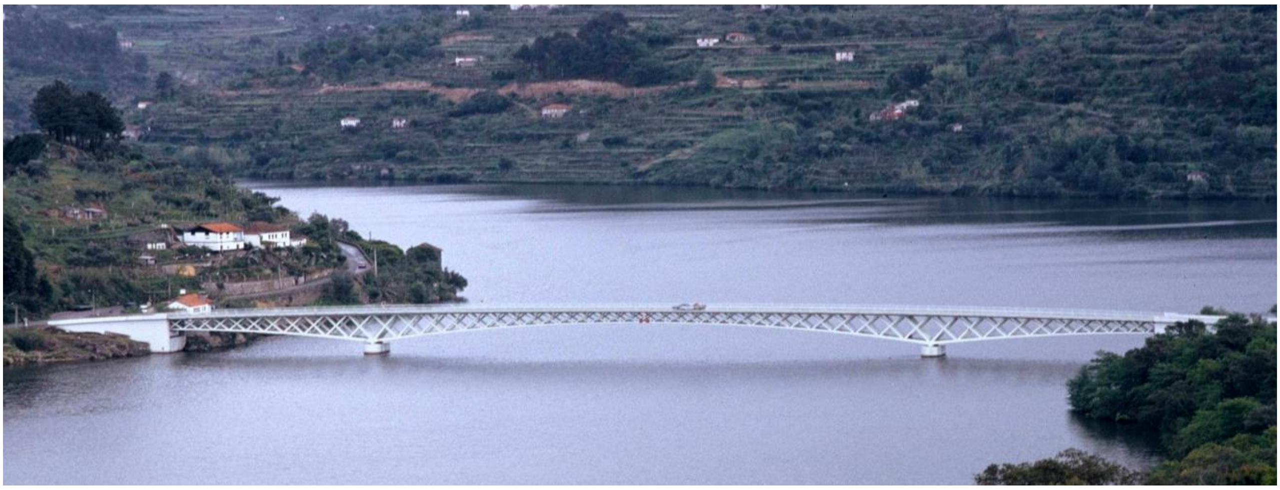

Figure 3. The 1973 Mosteirô roadway bridge by E. Cardoso.

Figure 4. The 1991 São João railway bridge by E. Cardoso.

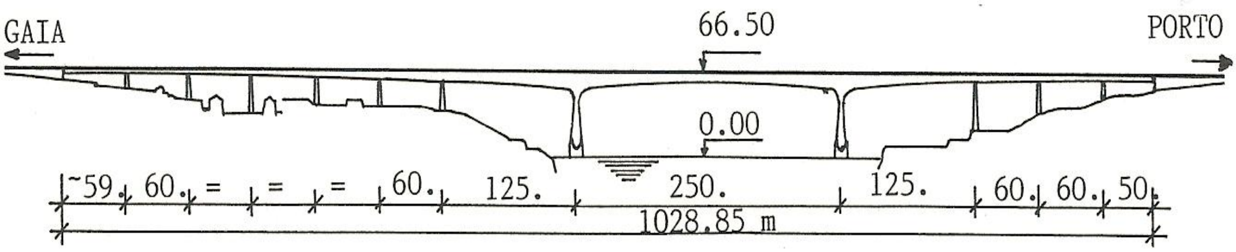

Figure 5. The São João bridge pi-shaped portal frame.

Figure 6. The elegantly shaped tall columns (pylons).

Figure 7. Trial painting tests area (left bank).

In the XIX-th century, the discovery of a new material – reinforced concrete, expanded the technological possibilities of achieving longer spans in bridges and buildings which were almost impossible in previous times. This new material required advanced mathematical theoretical formulations that were verified with laboratory experiments and field tests. The emerging technical schools were the cradle of a remarkable generation of structural designers (see P. L. Nervi [20]).

This new material technological possibilities become a challenge for designers able to combine mathematical skills with construction practice. In Italy, P.L. Nervi (see A.H. Huxtable [1], P. L.Nervi [21]) and R. Morandi (see G. Boaga [6], G. Imbesi et al. [7]) had a successful career both as designers as well as educators. The concepts stated by P. L. Nervi in his textbook "Costruire Correttamente" and the importance of experimental techniques are essential to understand the huge possibilities of structural concrete. The masterworks designed by P. L. Nervi combine a synthetic, intuitive, artistic approach together with the analytical, mathematical and scientific concepts one may say like P.L. Nervi "because they are so true" (see [21]). In the 1930's cooperation between P. L. Nervi and the Politécnico di Milano – Civil Engineering testing laboratories through Prof. Guido Oberti was fundamental. The approach of using reduced scale models to analyze structural behavior was a major tool to verify innovative design solutions. In the following years, other major structural designers also used analogical models to simulate the real behavior. In the 1940's, under the Manhattan project, carried out at the Los Alamos National Laboratory, a strong boost was given to mathematical modeling and machine computation.

