EFFICIENCY AND AESTHETICS

THREE FOOTBRIDGES AT VALENCIA DE DON JUAN, SPAIN

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Summary

The fundamental objectives of bridge design form the backdrop for a discussion of the parameters that determine the success of a project. Inasmuch as economic and aesthetic criteria cannot be standardized, successful design depends almost entirely on the talent and creativity of the engineer. The practical application of these general principles is illustrated with a description of three footbridges built as part of an enhancement project for the left bank of the Esla River at Valencia de Don Juan, Spain. The ideas underlying the conceptual design for the bridges over the river and its canal, in particular as regards the specific boundary conditions, are explained, along with the actual layout and a few comments on construction procedures.

Keywords: Site constraints; conceptual design; safety; serviceability; design codes; economy; elegance; creativity; steel; glued laminated timber.

1. Introduction

1.1 Context

The town of Valencia de Don Juan, León, Spain, recently undertook to upgrade the left bank of the Esla River, an area of great natural beauty located within walking distance of its historic quarter and Medieval castle. The riverscape enhancement project called for a 110-m footbridge to connect the two areas of the future park that was to flank both sides of the Esla. It also included the construction of a new canal spanned by two footbridges to provide access to the town's historic quarter from the park.

The design for the three footbridges was subject to numerous constraints in connection with the construction site and geometric, functional, constructional and economic requirements. These complexities were heightened by community demands, in keeping with a growing trend, for the works to fulfil more than a mere utilitarian purpose. In the present case the three footbridges were expected to meet high aesthetic standards in light of the natural beauty of the surrounding landscape and because the enhancement of the left bank of the Esla river was also intended to attract more visitors to the town. The challenge was therefore to design footbridges that would blend into without being wholly camouflaged by the landscape. In short, the project required a sober design based on modern structural concepts and construction materials and methods respectful of the environment.

1.2 Purpose of the contribution

Difficult boundary conditions may spur careful and indeed even innovative structural design. Since the successful translation of numerous constraints into a reliable, functional, cost-effective and aesthetically attractive structure is primarily a question of consistent conceptual design, the importance of this step for the design process as a whole cannot be overstated. The relevant ideas behind the structural concept for the three footbridges are described below in the framework of the complex interactions between geometry, functionality, construction materials, manufacturing, erection, overall structural concept, detailing, structural reliability and aesthetic considerations.

2. Conceptual design – a matter of engineering creativity

2.1 Design objectives

The fundamental objectives of bridge design are structural safety, service performance, economy and elegance [1]. All four goals must be attained, although their relative importance varies from case to case depending on the consequences of failing to do so. Structural safety is clearly the most important of the four, since unsafe bridges may lead to a loss of life or property.

By definition, structural safety and serviceability are achieved through the correct application of codes and standards. The knowledge required to reach these objectives can be acquired by studying the technical and scientific principles on which design rules are based. Consequently, the achievement of structural safety and serviceability depends chiefly on the engineer's analytical skills.

Economy and elegance, by contrast, are not subject to hard-and-fast rules [1]. Although some guidelines for improving bridge cost-effectiveness and aesthetics exist, fortunately such criteria cannot be standardized. Proficiency in designing economically sound and elegant bridges can be acquired, to some limited extent, through design experience. For all these reasons, economy and elegance in bridge design depend mainly on the engineer's creative talent.

2.2 Economy

When designing a bridge, cost comparisons of different solutions must be made in terms of life-cycle, rather than just construction, cost. In addition to building costs, life-cycle costs include operation – including user benefit –, inspection and maintenance, refurbishment, depreciation and demolition. Defining a cost-effective solution for a given bridge is therefore essentially a matter of consistent conceptual design, characterised by the appropriate choice of the structural system, foundation, deck cross-section and manufacturing and building procedures. The optimisation of span lengths or cross-sections has a lesser effect on economy [1].

2.3 Aesthetics

Although criteria for the design of elegant bridges cannot be quantified, observing a few basic rules suffices to avoid aesthetically objectionable solutions. First of all, elegance in bridge design is a question not only of structural form but of integration in the landscape [1]. For instance, where a single topographic element such as a river is the predominant obstacle in the chosen site, the main span of the bridge should be laid out in terms of that obstacle.

Furthermore, two of the most important determinants of elegant bridge design are transparency and slenderness. These features define what might be termed the visual efficiency of the engineering. Indeed, bridges are often seen to be elegant when characterised by the efficient use of construction materials in solutions with rather generous span lengths.

