PLAYING STRUCTURAL EFFICIENCY WITH ARCHITECTS

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Summary

This paper describes the experience of working together with architects in the design of footbridges where aesthetics and structural efficiency are intrinsically linked.

It is quite common to say that the deep understanding of the function and the location (physical and human environment) dictate the form of a bridge. In the specific cases presented in the paper, the particularities of several footbridges where the main advantages of their structural behaviour came from the symbiosis between architectural and structural conception, are emphasized. In some details, it can be said that the aesthetic choices intuited the good structural behaviour. As in other cases, it was the structural optimization that became the reason of the aesthetic options. Several examples are listed to illustrate this story where global structural response (longitudinal and transversal), static and dynamic behaviour, stiffness and resistance, cross section definition and structural material choice are discussed.

Aesthetics of the given examples result from architectonic concepts that reflect structural demands and physical laws and that aim at optimized structures.

Keywords: Conceptual design; aesthetics; structural efficiency; architects.

1. Introduction

The classical discussion about the necessity and the consequences of Architects' presence in the design of bridges, especially footbridges, is far from being over. It is usual to argue that pedestrian bridge projects, when led by architects, often lead to illogical solutions from a structural point of view, with lack of efficiency and therefore with obvious economic disadvantages.

However, it is undeniable that aesthetic and landscape integration considerations are of prime importance in the design of pedestrian bridges, because of their scale and proximity to their users and to the urban environments in which they are located.

Like any other human construction, footbridges imprint indelible marks on the landscape, definitively altering the natural or built environment where they are inserted. More, a pedestrian bridge has a special relationship with its users, for whom the bridge itself can be even a destination, rather than a means to reach it. Strolling calmly on a bridge allows not only a much more complete interpretation of its technique but also a better appreciation of its most exquisite details.

The design of the non-structural elements (parapets, pavement or recreation equipment, if any) in the bridge and in its accesses or the choice of finishing and lighting solutions are examples of "fields" where the need for specialized intervention of other technicians beyond structural engineers is unquestionable. In this context, architects have come to play an increasingly important role.

But also at conceptual design stage, collaboration with architects is admittedly welcome. The classic view that "there can be no doubt that any manmade product of great efficiency will also be aesthetically satisfying" [1] or that "when the bridge structure represents - with simplicity, functionality, in harmony with its surroundings - the flow of the forces to which it is called, and transfers them gracefully to the ground, the bridge inevitably has an aesthetically pleasing character " [2] is, nowadays, quite debatable if it is understood in a 'closed' or 'too technical' way. It is interesting to note that both authors of [1] and [2], despite their call for mechanical efficiency, have always included in their bridge designs a very strong sense of cultural and social care for aesthetics far beyond simple structural functionality.

In fact, as Fernández Ordoñez [3] sustains, "no greater mistake could be made than to subordinate beauty to technical aspects or to think that a perfectly functional bridge is necessarily beautiful". It is true that the tendency toward cool rationalization may lead, in an extreme case, to a product that does not fit human needs and aspirations [4]. Fritz Leonhardt [5] sums up this conflict with a rather simple explanation: "the often cited rule that form follows function is misunderstood if function is defined only structurally".

In this context, collaborative work between Structural Engineering and Architecture since the initial design phase allows, with certainty, to give "other dimensions" to the project of pedestrian bridges.

We can always say that it is the deep understanding of the function and the location (physical and human environment) that dictates the form of the designed object – the bridge. In the specific cases presented in the paper, the particularities of several footbridges where the main advantages of their structural behavior came from the symbiosis between architectural and structural conception, are emphasized. In some details, it can be said that the aesthetic choices intuited the good structural behavior. As in other cases, it was the structural optimization that became the reason of the aesthetic options.

In the following items, the experience of working together with architects in the design of footbridges where aesthetics and structural efficiency are intrinsically linked is described.

2. S. Pedro Creek Footbridge in Aveiro, Portugal

This project was developed together with prominent architect João Luís Carrilho da Graça (www.jlcg.pt) between 1997 and 2000 and the construction took place in 2002.

Aveiro, a town on the Atlantic coast, has a landscape unique in Portugal. The delta of River Vouga forms a large bay that is almost entirely surrounded by land. The landscape is very flat, so the whole area is in effect a large flood plain. The Bridge over the São Pedro Creek for pedestrians and bicycles joins two parts of the campus of the University of Aveiro, the 'old zone' of Santiago with the 'new zone' of Agra do Crasto.

