

**Zeitschrift:** IABSE congress report = Rapport du congrès AIPC = IVBH  
Kongressbericht

**Band:** 14 (1992)

**Artikel:** The new Oporto railway bridge

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**DOI:** <https://doi.org/10.5169/seals-853193>

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## The New Oporto Railway Bridge

Le nouveau pont de chemin de fer à Porto

Die neue Eisenbahnbrücke in Porto

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### SUMMARY

The 114-year old Maria Pia iron bridge designed by Gustave Eiffel became inadequate for meeting increasing railway traffic needs in the Douro river crossing. The 1991 new Oporto double-track structural concrete bridge designed by the Portuguese engineer Prof. Edgar Cardoso meets the most stringent requirements of structural safety, aesthetics and efficiency.

### RÉSUMÉ

Par suite de la croissance du trafic ferroviaire sur le fleuve Douro au cours des dernières décennies, le vieux pont de chemin de fer Maria-Pia, projeté par Gustave Eiffel, s'avère insuffisant. Conçu par l'ingénieur portugais Edgar Cardoso, le nouveau pont en béton précontraint à double voie, construit en 1991, répond aux exigences actuelles fort rigoureuses en matière de sécurité, d'esthétique et de capacité.

### ZUSAMMENFASSUNG

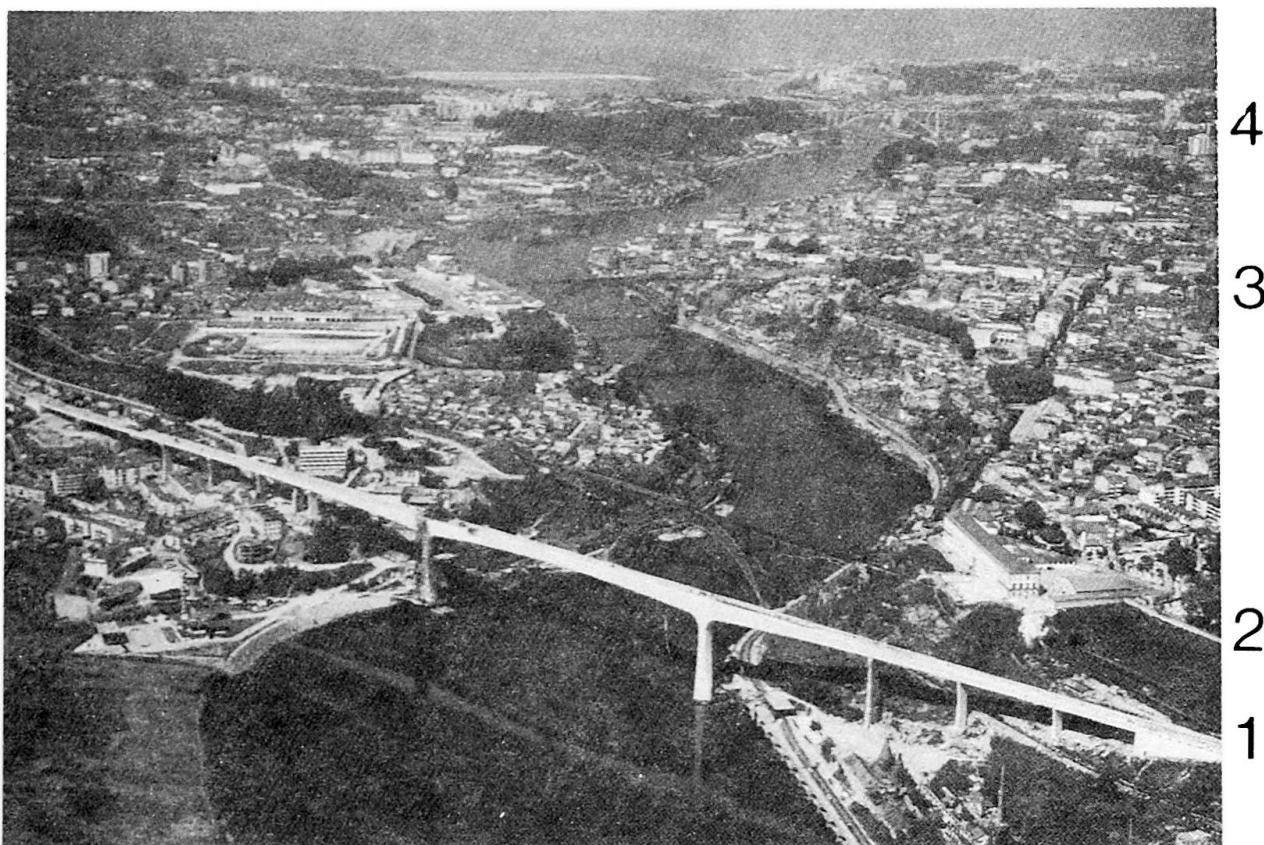
Die 114-jahre alte, von Gustave Eiffel entworfene Maria-Pia-Eisenbahnbrücke ist durch den wachsenden Eisenbahnverkehr über den Douro unzulänglich geworden. Die 1991 neu erbaute, doppelspurige Spannbetonbrücke, von dem portugiesischen Ingenieur Edgar Cardoso entworfen, vereint die strengsten Anforderungen in bezug auf Sicherheit, Ästhetik und Leistungsfähigkeit.



