Recent Developments in Concrete Arch Bridges

Guillermo Capellán(✉), Emilio Merino, Miguel Sacristán,
Javier Martínez, and Santiago Guerra

Arenas & Asociados, Ingeniería de Diseño,
c/Marqués de la Ensenada 11, 3º, 39003 Santander, Spain
{gcapellan, emerino, msacristan, jmartinez,
sguerra}@arenasing.com

Abstract. Arenas & Asociados has a special relationship with concrete arch bridges since Professor Arenas founded the company in 1999. This abstract tries to synthetize the evolution of concrete performance and arch bridge design and construction techniques, through the real example of three recent structures.

The first of them is the Third Millennium Bridge over River Ebro (Zaragoza, Spain). This concrete tied arch bridge is the largest of its type built to date, with a main span of 216 m. Its construction required the use of innovative techniques, among others, the development of white color high-strength self-compacting concrete. This concrete reached actual compression strengths of 85 MPa, higher than the 75 MPa required for the arch and 60 MPa for the deck, due to the need of prestressing at short concrete ages during construction, in order to reduce execution times.

Las Llamas half-through Arch Bridge (Santander, Spain) continues this saga. The arch is 102 m long, and it is built in white high-strength self-compacting concrete C-60. The deck's main girder hangs from the arch in its central 60 m, with two side spans of 21 m. Intermediate arch, box girder and hangers form the main longitudinal structure, while in transversal direction it is formed by 2.4 × 9 m inclined precast cantilever slabs and a top concrete slab transversally prestressed.

Finally, this evolution on the study and performance of high-strength concrete comes to an end with the impressive Almonte Viaduct (Cáceres, Spain). This high-speed rail concrete arch bridge, flies over River Almonte with a 384 m span. The arch has been constructed using 80 MPa self-compacting concrete, especially composed for the high setting temperatures of this project (UltravalSR concrete reaches 40 MPa in 12 h and 90 MPa in 28 days, and it was mixed with fly ash and river sand as well as admixture Glenium TC1425).

Keywords: Arch bridge · High performance concrete · Self-compacting concrete · Design · Aesthetics

1 The Third Millennium Bridge

The Third Millennium Bridge is a white concrete bowstring bridge, with a main span of 216 m and a 43 m wide deck. It became the largest bridge of its type using this material once completed in 2008.

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The design of a central arch with final open “A” frames, where the main arch divides itself into two inclined legs linked by a crossbeam, is an evolution of the 168 m span and 30 m wide steel-made Barqueta Bridge, designed by the same author and built for the Universal Exposition that took place in Sevilla in 1992. This bridge can be considered a test model for the design and construction of the much wider and longer post-tensioned high strength concrete-made Third Millennium Bridge (Fig. 1).

Fig. 1. Third Millennium Bridge over River Ebro.

The Third Millennium Bridge has become a basic urban piece of the city of Zaragoza, the 5th of Spain in number of inhabitants (nearly 700,000). The bridge location has a particular characteristic which makes it noticeably different from those of the other Zaragoza river crossings. It is located in a meander area, with pronounced curvature and complex hydraulic response, whose banks inundate with low water flows, at least once a year. Trying not to increase these flood problems of the site and to avoid river bed scour in such sensitive area, we decided to plan the river crossing with a single span, with about 220 m to span.

Thinking on giving an easy access to the bridge, we desired a deck level as close as possible to the bank level, avoiding large approach embankments which would divide the river sides. At the same time, when over the river and as a requirement of the hydrographical authorities, it was necessary to leave sufficient space for the water flows predicted for a 1 in 500 year flood. These two conditions become constraints on the depth of the deck, setting the basis for the chosen tied arch bridge design (Arenas et al. [1]).

1.1 Materials Choice

A number of technical, aesthetical and economic reasons moved us towards the selection of white concrete as the main material for the construction of the bridge.

Almost the entire bridge was designed in concrete, excepting the side pedestrian areas (formed by a wooden deck over steel ribs and covered by glass over a stainless structure) and, obviously, the hanger cables and their anchorages.

One of this reasons is the need to improve the dynamic behavior of the structure and avoid vibrations due to traffic and wind (Zaragoza is windy city and its main wind direction is almost perfectly perpendicular to the bridge axis). These actions become important with the distance we need to span and especially when, as in our case, a slender structure is desired. The designed bridge would have a much worse dynamic response if built in steel.