The intention was to introduce a bridge with minimal visual impact. The bridge was designed so that the crossing of the estuary would be done delicately.

The bridge is 330 m long overall and has 10 spans, the majority of which are 36m. The end supports are in concrete and they also support the concrete ramps, the intermediate supports are slender steel trestles. The deck of the bridge is a reinforced concrete slab spanning 4m supported by 4m deep steel trusses. The bottom members of the trusses are I sections with the rest of the members being square tubes.

The objective of the Architect was to use a structural criterion in the definition of the lattice architecture. For this reason, the design of the structure was formulated as an optimization problem in which the objective function to be minimized is the cost of the solution, which in this case was considered proportional to the volume of material used in the lattice bars. For architectural reasons, it was imposed that all bars had the same external cross-section but with different wall thicknesses. [6]

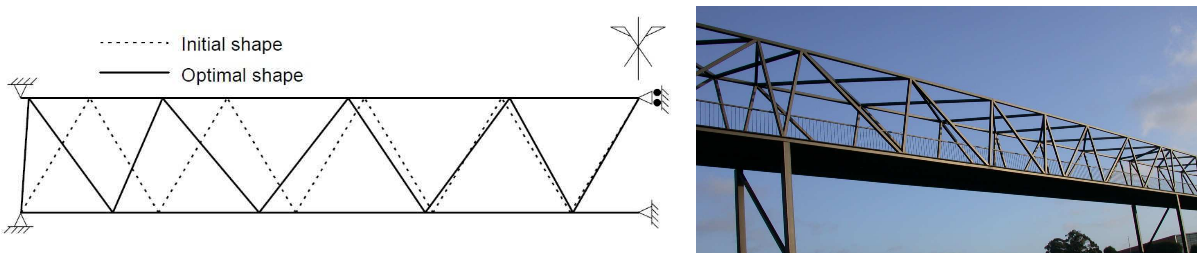

Fig. 1. Steel bridge: optimal configuration

The mathematics of optimization has a long history and the optimization of structures was first attempted in the 1950s. However, even with the advent of powerful computers, it is still regarded as a research topic. It is unusual then, for these techniques, to be used for a real engineering project as has been done here.

Fig. 2. S. Pedro Creek Footbridge photos

The tubes are very slender (14 x 12.5 cm in section) and the architect's choice, by painting them in black, slims them even further, dissolving the powerful structure in the world of the shadows of the trees and cane fields that border the creek to transpose. The game of triangulations is subtly varied, establishing a rhythm that is felt in the serene development of the big element but which, at first glance, almost brings us back to an accidental, non-systematized constellation. [7]

The almost non-existent design, fine black features like charcoal that crosses the dark brown 'black' stained by puddles and birds that bite mysterious flora, in the luminous shadow of the ria, is strictly controlled, optimized in the mathematical calculation that was in its origin, to offer us a pleasant crossing. Not being nostalgic, that anti-design, also almost makes us imagine crossing the water through an improbable old metal bridge from the old-time of the railways. We see an enormous straight line; we think how beautiful it is when architecture can be that simple, effective, intentional, useful, intelligent. We realize why architecture is not "cuteness", not colourful or arrogant rhetoric. [7]

3. Pedro e Inês Footbridge in Coimbra, Portugal

Open to the public in 2006, this bridge is the result of the fruitful collaboration with architect/designer – and former structural engineer – Cecil Balmond (www.balmondstudio.com).

In Coimbra, the river banks of the Mondego are very low, and often flooded in wet winters. As a consequence, building construction was never considered near the river, leaving the shores at the edge of the city, preserved as a natural setting. This little use by the city put in motion a strategy of reclaiming these areas into a public Green Park joined by a pedestrian and cycling bridge. This splendid setting called for a landmark bridge in its innovative structural solution, as an attribute to the University up in the hill on the northern river side, and in its simplicity of form, as an attribute to the Carmelites Convent up in the hill on the southern river side. [8]

Allowance for the practice of water sports such as rowing and sailing imposed a central span of around 100m. For this range of free spans, typical structural solutions include cable supported decks or systems that take advantage of some kind of arch effect. The cable supported solutions were unacceptable because very close upstream there is a cable-stayed road bridge and the two bridges would then visually clash.

The initial concept for the bridge was based on a straight three span arch that occurred from this very simple idea: to throw a stone and make it jump on the surface of the water.

