# OBTAINING LIGHTWEIGHT STRUCTURES WITH THE LOAD PATH METHOD

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## Abstract

The dead weight of a structure can be used as a measure of quality, for comparison of different solutions for the same purpose at a given site.

The “load path method” [1] can be used to discover new structural shapes and to develop lightweight structures from existing shapes, by visualizing and understanding the most important flow of forces through a given structure. Two examples are discussed.

In the “Cais das Pedras” viaduct project, located in the historical centre of Porto in the north of Portugal, light weight has decisively conditioned conceptual design. A short presentation of the structure currently under construction is made.

## 1. Introduction

The dead weight of a structure should be considered one measure of its quality, especially in urban areas, where every new construction is a “constraint” to the environment of the residents. Some masterpieces built in the past, such as the Maria Pia bridge over the Douro (Eiffel - 1877) demonstrate visual elegance that somehow has been lost.

In the case of bridges, the measure should be the mean weight per unit length. As an example, the dead weight of the five existing bridges near the historical centre of Porto (World Heritage) are compared in the following table. The first case is remarkable, being a railway bridge which was used for more than a century until it was substituted by the S.João bridge.

| Bridge - Date | Type / material | Length | Dead weight | Relative weight |
|---|---|---|---|---|
| D.Maria Pia - 1877 | Metallic arch | 400 m | 1500 ton | 37 kN/m |
| D. Luis I - 1882 | Metallic arch | 400 m | 2900 ton | 71 kN/m |
| Arrábida - 1966 | Concrete arch | 500 m | 48000 ton | 940 kN/m |
| S. João - 1991 | Concrete frame | 500 m | 40000 ton | 780 kN/m |
| Freixo - 1994 | Concrete frame | 700 m | 54000 ton | 760 kN/m |

Table 1 - Weight of the bridges of Porto, without foundations (approximate values)

In the case of low viaducts in cities, light weight should constitute a main objective. In Table 2, the deadweight of two solutions for a 7.0m wide automobile road are compared.

The upper plate is a relatively thin element, even when made with concrete. The lower webs create a much larger visual constraint.

The webs, the lower chord and the lateral walkways can be metallic and lightweight, giving transparency to the whole and reducing the size of the piers.

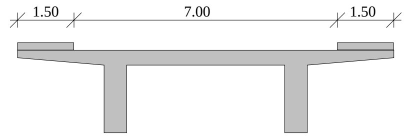
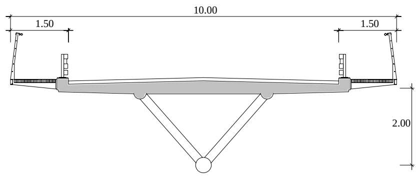
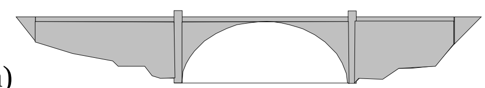
| | |
|---|---|
|   | 150 kN/m |
|   | 90 kN/m |

Table 2 **-** Transversal section and dead weight of two viaduct decks

The concern with economy of costs and resources was always a "leitmotif" to the discovery of new structures, and the case of the Maria Pia bridge, a century ago, seems to be a good example. The need for a railway bridge over the Douro was the reason for the first classical project, based on a opaque masonry stone arch (Figure 1a). Fortunately for the people of the city, Mr. Eiffel proposed a different and new solution for that time (Figure 1b) which has been “working” for more then hundred years with a unique transparency and lightweight.

a) 

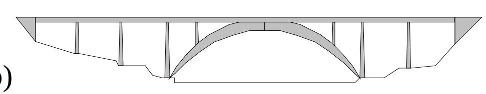
b) 

Figure 1 **-** Evolution of concepts in the past (around 1870) (Maria Pia Bridge in Porto)

The challenge of today, when powerful means of production and transportation of heavy loads are at our disposal, is not to behave like “a bull in a china shop"! The actual reasons to reduce weight have much to do with concern on reducing the visual impact of constructions on the environment.

## 2. Understanding structures

In order to efficiently lighten a structure, a profound knowledge of its internal behaviour is needed, with a clear identification of fundamental and secondary zones.