In Spain, E. Torroja (see E. Torroja [3], J. A. Fernandez-Ordóñez et al. [10]) combining both mathematical skills with experimental testing to pioneer the design of large span RC shells, bridges, water supply systems. In France, E. Freyssinet and Y. Guyon (see [22, 23]) followed the same trends observed in the other European countries combining strong theoretical backgrounds with singular construction solutions. In Germany, the remarkable bridge engineer Prof. Fritz Leonhardt made an outstanding contribution both as a teacher and as a designer (see F. Leonhardt [5]). In Switzerland, Robert Maillart had unique contributions in the field of bridge design (see D. P. Billington [2], M. Bill [18]). In Portugal, Prof. E. Cardoso (1913-2000) in consonance with other European masterbuilders made creative contributions not only into the aesthetics of his structural solutions, as well as, into the technological and construction procedures to be used (see L. L. Soares [12]). An excellent mathematician and a university bridge designer teacher, he was able to combine a strong theoretical background and sound experimental reasoning with aesthetic concerns regarding the structural systems shape and function. The extensive use of reduced scale models was used, as a natural tool, in large extent in his design office to understand the physical phenomena. The São João Railway bridge was no exception, Figures 2, 3.

3 THE SÃO JOÃO RAILWAY BRIDGE

The 1.03 km long bridge is a portion of a total 4.0 km long new railway link between the cities of Gaia (Devesas) and Oporto (Campanhã) central railway stations. The Douro river crossing is done now at 66.50m above the water level which is 4.00m slightly above the previous crossing with the Maria Pia bridge, see Figures 4, 5, 6 and 7.

Important aspects deserve to be considered: (a) structural safety; (b) aesthetics; (c) economics; and, (d) the scientific knowledge acquired during the bridge design and construction process. The 1983 initial construction cost estimate for the whole project – train stations, railway lines, one tunnel, the São João bridge and several overpasses reached nearly 50.0 mEuro. This value was reviewed and, ten years later (1992), the total amount reached 150.0 mEuro. Several factors contributed to this deviation: (a) unforeseen construction site conditions; (b) improved design specifications that led to change-the-order costs; (c) time delays by poor weather conditions; (d) river floodings; and, (d) in-situ tests.

The π-shaped 1028.85m long portal frame fording the Douro river, 66.50m above the stormy waters. The longitudinal girder made continuous over the main supporting pylons has a 250.0m central span and 125.0m side spans, which makes her one of the longest bridge spans in the world for this type of bridges. On the left bank, Gaia approaching side the girder has one 58.85m and five 60.0m long spans. On the right bank, Oporto side, there are only two 60.0m and one 50.0m long spans, see Figure 5. In plan, the south Gaia approach is partly drawn with a very large radius curve whereas the remaining portion is made straight until the Oporto bank abutment.

4 THE CONSTRUCTION SEQUENCE

The two main pier foundations were located into the Douro river stormy waters, near the river banks, at a variable depth of -10.00m to -20.00m. Difficult ground conditions were similar to those found by G. Eiffel more than one century ago. The immersed pylons solution required the use of 14.00m o.d. steel cofferdams with a contact edge designed accordingly with the underwater foundation survey, which was previously made. After cleaning the deep (gravel, mud) soil layer, the extensively cracked granite rock mass was pinned with 180 micro-piles made with groups of seven 50-mm high-strength steel rebars (f_{sy}= 500MPa). These 10.0m to 20.0m long piles served as connectors between the main piers cast in-situ base foundation and the sound bedrock. Pozzolanic material was added to the concrete admixture in the submerged piers zones subjected to aggressive salt water from high rise Atlantic Ocean tides and flooding from winter dam's discharges.

The main piers with the foundations near the river Douro banks were conceived based on a 12.00m o.d. hollow cylinder intersected by two families of hyperboloids, see Figures 6 and 7. The 1.00m thick reinforced concrete (RC) wall has 1000-Ø25mm high strength steel rebars (f_{sy}= 400 MPa) and, at 45.00m height, the pier section smoothly changes into a "strangled" hollow rectangular section, with 6.70m x 5.00m cross section dimension, reinforced with 1414–Ø25mm rebars. Topping the pier, the 20.0m long twin-cell box girder was long enough to install two 40.0 ton. mobile gantries (form travelers) used to build the girder by the cantilever method, see Figures 8 to 15.