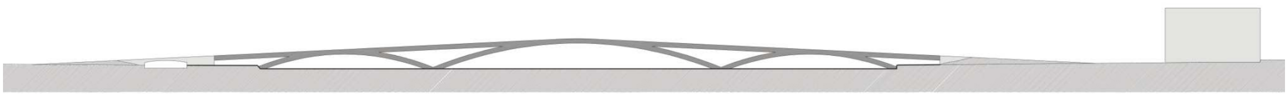

Fig. 3. Pedro e Inês Footbridge initial concept

The design has evolved to a more articulate architectural statement, which also enhances the user's experience as they traverse the space between the banks of the Mondego. The fundamental architectural "move" proposed was the elimination of the outer arch legs and a "cut" with a transverse shift of the bridge deck at its midpoint, generating a space at the centre of the bridge where pedestrians and cyclists are encouraged to stop and experience different views of the bridge, water and landscape. As a result of this "move", the bridge is transformed from a connection element between two points into a destination in itself.

Fig. 4. Pedro e Inês Footbridge "cut & shift" evolution

This architectural development had, in fact, two important structural consequences:

1) In the initial 'three arch solution' the unbalanced horizontal reactions at the outer arch legs were very difficult and expensive to accommodate by the bridge foundations that due to low resistant capacity of the underground soil layers had to be indirect with 30 m deep vertical piles. The 'new solution', with no outer arch legs, behaves more like a continuous beam, less dependent on horizontal arch thrust.
2) The anti-symmetrical development of both arch and deck cross-sections along the longitudinal axis of the bridge, which results in a complex torsion behaviour under vertical loads, led to an increased lateral stiffness when compared to the traditional structure with symmetrical cross-sections positioned. [9]

It is interesting to highlight how the individual geometric changes affect structural performance. From the results of the preliminary studies, certain architectural variations of the bridge geometry appeared to cause an imbalance of forces, which were detrimental to the bridge efficiency. However, the final arrangement is one where sculptural form and balance of forces form an optimum and totally "unpredictable" synergy. In a very clear manner, an original architectural concept converges with an unchangeable structural objective.

Fig. 5. Pedro e Inês Footbridge, a) aerial photo, b) below deck view

The bridge gives the illusion of stopping mid-air in a thrilling architectural gesture that at first glance appears impossible. What usually serves as merely a conduit becomes a territory for narrative, like the bittersweet legend of Portuguese king-to-be Pedro and his beloved lady-in-waiting Inês, from whom the bridge takes its name. [10]

This project offered an unprecedented opportunity to merge the architectural intent with engineering clarity. Within the restraints of budget and brief, this design could stretch the very definition of "BRIDGE", exploring its artistic and social potential as well as challenging some of the traditional principals of bridge engineering.

Fig. 6. Pedro e Inês Footbridge central "piazza"

4. Carpinteira Footbridge, at Covilhã, Portugal

Conception and design of this footbridge was developed in collaboration with prominent architect João Luís Carrilho da Graça (www.jlcg.pt) between 2003 and 2006 and the construction took place in 2009.

Fig. 7. Carpinteira Footbridge photos

The bridge is specially characterized by the deck stretching over the valley with a shape that reflects the meandering of footpaths in the mountains surrounding the city of Covilhã [11].The "Carpinteira" footbridge is an example of bridge "synchronizing" perfectly with the physical configuration of the local landscape. The "Carpinteira" Valley is located inside the city of Covilhã and is characterized by steep slopes where only retaining walls and scattered buildings existed. The footbridge provides a pedestrian passageway 220 meters long at the maximum height of 52 meters over the valley, connecting the northern residential quarters of Covilhã with the city centre. Again, some traditional bridge-engineering principles were challenged.

The "S" shape bridge deck, along five continuous spans, is made up of two longitudinal steel beams and a transversal truss structure defining, together, a U-shape cross-section.