Harmony is another key to elegant bridge design. In this context, the main considerations are order, equilibrium and regularity [1]. Order can be achieved by reducing the number of bridge member orientations and arrangements to a minimum. Under such circumstances, bridge stability is normally perceived from all perspectives. In a similar vein, equal span lengths should be chosen for bridges with an approximately constant height, whereas in bridges where height is variable, a uniform ratio of span length to bridge height should be adopted.

As far as artistic shape is concerned, good form-following-function design normally yields solutions that meet even the most exacting aesthetic standards [2]. Except in the case of very gifted designers, forms that do not follow the flow of internal forces tend to lead to unattractive results. Bridges are a product of engineering: by no means do they need adornments or inefficient members to enhance their elegance.

2.4 Interaction between aesthetics and economy

Given the relationship between elegance and the efficient use of materials, a convincing conceptual design for a bridge is also usually a cost-effective solution, but not necessarily the cheapest one. The most economically rational span length is in fact relatively short and often judged to be conservative or even mediocre. Longer spans, which suggest technical efficiency, also increase transparency considerably. Hence the recommendation by some authors to employ spans that are slightly longer than the least expensive configuration [1]. In exposed bridges, cost increases of up to approximately 8% to adopt an aesthetically convincing structural concept may certainly be justified.

2.5 Procedure

The conceptual design of any structure must be based on a “structural idea”. Building on such an idea, the solution is further developed with a series of consecutive sketches, while viability is substantiated through simplified structural analysis. The most important details should be developed at this early stage. In addition to overall design and structural detailing, the main dimensions of the key members defined in the solution adopted should be established at this conceptual stage.

3. Esla River footbridge

3.1 Constraints

This footbridge project was chiefly governed by the unfavourable geotechnical conditions prevailing, characterised by very low soil resistance. Moreover, as in most public works, economic constraints constituted a decisive factor for the adoption of a given structural solution from among the various feasible design options. In the present case, economic criteria were particularly important in light of the limited budget for enhancing the left bank of the Esla River. And given its location and exposure, the Esla River footbridge had to meet high aesthetic standards.

3.2 Conceptual design

3.2.1 Basic ideas

The basic ideas for the conceptual design of the Esla River footbridge were directly deduced from the aforementioned conditions. The footbridge was designed to the form-following-function principle, according to which structural form stems from functional requirements and site constraints.

For the present bridge, a bow string – in which the horizontal thrust is resisted by the tension member, in this case the bridge deck – was found to constitute the most efficient structural system. To accommodate the geotechnical restrictions, the design envisaged transferring only vertical loads to the ground, by means of piles.

The only cost-effective material for manufacturing the bow string arches was structural steel. Cross-sections were defined to fit the structural function of each member. In the present case, cross-section geometric dimensions were minimised and strength and stiffness maximised. Compatibility between members and joints was another important issue in the choice of cross-sections, along with the specific surface to be protected against corrosion. Account was likewise taken of bridge aesthetics because of the decisive impact of cross-sections on the viewer’s perception of the structure.

In view of all the foregoing, hollow cross-section structural members were chosen. The need to achieve in-plane and out-of-plane stability advised the use of box-sections in arches. Box-sections were likewise chosen for the ties, but here for reasons of appearance and durability, since mud and moisture are prone to accumulate in open sections. Circular hollow sections, much less costly than cables or tension rods, were used for the hangers.

Good detailing was a matter of particular concern, for it is essential to suitable load transfer mechanisms, fracture toughness and fatigue resistance, as well as durability. It may also provide for simpler structure manufacture and has a significant effect on final appearance. The following aspects were considered in the design of the structural details for the Esla River footbridge:

- Structural detail geometry was defined to avoid the concentration of stress, i.e., with smooth transitions between different structural members.
- Compatibility between the structural behaviour of the joints and the behaviour of adjacent structural members was a major concern.
- Simple load transfer mechanisms were conceived and complex multi-piece connection details avoided.
- Connection devices were positioned in their preferred action modes (i.e., shear rather than direct tension).
- Details were designed to be compatible with manufacturing methods, which were kept as simple as possible. Indeed, simple manufacturing procedures can contribute to improving the quality of workmanship. This is an important issue because some failure mechanisms such as brittle fracture or stability problems are highly dependent on the dimensions of built-in imperfections.
- Accessibility for inspection and maintenance was provided, particularly in the case of construction details where the onset of deterioration mechanisms (e.g. corrosion) could not be excluded.

Manufacturing and assembly procedures compatible with the assumed tolerances were established. Since appropriate quality control contributes to the fulfilment of these requirements and in light of the interaction between design, execution and quality, the chief quality control measures were planned at an early design stage. Construction called for close co-operation between designer and contractor. Changes in the original design had to be approved by the designer and last-minute changes, which so often give rise to problems during the subsequent service period, were strictly avoided.