## 1. INTRODUCTION

In the North of Portugal, between the cities of Oporto (north bank) and Gaia (south bank), flows the river Douro whose crossing represents a great challenge to structural bridge engineers.

In 1991, with the addition of a fourth railway-type bridge to the already existing railway and highway bridges, a major improvement in the north-south communications network has been reached. This new railway bridge represents one of Prof. Edgar Cardoso finest designs in his 55-year long successful career as a bridge engineer.



- Legend: 1 - New Oporto Railway Bridge (1991), Prof. E. Cardoso;  
 2 - Maria Pia Railway Bridge (1877), Gustave Eiffel;  
 3 - Luiz I Roadway Bridge (1886), Theophyle Seyrig;  
 4 - Arrábida Highway Bridge (1963), Prof. E. Cardoso.

Fig. 1 - Aerial View of the Oporto-Gaia Bridges.

The other three bridges are: (a) the 1877 railway iron arch bridge designed by Gustave Eiffel; (b) the 1886 roadway twin-deck iron arch bridge conceived by Theophile Seyrig; and, (c) the 1963 reinforced concrete arch highway bridge designed by Prof. Eng. Edgar Cardoso.

Among the four bridges of Fig.1, only the first and the second one which are of the same railway type are studied. The limitations and solutions the two bridge masterbuilders faced more than 100 years apart in the design and construction of these two major civil engineering public works will be shown with particular emphasis on the New Oporto Railway Bridge.

## 2. THE 1877 GUSTAVE EIFFEL MARIA PIA BRIDGE

In 1875, the Royal Portuguese Railroad Company organized a major European bridge

design competition for the Douro river railway crossing between the cities of Gaia and Oporto. The winner was the 43-year old French engineer Gustave Eiffel. The solution presented to the committee consisted of a single steel arch hinged at the abutments and with the maximum span of 160.00 m and the total height of 62.40 m, Fig. 2, [1, 2].

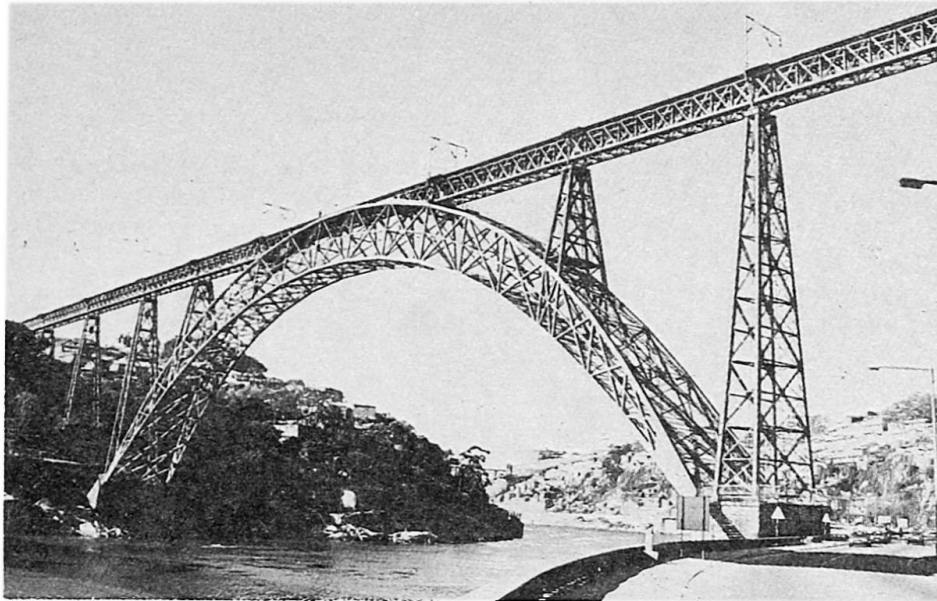


Fig. 2 - Gustave Eiffel 1877 Maria Pia Bridge.