Fig. 8. Carpinteira Footbridge photos

In plan, the central segment takes a path perpendicular to the line of the valley and the other two sections are inflected and oriented towards their anchoring points. The connection between the two points is no longer the shortest distance between them. This tense geometry interferes with visual orientation and with the perception of dominating mountains, on one side, and with the vastness of the valley on the other. [12]

The marriage of form, functionality and engineering in this pedestrian bridge is almost total, and all this done deceptively simply without overt dramas and gymnastics. This beam despite being robust, solid and reassuring is also light and seems to be playfully free floating across the valley. This bridge has to be termed as 'abstract' – it does not pretend to be anything else than it is. [13]

5. Galp Energia Footbridge, in Lisbon, Portugal

The Galp Energia Footbridge over the "2nd Circular" motorway, in Lisbon, Portugal, was open to the public in 2015. The solution was developed by "MXTstudio Architects" (www.mxtstudio.com) and "Adão da Fonseca - Structural Engineers" and was the winner of the "International competition for ideas of a new pedestrian and cycling bridge in Lisbon, Portugal", in 2009.

The "2nd Circular" is the busiest road inside Lisbon, literally cutting the city in two halves. It is, as the former City Mayor described it, a scar in the surface of the city that should be humanised. The footbridge will stand in a new map where new and old narrow paths for individuals lay over, cross and connect to the existing city routes and transport roads, both individual and collective. Indeed, the setting and context of this bridge, uniting lanes and footpaths going through new quarters of the city, generates an opportunity for a new map. A new map for the inhabitants of those new quarters, creating new passages that will liven up the city grid, thus called ecologic passages. The bridge will spring a new network of paths moving up from the ground, over the busy highway of the "2ª Circular", just letting back a trace of light that produces a choreography of the varies scales and modes of movement. [14]

Fig. 9 Galp Energia Footbridge, with network of paths over the motorway

The objective of separating the two major types of crossing, pedestrian and cycling, in the bridge deck led to the proposal of a hierarchy of different spans of the bridge, with clear prioritization of use across the surface of the bridge. This hierarchy uses perfectly the morphological characteristics of the solution, which is organized as a network of paths on the 2nd Circular, and not as a single pass.

The structural solution of a constant triangular cross-section emerged from the collaboration between architecture and engineering, with the objective of obtaining elegancy and lightness together with simplicity in the construction process and a deck capable of spanning over the motorway.

The cross section of the bridge is constant and is defined by an equilateral triangle with 3.30 m sides, with the pavement for pedestrians and bicycles making up the upper side. The two lateral sides extend 0.70 m above the pavement, providing part of the guardrails. The pavement is coated with a bituminous layer similar to that used in bike lanes pathways that lead to the bridge, avoiding any discontinuity.

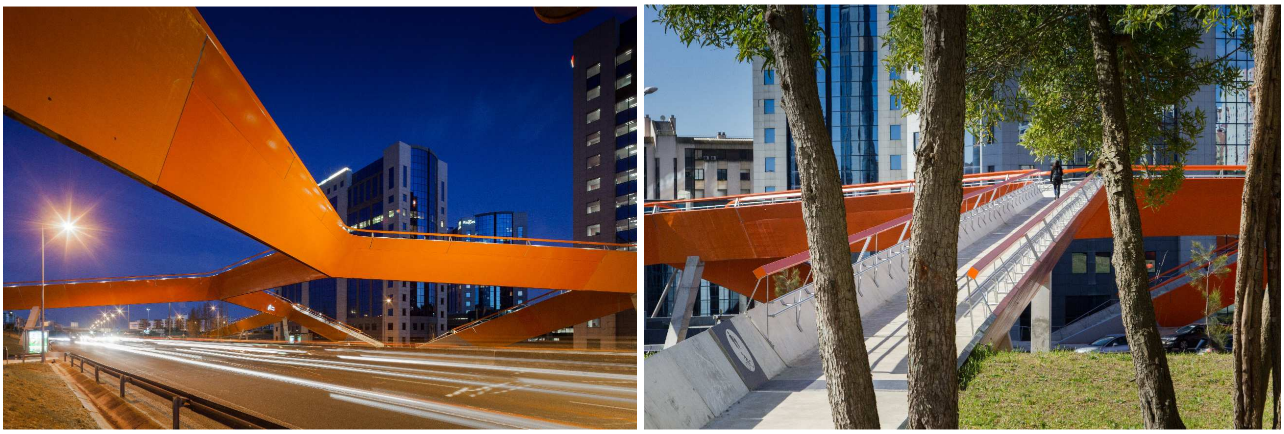

Fig. 10 Galp Energia Footbridge, view from below

In order to enable the original budget to be maintained, the original concept of using onky a steel cross-section, evolved into an hybrid solution, with a steel section being used above the motorway, where the construction process required a lighter solution, and a concrete section being used for the stairs and ramps.