3.2.2 Footbridge layout

The bow string consists of two inward-leaning arches with a rise-to-span ratio of 1/12 (Figure 1). The twin arches are inter-braced with transverse members spaced at 12 m from centreline to centreline for greater buckling strength. The 4.75-m wide bridge deck is positioned between the arch ties, which are set 5.45 m apart. The slant of the arches determines the rhomboid shape of both the arch and the tie cross-sections. The ties, in turn, are interconnected by composite transverse beams spaced at 3-m intervals that support the composite bridge deck. The deck is attached to rigid transverse beams at both abutments to contribute to horizontal thrust resistance. Vertical loads are transferred to the arches by a suite of hollow-section steel tube hangers, set 6 m apart.

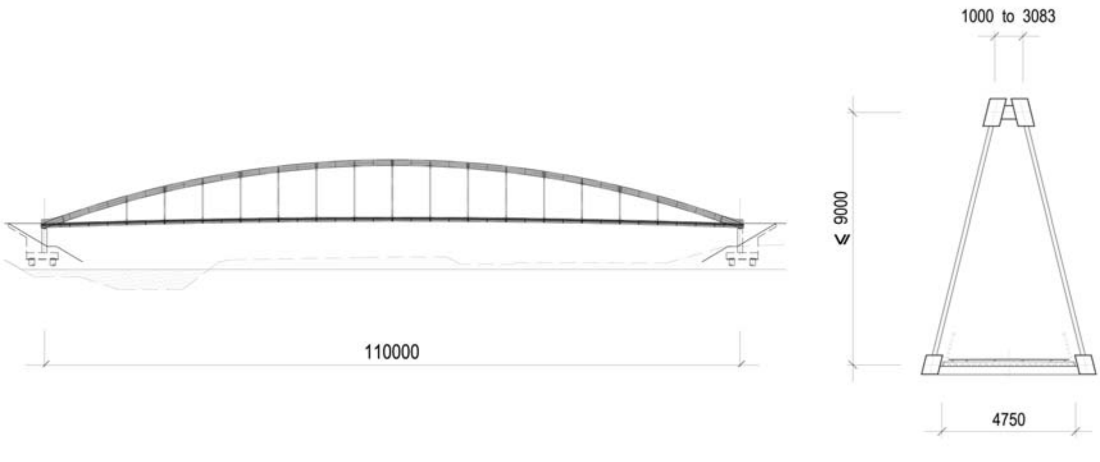

Fig. 1 Esla River footbridge. Elevation and cross-section

Not only all the structural details (Figure 2; Figure 3) but also the finishes were designed with great care: the wood sheathing laid on cladding rails for proper ventilation; enhanced pedestrian and cyclist safety thanks to the inward slant of the horizontal tube handrails running parallel to the plane of the arches; and spotlight illumination to afford a handsome night-time view of the bridge (Figure 4).