Drawing the load path [1] through a structure with a given form gives an overall view of the problem and can be used to identify fundamental zones, thus orienting the change of shape in a optimisation process.

The field of the stress vectors in planes oriented normally to a given direction X, represents also the velocity of the flow of “force with direction X” (which can be thought of as a fluid in this context). Usually, the most interesting cases are the flow of given external forces with at least two different orthogonal directions.

### *2.1. Evolution from a wall to an arch*

In the case of a cantilever wall with distributed vertical forces on the top, Figure 2 shows the flow of vertical and horizontal forces. The horizontal forces circulate in the interior of the wall because there are no external loads or reactions with that direction.

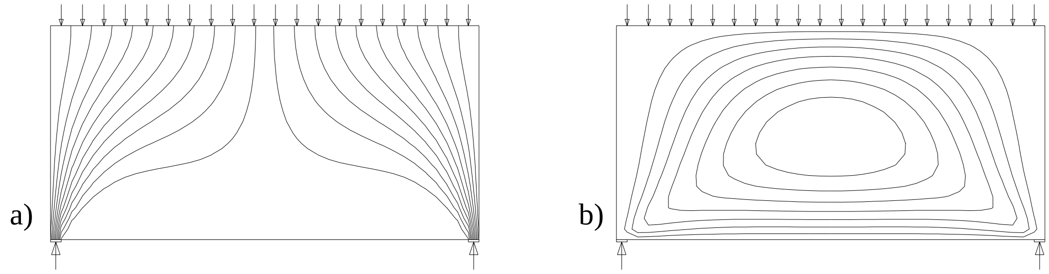



Figure 2 - Load path of vertical (a) and horizontal (b) forces in a cantilever wall

Analysing the same wall with other boundary conditions, i.e. with horizontal fixed supports, the flow of horizontal forces changes completely, as can be observed in Figure 3, when compared with Figure 2.

The lower zone of the wall has then practically no structural function and can be supressed, an arch beeing formed. The upper zone, over the arch, has also a characteristic behaviour, bringing the vertical forces from the top of the wall to the arch, a role which can be taken by small discrete columns as in Figure 1b), making the full wall unnecessary in that zone.

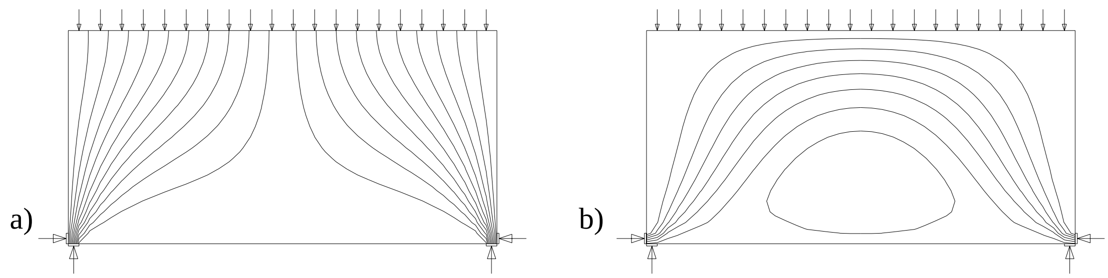



Figure 3 - Load path of vertical and horizontal forces through a wall with fixed supports

*2.2. How to lighten a beam*

With the aim of interpreting the behaviour of a beam, two cases were analysed with software written by the author: a cantilever beam and a continuous two-span beam, loaded with distributed vertical forces (Figure 4).

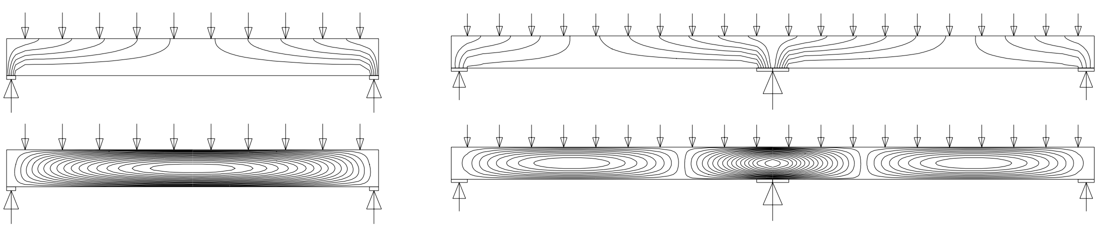


Figure 4 - Load path in beams

The lines in the figures characterise the flow of forces and were drawn under the following rule: between any two adjacent lines flows the same and constant quantity of force. In the chosen examples, the beam section is 1.0m high, the spans L=10.0m and the loads q=100kN/m. The force quantity between any two lines is 100kN.