The bridge has a total length of 352.75 m, the straight trellis girder is supported by piers whose height varies according to the ground. The girder deck is divided in three parts : (1) the Gaia flanking deck, 169.87 m long, supported by the masonry abutment, the two ground based iron piers, the two piers fixed to the arch extrados, and the arch; (2) the 51.88 m long central deck integral with the arch; and, (3) the 132.50 m long Oporto flanking deck with support conditions similar to Gaia side.

The estimated 965,000 French francs price was 46% less than that of the second-placed competitor, the well-known Fives-Lille Co. - 1,410,000 francs. The difficulties arising from this construction project were enormous: (1) the water depth in the V-shaped granite valley could reach easily 20.0 m; (2) the frequency and extent of flooding during the winter season; (3) the high gravel soil depth covering the bedrock; and, (4) the very rapid swirling currents. The logical design was a single iron arch, hinged at the masonry abutment supports. During the construction phase, each arch portion rising from the river banks was moored with temporary steel cables until both parts met and the arch was closed.

In this project, G. Eiffel noticed that two major design 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 danger of train derailment and the bridge had no accident stop barriers. In G. Eiffel improved design of the 1881 Gabarit viaduct, the railway trellis girder was made continuous from one abutment to the other, and the rail track was placed 1.66 m below the upper flange girders plate to encase the train during a major derailment situation.

The Maria Pia bridge project made Gustave Eiffel, at the age of 46, the leading bridge engineer in Europe and gave his relatively young construction company widespread reputation.

The 1902 progressive renovation of the Oporto-Lisbon one-track into a twin-track line created major traffic constraints on the use of the Maria Pia bridge.



The other two major limitations were the maximum speed of 20 km/h and the load, a 160 kN concentrated load per axle and a 38 kN/m uniformly distributed load. Therefore, a new railway bridge became a must in the North-South railway link and, in the early 1980's, the Portuguese Government agreed to a new bridge construction project along with major improvements in the Great Oporto Metropolitan Transit Network.

### 3. THE NEW OPORTO RAILWAY BRIDGE

#### 3.1 The New Requirements

The 1.03 km long bridge is part of a 4.0 km completely new railway line linking the Gaia-Devesas to Oporto-Campanhã central railway stations. The Douro river crossing is done at a 66.50 m height which is slightly above (4.0 m) the Maria Pia track, Fig. 3.

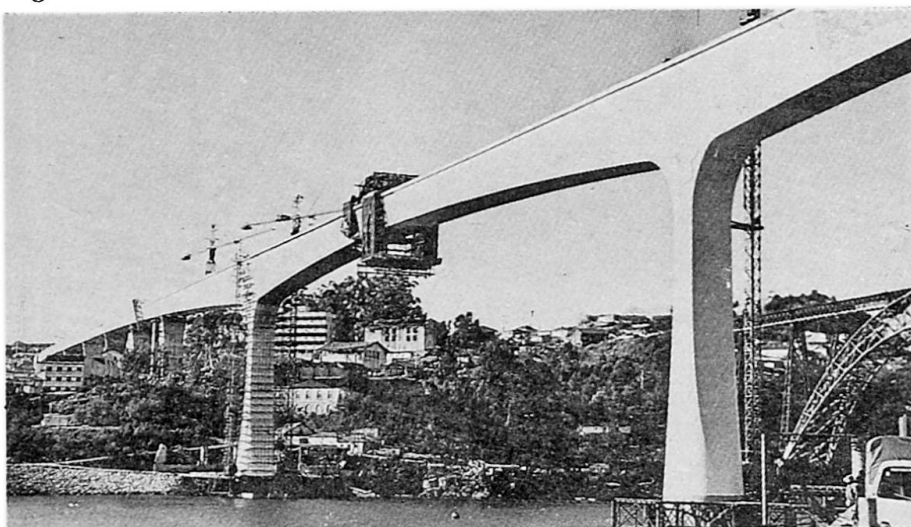


Fig. 3 - The New Bridge near its Completion in 1990.