The twin-cell structural concrete variable depth box girder, without any expansion joints along its length, was built by the cantilever construction method. This was the best assembling procedure solution (J. Mathivat [11]): (a) a wide span structure over a deep valley stormy river may require a traditional costly centering and falsework; (b) sudden river rising waters; (c) traffic and river boat navigation limitations; (d) reduction in formwork costs through repetition; and, (e) mechanization of repetitive tasks and improvement in the workmanship.

Figure 8. The construction phase (right bank - Oporto).

Figure 9. The main tall column - 66,50m high.

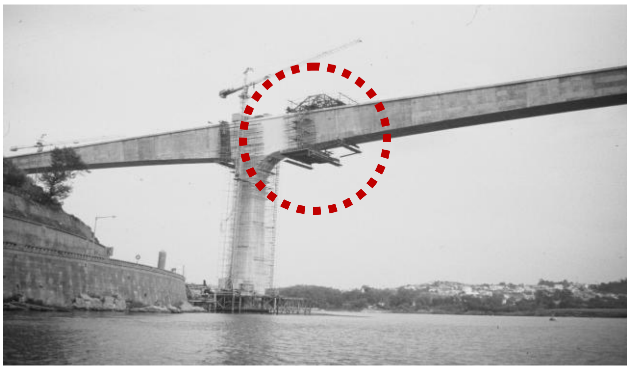

Figure 10. The painting phase from the right bank.

Figure 11. The pylon base after 20 years in use.

Figure 12. The experimental lab (left bank - Gaia).

Figure 13. The test set-up (full-scale).

Figure 14. The support gantry.

Figure 15. The test set up and a trial painted surface.

The main girder was built with seventeen pairs of cast in-situ segments, built simultaneously from each side of the main piers. They had slightly different geometric dimensions which had to be accommodated by the gantries suspended formwork. The segment height varied from 12.00m near the main piers down to 7.00m at midspan, whereas the length increased from 5.00m up to 7.50m. The first segments near the main piers weighted nearly 600 ton., whereas the weight reduced to 300 ton., near the midspan region. Each newly cast segment was longitudinally prestressed with three pairs of 5.000 kN, one pair in each web, high-strength prestressing steel bonded cables against the previously built segment. The use of temporary steel shoring along the river banks was deemed necessary under the girder, to control excessive deformations, to perform some deformation's adjustments and to resist exceptional construction site overloads. The 6.00m central span closing segment, before the final casting had the two end sections pushed apart with hydraulic jacks that applied a 4000 kN (400 ton) "autocontrainte" (prestressing) force, being removed afterwards.

The girder 12.00m wide cross section has the deck slab placed 1.25m below the flanges top fibers in order to protect a train after derailment to fall down into the river waters and the protruding web guards also increase the cross section moment of inertia. The balastless rail tracks are continuously bolted to the top slab deck along the 1028.85m girder length without any expansion joints, except at the abutments.

5 AESTHETICS AND COLOR NEEDS

The designer always considered that every bridge deserved to be considered to an *oeuvre d'art*, and every location has its own adequate bridge solution. The first concept, is strongly dependant on the designer's capacity to "project" his own values into the environment where he acts. The relation between the object, the location and the designer can only be achieved into the superior state of an *oeuvre d'art*, depending on several factors, e.g., creativity, imagination, knowledge, experience and a strong will. The role of poetry is unquestionable, (see M. Heidegger [14]). The adopted color is not a simply layer of coating but it is a major statement that enhances several aspects that must serve as guidelines: (1) the iconic content; (2) the tectonics of structural concrete as a plastic, mouldable material; (3) the site/landscape integration; (4) the functional / sustainable construction; and, (5) the economics. The careful observation of this *oeuvre d'art* within the sprawling river Douro at this singular location leads the observer to a moment of silence where the work speaks by itself, (see [M. Rohtko [13], N. E. Johnson [19]).

Prof. E. Cardoso often mentioned the São João bridge was designed to be painted with the color of the sky – a light grey-blue color. This color is quite a challenge for a major construction and several tests were carried out, see Figures 7 and 15. The study of color and its interaction with the built environment and a strong background is required (see F. Birren [4], J. Albers [9]), The main advantages are related with the smooth finished concrete surface, instead of the uneven tainted surface resulting from different construction phases and concrete admixture's designs. The heat absorption capacity is also greatly reduced as for a thermal 50^0C gradient a length variation of 0.50m to 0.60m may be expected. The protection against chloride attack under an aggressive humid environment can be obtained by adding a rubber water solution base to the pigments.

After twenty two years of intensive continuous use the designer's premonition that an *oeuvre d'art* was being built has been attained. Every citizen or visitor passing along the river Douro shores is surprised with its original design, the member's slenderness and the powerful aesthetic message for the incoming generations.

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