If we continue talking about aesthetics, concrete can create a seamless monolithic structure, a continuous object with shapes connected without cut planes, an object aspiring to compose a great white stone sculpture over the river. Concrete is a noble material with wonderful ageing if a concerned execution and a social respect for its surfaces exist. The white color increases this nobility and its visual quality.

We must also acknowledge that the emotional connection of J.J. Arenas with the dry and earthy landscapes of the region, just 75 km from his birthplace and where he spent part of his life, had something to do with the decision of material choosing. When concrete is chosen as the main material, the self-weight of the bridge becomes de greatest problem for its structure (in fact for the bridge itself as every element seen is structurally needed and its design is an expression of its internal forces). The use of high-strength concrete becomes a need because the thickness of every structural element must be as reduced as possible, especially of those which compose the deck, to enable the bridge support itself.

Looking for this reduction of self-weight, the high quantity of complex reinforcement bars, internal post-tensioning steel ducts and external post-tensioning deviators needed, do not leave free space to use vibrators to accommodate the fresh concrete into the false work. The using of self-compacting concrete for the entire structure guarantees an accurate setting up.

All the mentioned conditions required to meet the challenge to develop a new material to build this bridge, a high strength and self-compacting white concrete. Enough tests were done during detail design phase, to prove the objective was attainable, reaching 92 N/mm^2 of compression resistance and an instant elastic modulus of 41,250 N/mm^2.

Getting the right mix during construction for the high strength, self-compacting white concrete was an ongoing challenge. This concrete was very sensitive to changes in the atmospheric conditions. Constant tests and adjustments in the blend were needed to ensure it was consistent. Clearly differentiated seasonal mixtures were created. A complete concrete production facility and a testing laboratory were specifically built on site for guaranteeing a permanent control of the blend properties. Real scale models including reinforcement bars and post-tensioning ducts were done to verify the accurate setting up of the designed blend in the most complex elements (Fig. 2) (Martínez and Segura [5]).

The construction of the Third Millennium Bridge was carried out by contractor Dragados. It required highly complex erection procedures due to its size, comprised in three main activities:

Fig. 2. Site concrete production facility (left), site testing (center) and real scale model (right).

- Deck erection using the launching method over previously built final substructure and additional temporary piers.
- Arch construction over scaffolding arranged over the previously launched deck.
- Introduction of a horizontal load in the crown section of the arch with hydraulic jack, to put into play the final loads in the whole structure.

2 Las Llamas Bridge

Las Llamas Bridge is a white-concrete half-through arch bridge placed in Santander, the city in the North of Spain were Arenas & Asociados has its main office. The new bridge connects the University Campus and the main access route to Santander's coastline.

The arch has a total span of 102 m with two intermediate steel hinges 81.6 m apart. The deck's main girder is suspended from the arch along 60 m, with two side spans of 21 m. The arch is a uniquely designed form centered on the bridge, separating into two inclined legs reaching the ground below the deck. The depth of the arch increases from the key section down to the springings, varying between 720 and 1,200 mm.

The deck is organized in a central box-girder structure with two lateral cantilevers. The central box girder is 5.8 m wide and 2.25 m deep. Cantilevers, conceived as inclined precast elements, are 9 m long and have openings with light projectors to illuminate the ground below the bridge. The superior deck slab is supported on the inclined cantilevers by means of conventional 90 mm deep precast slabs, completed in situ to conform the 250 mm deep slab. From the functional point of view, the 23.6 m wide deck provides two 6.5 m wide roadways, a central reserved section of 5.2 m that includes the arch structure and a 3 m bike lane, and the 2.7 m wide lateral pedestrian sidewalks (Fig. 3).