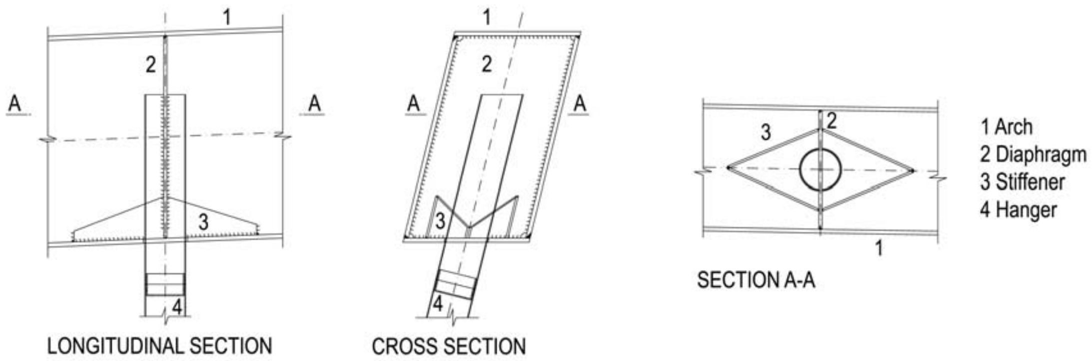

Fig. 2 Load transfer from hangers to arches

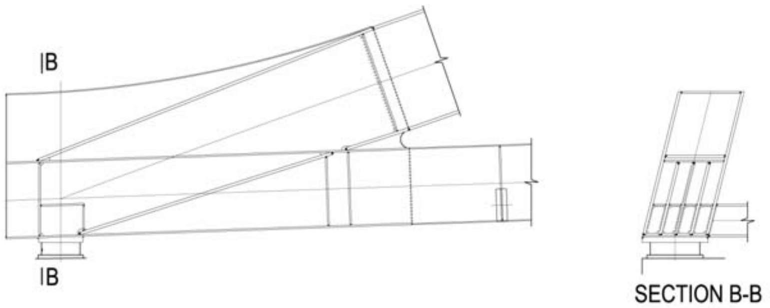

Fig. 3 Load transfer from arches to ties

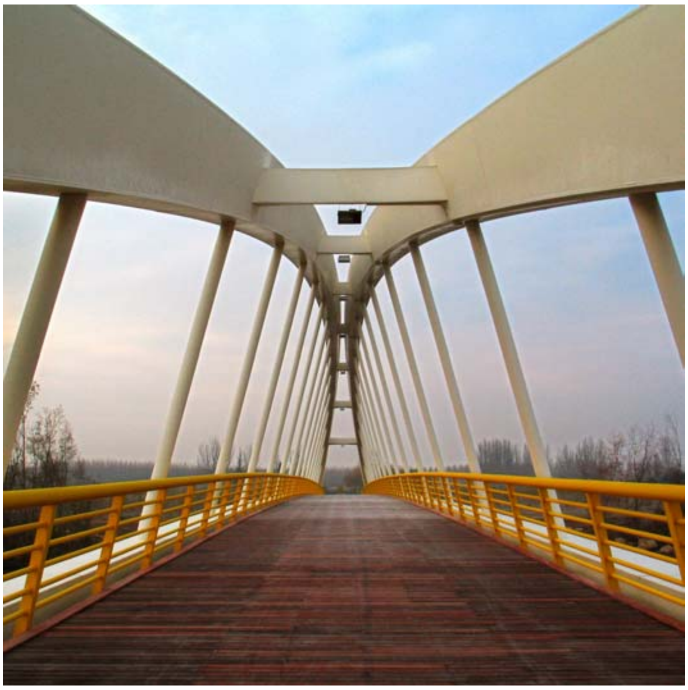

Fig. 4 Esla River footbridge finishes

3.3 Construction

Footbridge assembly was significantly simplified by building a provisional artificial island during the summer months, when the water level in the river was at its lowest. Four temporary supports were built on the island to erect the arches and deck (Figure 5), pre-assembled in the steel structure sub-contractor's nearby shop. The temporary supports for the arches and deck greatly facilitated hanger installation, which required no subsequent regulation or adjustment. The composite deck was built after the temporary supports were dismantled. Finally, the artificial island was also removed.

The simplicity of the structural solution and construction procedures adopted made it possible to complete the footbridge in a short time (Figure 6) and at quite a low total unit cost, on the order of €785/m^2.

Fig. 5 Provisional artificial island and temporary supports for bridge assembly

Fig. 6 Esla River footbridge after completion

4. Esla canal footbridges

4.1 Constraints

In addition to aesthetic considerations, this footbridge project was subject to numerous geometric, functional, constructional and economic constraints. As in the case of the Esla River footbridge, economic criteria were particularly important due to the limited budget available for enhancing the left bank of the Esla River.

4.2 Conceptual design

4.2.1 Basic ideas

The two Esla canal footbridges were also designed to the form-following-function principle. Cross-sections were chosen to ensure their adaptation to the structural function of the respective member. In this case also, maximum strength and stiffness were sought with minimum cross-section dimensions. Another requisite considered in choosing cross-sections was compatibility between members and joints. Lastly, attention was paid to bridge aesthetics, for the importance of cross-sections in the viewer's perception of such structures.

A good deal of thought also went into detailing, given its primary role in appropriate load transfer mechanisms and durability. Proper detailing may also simplify the manufacture of structural elements and naturally contributes to the visual impact of the bridge.

4.2.2 Footbridge layout

The 2.8-m wide decks on the two footbridges, each spanning a length of 15 m, consist in two twin arches made of glued laminated timber with underlying tension members (Figure 7). The two twin arches, separated by 1.8 m, are connected by transverse beams positioned at 2.5 m from centreline to centreline. The 94-m radius of the arches is mandated by the maximum allowable slope in pedestrian bridges, while the vertical clearance required over the canal determines the position of the horizontal tension members – high-performance galfan coated cables. The arches and cables are connected by vertical structural steel posts spaced at 2.5-m intervals and aligned with the transverse beams. The slenderness of the system, with a rise-to-span ratio of 1/25, subjects the timber arches to substantial bending moments which are partially offset by the eccentric connection between tension members and arches at the abutments (Figure 8). The cables were slightly pre-stressed to improve system performance, and more specifically to increase the fundamental natural frequency and reduce deformation as a result of the reduction of slip in mechanical joints.