The flow of horizontal forces is much more intense than the flow of vertical forces as can be observed by the proximity of the flow lines in the zones of the upper and lower chords, especially in sections in midspans and over the supports. Based on this fact, it can be concluded that it is possible to lighten the web of a beam, in order to exploit the material in the web in a similar way as used in the chords.

For a rectangular section, the evolution is to an “I-shaped” section, or even better, by substituting the full web between the chords by an equivalent truss, as it was recently done in the structure of a “nose” used to build viaducts by the “incremental launching process” (Figure 5).

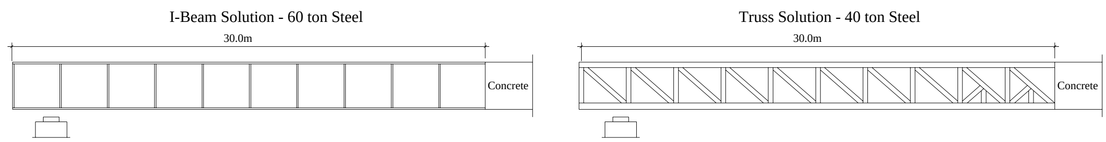



Figure 5 - Two solutions for the “nose” used in the incremental launching process

In the beams of Figure 4 it can be seen that the flow of forces in the web, both vertical and horizontal, is not linear but shows curvature, which means that they interact with each other. From this interaction follows the need for a bidimensional web or an equivalent triangular truss. In the chords the flow of vertical forces is practically non- existent, and only straight elements are needed, to bring horizontal forces together.

A detailed analysis of the support zones shows that the flows of horizontal and vertical forces are straight (linear) and thus independent, i.e. they do not interfere with each other. The beam can be vertically supported at any level of the section, wherever it is more convenient for conceptual, detailing and assembly purposes (Figure 6).

a) b)

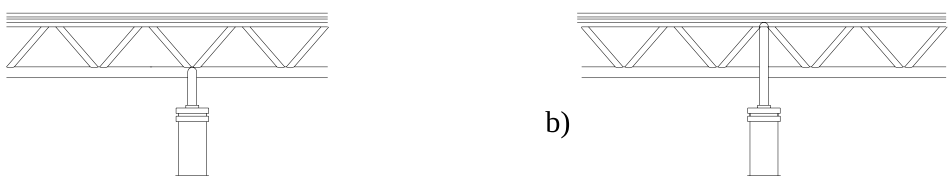


Figure 6 - Two solutions for the support of a truss beam

## 3. The “Cais das Pedras” viaduct

### *3.1. Location and conditions*

In order to preserve the ancient harbour “Cais das Pedras” in the historical centre of Porto, it was decided to build a small viaduct, to improve traffic flow conditions and pedestrian safety on the riverside road along the Douro. The new bridge offers a surprising vantage point over the old harbour and interesting surrounding buildings, such as the “azulejos” of the Massarelos church.

The viaduct is 400m long, situated at a low level about 6 m over the mean water level between tides. In a plan view, it describes a large curve (R=330m) in front of the harbour and has a total width of 10m (7m for the automobile road with walkways of 1.5m on either side).

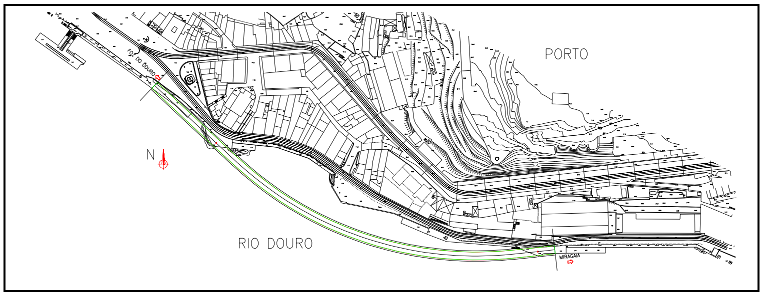



Figure 7 - Plan of site

The old street will be used by people who will see the viaduct when looking towards the river and thus the situation is aesthetically delicate, since any obstruction of the view over the Douro would not be acceptable.