2.1 Technology and Innovation

Las Llamas Bridge is located quite close to the Engineering Faculty where Professor Arenas taught his classes on bridge engineering for more than 40 years. This fact was seen as an opportunity to experiment with innovative solutions in the structure, as well

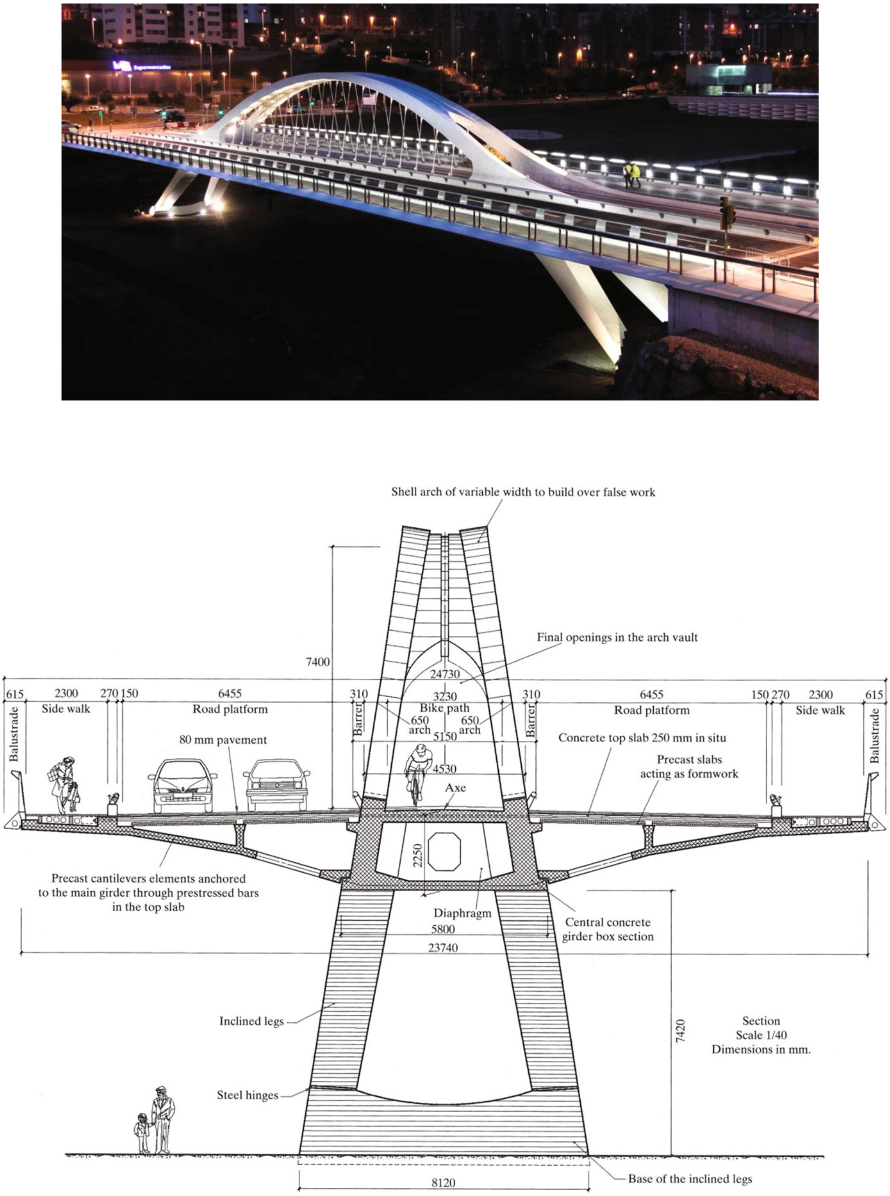

Fig. 3. Night view (above) and cross section (below) of Las Llamas Bridge.

as new materials and technologies. Realization of the chosen design called for unique structural solutions and erection procedures.

The process of using white, self-compacting, high-strength concrete together with the density of reinforcement bars, was a challenge in innovation owing the geometry and strength of the arch. The characteristic strength of the arch concrete f_{ck} was 60 MPa and was poured in one, single operation with formwork around the arch section to avoid the possibility of causing vibration in the fresh concrete during pouring.

The precast cantilever elements had both constructive and aesthetical advantages, at the same time that reduced the self-weight over the falsework and temporary foundations (Capellán et al. [2]).

2.2 Construction

Isolux Corsán carried out the erection works. After building foundations, the central box-girder and inclined legs were built over framed falsework, founded over provisory driven precast piles. Inclined legs were poured first, and over them the central box-girder was materialized in two phases: first the bottom slab and webs, and then the top slab.

Once the central girder was finished, the arch was erected using falsework supported by the girder over its temporary falsework towers. It was not until the hangers were placed and tensioned to their initial force and the longitudinal pre-tension was partially stressed that the falsework could be removed.