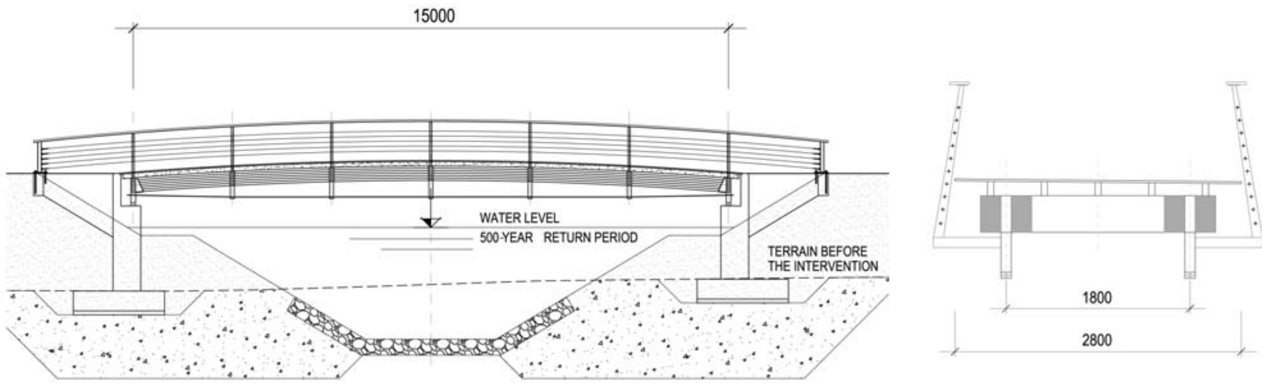

Fig. 7 Esla canal footbridge. Elevation and cross-section

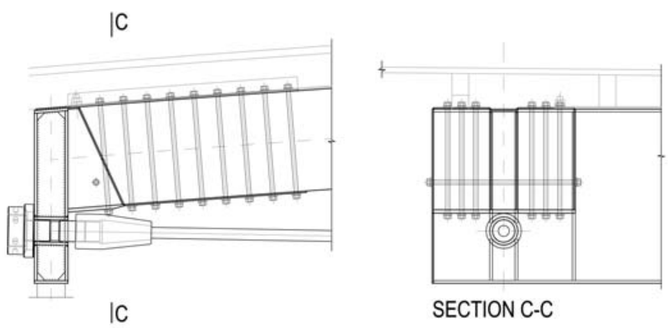

Fig. 8 Eccentric load transfer from arches to cables

Timber member durability was ensured by appropriate conceptual design and detailing for proper ventilation. Great care also went into all the details (Figure 9) and finishes, while transparent handrails were chosen to enhance the bridge's slender airiness.

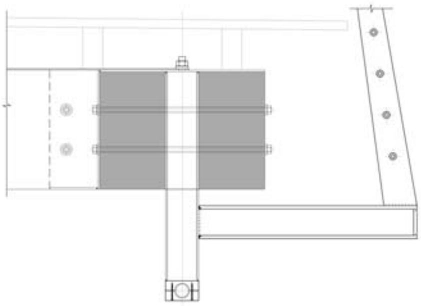

Fig. 9 Twin arch and cable joined by a vertical post, transverse beam and post for handrails

4.3 Construction

During construction, the timber arches were supported by the abutments and two temporary intermediate supports. The cables were slightly pre-stressed after installation of the transverse beams, wood sheathing and the cables themselves to offset any slip in the mechanical joints. The final pre-stressing force was applied by lowering the temporary supports and applying the dead loads (Figure 10).

Account taken of the small dimensions of the footbridge (Figure 11), the total unit cost, at approximately €800/m^2, was reasonably low.

Fig. 10 Esla canal footbridge during construction

Fig. 11 Esla canal footbridge after completion

5. Final remarks

The three Valencia de Don Juan footbridges had to be planned very carefully, bearing in mind the complex interactions between structural concept, geotechnical constraints, geometry, functionality, and manufacturing and construction procedures. Although difficult boundary conditions are generally viewed as a drawback in bridge design and construction, such conditions may also inspire the development of a consistent or even innovative structural concept. Conceptual design aims not only to translate constraints into a reliable and functional structure, but to devise solutions providing for an adequate balance between economy – in terms of life cycle cost – and aesthetics. The above three examples show that a modern and technologically advanced approach to bridge design, in which all structural members and details are kept as simple as possible, may lead to such an adequate balance and that inefficient members or adornment are by no means requisite to bridge elegance.

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