At a total cost of Esc. 26,000. million (US \$ 175. million), the new 4-km long rail track and the other public works which include the bridge have to meet modern requirements: (1) a high daily traffic volume of 400 trains/day; (2) a high speed twin-lane circulation of 120 km/h; and, (3) the substantially heavier loads of 250 kN concentrated load per axle and 80 kN/m uniformly distributed load. Other important aspects that needed to be considered were: (1) structural safety; (2) aesthetics; (3) economics; and, (4) the scientific knowledge acquisition process during the bridge design and construction phases.

#### 3.2 The Bridge

The bridge's general layout consists of a single structural concrete 1029 m long twin-cell box girder monolithic with the two 50 m tall main piers, Figs. 3 and 4.

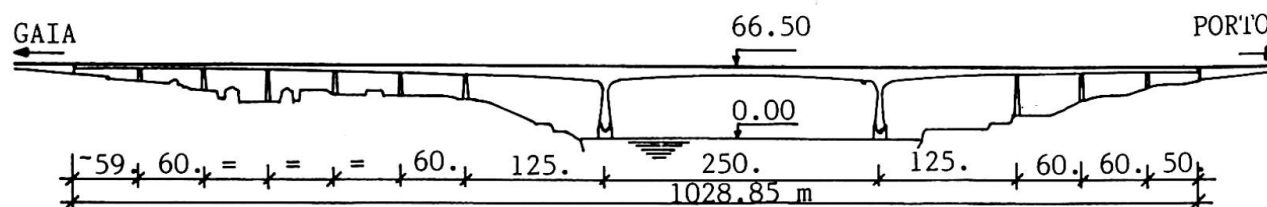


Fig. 4 - Bridge Side Elevation.

The grandiose  $\pi$  - shape portal with a continuous girder over the supporting piers has a 250 m. long main span and 125 m. long side spans. On the left bank (Gaia) approaching side, the girder has one 58.85 m and five 60.00 m long spans



and on the right bank (Oporto) side has only two 60.00 m and one 50.00 m long spans. In plan, the Gaia approach is partly made with a very large radius curve and the remaining portion is made straight until the Oporto bank abutment.

### 3.2.1 Bridge Foundations

The two main pier foundations were located in the water near the river banks at a variable depth of -10 to -20 m. Difficult ground conditions were similar to those found by G. Eiffel 114-years ago. Prof. Eng. Edgar Cardoso solution required the use of 14. m o.d. steel cofferdams with a contact edge shaped accordingly to the foundation profile. After cleaning the deep (gravel, mud) soil layer, the cracked granite rock mass was pinned with 180 micro-piles made out of five 50-mm diameter high-strength steel rebars ( $f_{sy} = 500$  MPa). These 10 - 20 m long piles served as connectors between the base of the cast in-situ concrete main pier and the sound bedrock. Pozzolanic material was added to the concrete mass for better salt resistance in the submerged main pier section.

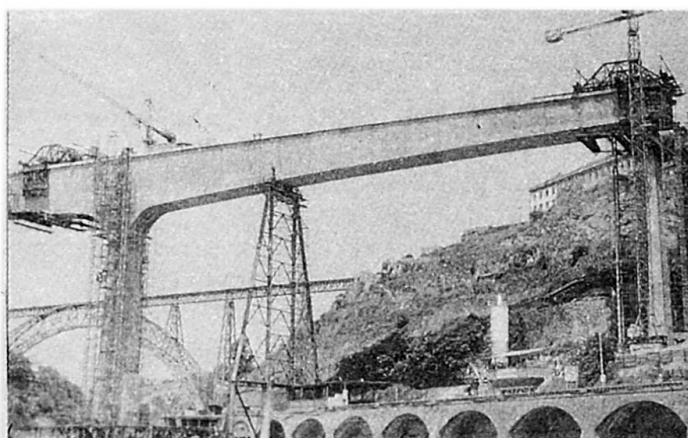
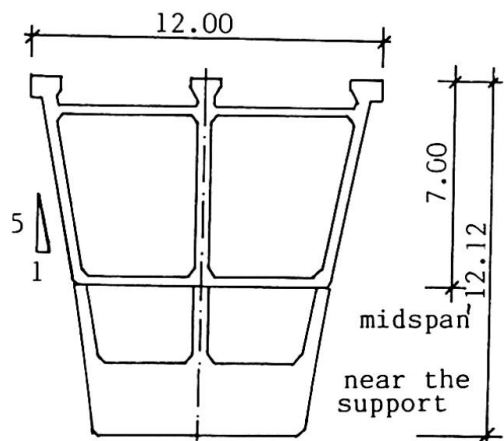
### 3.2.2 Main Piers