13 tons precast inclined cantilevers were placed with provisional supports until transversal pre-stress bars were installed. The upper slab was poured over the precast slabs. The pre-stressing of the transversal bars completed the bridge structure, following the corresponding finishing operations.

3 Almonte HSR Viaduct

Almonte Viaduct crosses over River Almonte in its flow into the Alcántara Reservoir through a 996 m long viaduct. It overflies the reservoir with a great concrete arch bridge, with a main span of 384 m, which makes it the largest high speed railway arch bridge built to date. The bridge forms part of the section conceived to connect Madrid and Lisbon through High Speed Railway.

The bridge design emerges from a series of imposed conditions, as the particularities of railway high speed traffic and main span (already mentioned) and the profound reflection on the problem to be solved bearing in mind multiple criteria: functionality, structural behavior, economics, durability and maintenance, constructability and landscape integration.

The viaduct is constituted by three different zones:

- An approach viaduct (Madrid side) with a series of span 36 m + 6 × 45 m.
- The main span over the River with a 384 m long superior deck arch.
  Eight spandrel columns rise over the arch to support the continuous joint-less deck that runs over the whole 996 m viaduct. The spans distribution over the arch is 45 + 7 × 42 + 45 m, with deck and arch merging in the 17 central meters to configure the structure's fix point.
- Another series of access spans (Cáceres side, 7 × 45 m + 36 m).

The arch geometry is singular and is conceived in high performance self-compacting concrete (C-80). It has a hollow octagonal section with variable depth in its 210 central meters, splitting into two variable-hexagonal-section legs until reaching their springing points. These transverse split ameliorates the bridge's transversal behavior and its response against out-of-plane instability phenomena (Capellán et al. [3]).

The arch is erected with a cable-stayed cantilever method (Fig. 4). The total length of the arch is divided into 67 in-situ cast segments, 33 on each half plus one key segment. Cantilevers are supported temporarily by stay-cables which are anchored either to the main piers (P6 & P15) or to one of the two temporary steel towers located on the top of the deck as an extension of those main piers. Segments are built using a pair of form-travelers in each side of the viaduct. Once both form-travelers reach the single section part of the arch they change their configuration and turn into a single device.

Fig. 4. Almonte Viaduct under construction.

3.1 Concrete Typology

Due to the geometry of the segments as well as the complex and dense positioning of the rebar in them, the use of a self-compacting concrete was needed to guarantee that all the segment were correctly filled without leaving any kind of hole or cavities.

The high characteristic resistance required (80 MPa) is also a new factor as it is not usual to work with such a high level of characteristic resistance for self-compacting concrete. Besides these requirements and in search of optimizing the work cycle so each segment could be executed in less than 12 working days with 24 h shifts, 7 days a week, concrete must reach 40 MPa in a few hours so the carriage could be released and advanced with total security (Cavero et al. [4]).

A pipes and pumps system capable of lifting concrete 80 m (vertical distance from the pumps to the key of the arch) and transporting it more than 200 m, was used. The selected material and its main characteristics were the following:

- **Ultraval SR special cement:** Contains low quantities of AC3, in order to avoid the possible delayed ettringite formation due to high temperatures reached during the concrete setting time, and permit not to reach 75 °C during the concrete set and cured. It contains also higher grinding fineness than standard cements getting high beginning resistance (>40 Mpa) in 12 h and more than 90 Mpa in 28 days with maximum quantities according to Spanish normative EHE-08 (460 kg/m^3). It is produced by Cementos Portland Valderrivas - FCC Group, in Navarre (North of Spain).
- **River sand:** Produced 135 km away from site, are essential to avoid concrete blockage and segregation, making possible the concrete pumping to long (200 m) and high (70 m) distances.
- **Fly ash and chemical admixtures:** Fly ash use gives higher long-term resistance, improving self-compact quality. Besides, last generation of super fluidizers have been used, which are essential to keep the concrete in good conditions to be set in the first 90 min.

4 Conclusion

The performance of high-strength concrete has allowed the construction of these three remarkable bridges.

This evolution, together with the new construction techniques developed, may lead to a new order in concrete bridge design, with higher resistance strengths, larger spans and slimmer structures. The Third Millennium Bridge and Almonte HSR Viaduct are great examples of these achievements in their bridge typology.

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