Visually, the design looks as though it has been dropped into its location, the distinctive form is colored in orange and clasps onto each side – the built environment and the greenery. simultaneously, a triangular-supported handrail runs the length of the bridge where at night is lit by LED lights. [15]

6. Forte da Casa Footbridge, in Vila Franca de Xira, Portugal

Open to the public in 2014, the programme fot the international competition won by “MXTstudio Architects” (www.mxtstudio.com) and “Adão da Fonseca - Structural Engineers” was to connect directly the urban centre of Forte da Casa, a residential district in the Vila Franca de Xira County, in the outskirts of the city of Lisbon, with the Tagus Estuary Riverside Park. Forte da Casa is not a very interesting urban area, with a high density traffic road and a busy railway cutting it off from the natural spaces along the bank of the river Tagus estuary, most notably from the Riverside Park. Hence, the new pedestrian bridge is configured in a single object with a strong identity. A simple gesture in a complex urban reality, capable of becoming an iconic structure within the urban space and the Tagus flatlands. [16]

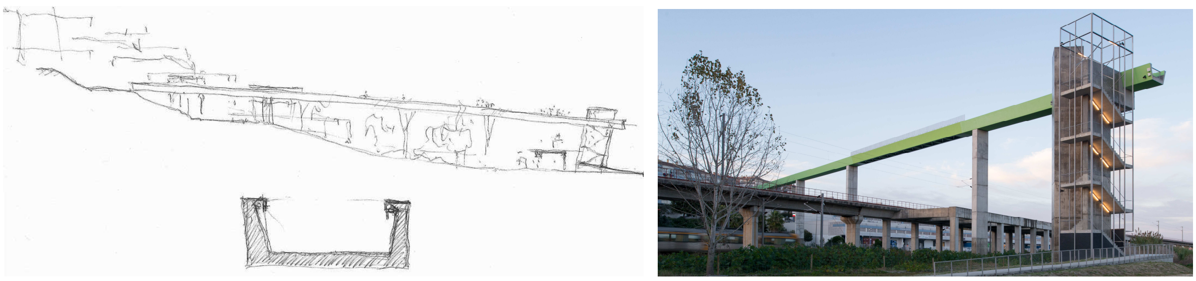

Fig. 11 – Forte da Casa Footbridg, a) concept, b) general view

The bridge is approximately 220 m long - a straight line on plan and with a constant slope across the valley. It is made up of 7 spans, the biggest of which is 42 m above the railway track connecting Lisbon to Porto. On elevation, the desired visual lightness is expressed by the slenderness of the cross section, 1.50 m high and 3.50 m wide, so that, at a distance, it appears as a simple line taking off over the valley.

The height of the deck above the ground recommends the use of opaque and high guardrails, in order to mitigate any sense of vertigo and exposure to wind. Therefore, a U-section was chosen for the deck, with external dimensions of 3.25 m (width) by 1.50 m (height), from which 2.50 m is the available width for pedestrians, with the deck 1.10 m below the top of the guardrails. The deck in essentially a precast pre-stressed concrete U section in most spans, becoming a steel section in the span above the railway lines, where the span is larger and where speed of construction is very important. For this span, the use of a pre-fabricated steel deck seems a solution able to provide both structural and erection conditions.

This is a type of bridge with proven effectiveness that integrates beams and guardrails in one element, thus optimizing the use of the structural material. This hybrid beam / guardrail element also includes a set of technical facilities as lights, which will be provided by LED luminaries that optimize maintenance cost.

7. Conclusions

At a time when the means of calculation and construction technologies allow practically everything, in the face of a great confusion of forms, typologies and images, the objective of the solutions for all these bridges was to avoid any formal excess and reach with its structure the essence of its architectural conception.

A bridge is like a centaur, half material and half design [3], and each one of these footbridges is a 4 hands piano piece where collaborative work between Structural Engineering and Architecture since the initial design phase led to efficient and economic solutions with extraordinary artistic results.

The cases listed illustrate this story where global structural response (longitudinal and transversal), static and dynamic behaviour, stiffness and resistance, cross section definition and structural material choice are intrinsically linked both with mechanical performance and formal architectural decisions. And we realize how beautiful it is when architecture can be that simple, effective, intentional, useful, intelligent [7].

Aesthetics of the five given examples result from architectonic concepts that reflect structural demands and physical laws, but that aim at optimized structures and keep designs in the initial budgets.

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