The Douro river has an irregular regime and severe winter flooding has occurred in the past, submerging the zone where the viaduct is now located. The potential for flooding and the possibility of collision by ships were also important conditions to the project.

*3.2. General characteristics of the solution*

The 400m length is subdivided into 12 spans with about 35m each, in order to reduce the number of columns and foundations in the river, and to utilise a transversal section not higher than 2m, giving a 2m clearance under the viaduct at high tide.

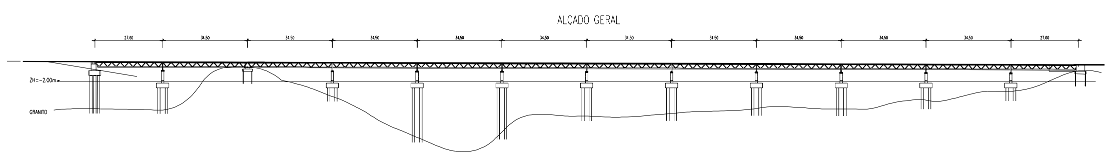



Figure 8 - Side view of the viaduct

Due to the relatively low level over the river, a section with a constant height was chosen, with chords parallel to the water.

Instead of a full concrete solution, a mixed steel-concrete structure was chosen. The upper chord is a concrete plate, and the other elements (lower chord, web-diagonals and lateral walkways) are metallic trusses made of CHS Fe510 steel.

The dead weight of the structure is about 90kN/m as shown in Table 2. The lower eigen frequency of the structure is about 2 Hz.

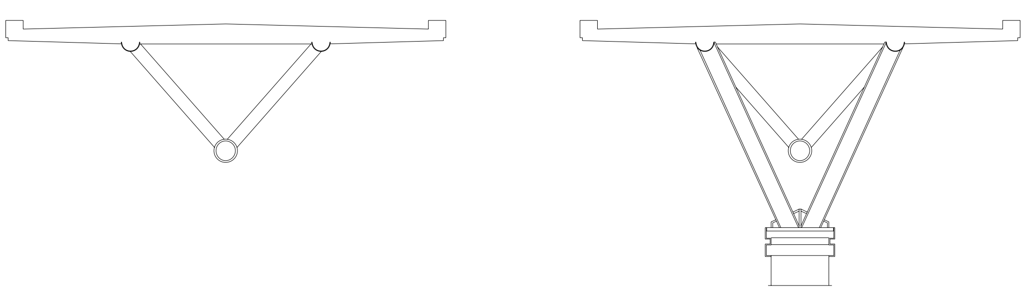


Figure 9 - Transversal span and support sections

One of the most characteristic aspects of the structure is the form of the link between the main truss and the piers, independent of the lower chord. The reasons for this form are associated with the considerations described in 2.2 and are due on one hand to the simplicity of the construction of the lower chord and on the other to a better support for torsion effects. The link between piers and lower chord was planned in the early stages of the project, but then abandoned because of the complexity of the node, which would be critical in terms of resistance and construction difficulty for local conditions.

*3.3. Actions*

The critical actions which have conditioned the dimensions and the strength of the structure were primarily the vertical Code loads, associated with the shrinkage effects and temperature. The horizontal critical loads were those due to the impact of a 2000 DWT ship.

To quantify the hydrodynamic water actions, a mathematical model of the Douro was used, calibrated for the zone between the Crestuma dam and the Atlantic ocean. Statistically, in a period of 500 years, there is the probability of a flood which would give a flow of 22500 $m^3/s$ with a max. velocity of 4.5 m/s and an upper level of 11.5m above the mean water level (about 5.5m above the viaduct).

The submersion effect was not critical due to the special situation of the viaduct. The centre of the viaduct practically follows the direction of the water flow and the structure is fixed in both abutments to a granite foundation. Damage to the side walkways in case of accident will be acceptable.