The highly aesthetic and functional main piers resulted from the intersection of two families of hyperboloids with the base cylinder, Fig. 3. The 12. m o.d. hollow cylinder has nearly constant 1.0 m thick walls and the cross section smoothly changes into a "strangled" hollow  $6.70 \times 5.00$  m square at 45.0m height. Topping the pier, the initial hollow box girder was cast wide enough (20.0 m) to install two 40 ton. mobile gantries needed to build the main girder.

### 3.2.3 Main Girder

The twin cell box girder was built by the cantilever construction method which was the best solution for this restraints [3] : (1) a wide span structure in a deep valley (costly centring and falsework); (2) sudden flow rivers; (3) automobile traffic and boat navigation limitations; (4) reduction in formwork costs; and, (5) mechanization of repetitive tasks and improvement in workmanship.

Each one of the 17-pairs of cast in-situ segments, built simultaneously from each side of the main piers, had different geometric dimensions which had to be accommodated by the gantries' suspended formwork. The segment height varied from 12.0 m near the main pier down to 7.0 m at midspan, whereas the length increased from 5.0 to 7.5 m. The first segments weighted 600.0 tons decreasing to approximately 300.0 tons near the midspan. Each newly casted segment was longitudinally prestressed with three pairs of 5,000 kN high-strength prestressing steel cables against the previous built segment. Along the river bank, temporary steel frame shoring was used underneath the girder arm to control exceptional overloads and to perform some deflection adjustments, Fig. 5 - a, b.



a. Girder Cross Section.

b. Temporary Steel Frame Shoring.

Fig. 5 - Main Girder Characteristics and Shoring Details.



The central span closing segment was 6.0 m long and before the final cast was done the two end sections were pushed apart with hydraulic jacks with a 4,000 kN autocontrainte (prestress) force.

The girder 12.0 m wide cross section has the deck slab 1.25 m below the flanges top fiber, Fig. 5 - a, to: (a) protect on a derailment; and, (b) increase cross section moment of inertia. The rail balastless tracks are continuously attached along the 1029 m girder length.

### 3.3 Other Improved Technical Solutions

A full-scale model test including three pairs of 5,000 kN longitudinal prestress cables per web, showed that box girder web cracking would arise if special construction measures weren't adopted, such as: (1) vertical web prestressing with unbonded tendons; and, (2) longitudinal structural steel tubing as prestress ducts. These tubes were considered as passive reinforcement in the strength calculations. For deflection control, Prof. Edgar Cardoso used external cables prestressed inside the 500. m main box girder hollow section so that the train live load could be compensated.

## 4. CONCLUSION

Spanning in time more than 110 years, the construction of the two Oporto railway bridges represent first achievements in the art of bridge engineering. The Maria Pia (1877) iron arch bridge built by the French engineer Gustave Eiffel was one of the greatest contributions to the people's welfare by the Industrial Revolution iron masterbuilders. Excluding the suspension bridges, the Maria Pia bridge 160.0 m span made it one of the largest by that time, along with the Britannia bridge (140.0 m), the Kuilenbourg bridge (150.0 m), and the Saint Louis bridge over the Mississippi (158.5 m), [2].

The 1991 New Oporto Railway Bridge with the gracious  $\pi$ - shape multi-span portal frame designed by the foremost Portuguese bridge engineer, Prof. Edgar Cardoso, represents his culminating effort and knowledge in the field of structural concrete. For a box girder railway bridge, the 250.0 m central span, makes it one the largest spans existent in the world. The difficult site conditions, space limitations required technical solutions that were not common in current bridge design and construction.

Both bridges - one in iron and the other in structural concrete - are excellent civil engineering contributions to human progress as they bring together people separated by a tempestuous river.

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## AKNOWLEDGEMENTS

The author would like to express his sincere thanks to Prof. Eng. Edgar Cardoso for his most important comments made during the inumerous construction site visits. The assistance of the Technical University of Lisbon is also gratefully acknowledged.