The normal flow of the Douro is a dynamic action to the piers. The formation of vortices in a turbulent regime is a dynamic process with a frequency much lower then the eigenfrequency of vibration of the piers. These piers have piles as foundations, which are fixed to the granite bedrock.

*3.4. Behaviour of the structure under the action of eccentric loads*

The “V” form of the web reduces the need of supports to a line of piers under the centre of the viaduct, but implies a much more elaborate conception of the equilibrium for eccentric loads as well as transversal tension effects on the upper concrete plate.

The fundamental elements in the conception of equilibrium are:

a) The triangular space frame with high torsional strength;
b) The “V-shaped” piers fixed at the base;
c) The concrete upper plate, which functions as a horizontal arch fixed at both ends.

The space frame guarantees equilibrium between piers. Then, there are two different possible equilibrium systems, which provide a certain redundancy, which is favourable in terms of global safety. The general schemes are shown in Figure 10.

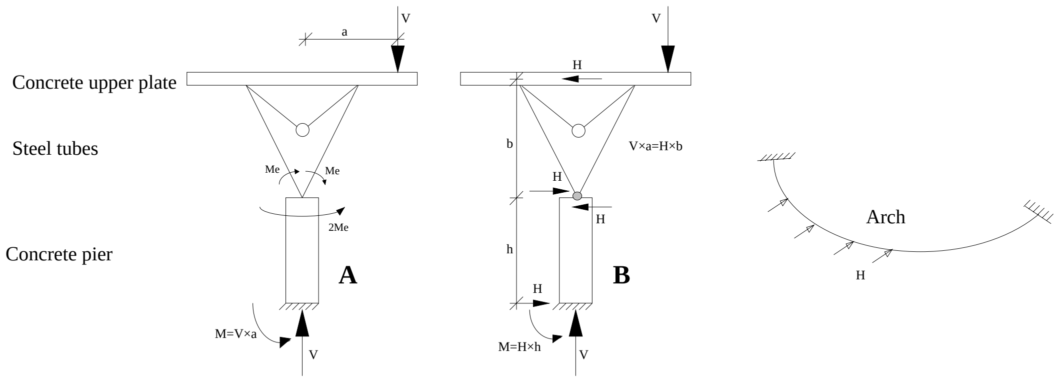



Figure 10 - Equilibrium for torsion effects. Mechanisms A e B

The steel tubes of the upper part of the piers are continuously fixed to the concrete lower part and have a high bending strength (mechanism A). The high axial and bending rigidity of the horizontal concrete arch, enable an equilibrium based on a couple of horizontal forces (mechanism B), where the upper forces are conducted by the arch to the abutments and the lower ones by the piers to the foundations.

*3.5. Construction*

The decision to build the viaduct was associated with the preparation for an important summit of Iberian and Latin-American states scheduled for 98.10.17, and the viaduct had to be built in only 5 months.

The structure was first planned to be fully pre-fabricated in 12 separate parts, which would be coupled *in situ*, one span per week. For cost and planning reasons in the special market conditions in Portugal, the steel structure was redesigned with a steel upper chord and put in place span by span. The concrete plate was then cast in place. The total cost of the viaduct was about 4MEuro, i.e. 1000 Euro/m2.

**4. Conclusions**

A criterion to compare alternative structural solutions, based on the dead weight, is proposed to make decisions on the quality of structures. Low weight means high quality, especially in the case of bridges.

A procedure is described to understand the internal structural behavior, that can be used to lighten structures. Examples of application to arches and beams are given.

The “Cais das Pedras” viaduct is presented, built in the historical center of Porto - Portugal, an area classified as World Heritage by UNESCO, and in which light weight and transparency were the basis of conceptual design. Instead of a 2m high full concrete beam, a composite structure was adopted, with an upper concrete plate and a lower steel truss made of circular hollow sections. The concrete plate thickness of 0.30m was found acceptable by the project team of engineers and architects.

[1] Fonseca, J., “Zum Bemessen und Konstruieren von Stahlbetonplatten und -scheiben mit Lastpfaden” (On the Design and Detailing of Plates and Walls of Structural Concrete with Loadpaths), Thesis, University of Stuttgart, 1995 (in German).

[2] Revista de Obras Públicas e Minas - Setembro e Outubro de 1881 (in Portuguese)