THE "DIAGRID SYSTEM": A NEW AESTHETIC AND STRUCTURAL CONCEPT FOR AN OUTSTANDING BRIDGE ON THE ACCESS TO THE NEW T4 TERMINAL AT BARAJAS AIRPORT (MADRID)

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ABSTRACT

The new Valdebebas Bridge, with a 150 m span, is due to become one of Madrid's most relevant landmarks. Its conception was governed by the surrounding services constraints, aesthetical concern and structural efficiency. The result is a bowstring steel arch with composite deck, whose shape inspired in industrial design, blends with Barajas Airport's T4 Terminal. The bridge also displays an innovative connection between arch and deck: diagrid, a steel mesh which, adequately combined with the lighting devices endows the bridge with unique personality.

Keywords: Diagrid, bowstring, lighting, industrial design, structural orthodoxy.

1 TENDER FOR A SINGULAR UNDERTAKING

In March 2007 the most renowned Spanish bridge engineers were forwarded an invitation to an exclusive tender for a singular bridge which will connect the new Valdebebas urban area with the Barajas airport's T-4 Terminal. The bridge will span 150 m, approximately, over the M-12 road without any intermediate support so as not to pre-condition hypothetical road widening operations. The vertical clearance restrictions, relative to the M-12 road as well as to aeronautical prescriptions, were very stringent too.

The tender was not governed by strictly functional or structural parameters, being highly influenced by the surroundings where the undertaking would take place, the "Parque de Valdebebas" urban development plan. Therefore, the bridge is bound to become a first-rank urban reference, Valdebebas's calling card and also an access to the T-4 terminal from the new urban area in "Parque de Valdebebas". The aim is to design a singular bridge with enough personality to stand out among urban and architectural landmarks such as the Madrid Community New Justice Town, Real Madrid's new Sports Town, the Fair Facilities enlargement and the T-4 terminal itself, designed by the prestigious architecture bureaus Lamela and Richard Rogers.

IDEAM’s proposal, under the coordination of a team of engineers and architects, authors of this paper, eventually won the tender (Fig. 1). The construction project was carried out in 2008. The works are due to start in the second semester of 2010 [1].

Figure 1. Winning proposal’s render with elevation view

2 CONCEPTUAL DESIGN OF THE WINNING PROPOSAL

Urban, ambitious in its design, innovative in its materials, formal conception, structural typology and constructive process, the designed bridge was conceived as an object and, as such, as a representative icon of the undertaking.

The bridge is deliberately presented with clear, precise lines, closer to Roger Tallon’s industrial designs or those from the aeronautical industry than to the typical structural typologies for a 150 m span.

The airport’s influence was never omitted: it inspired the bridge’s aerodynamic shape, the deck’s conception as a shell, the choice of the galvanized aluminium paint that endows the structure with a look similar to the T-4 terminal’s roofing (Fig. 2).

Figure 2. Render of the bridge opposite to Barajas Airport’s T4 Terminal

At the same time, the bridge is inspired by a powerful, comprehensive structural conception, from which its main virtues stem: clearness, formal simplicity, structural purity and dynamic, suggestive, attractive geometry.

The bridge’s shape, with a very peculiar geometric character, almost aeronautical, evolves from an inverted T cross-section (Fig. 3), associated to a shallow lower-deck arch typology (bow-string), a classical scheme which allows to bridge long spans without transmitting horizontal thrust forces to the foundations.

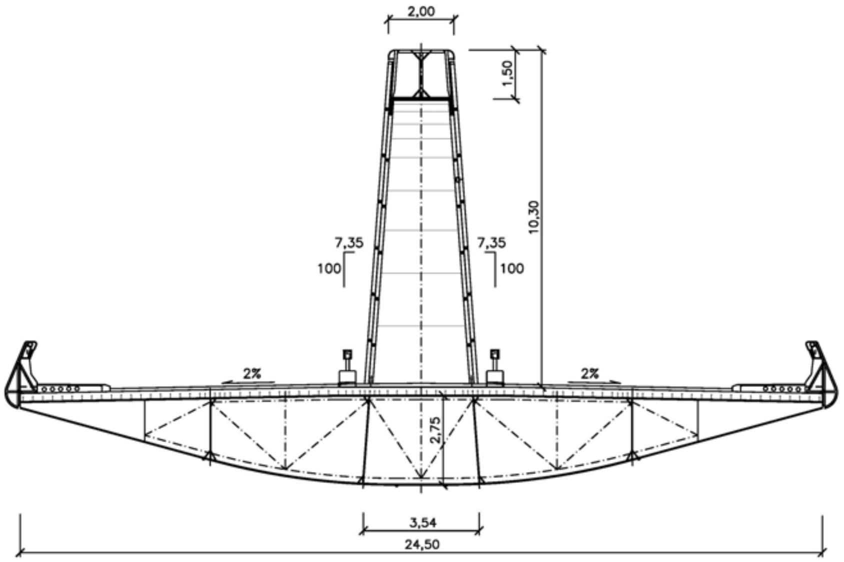

Figure 3. Bridge cross-section

The design's most relevant and singular formal aspect consists of a double diagrid (Fig. 4), a permeable structural mesh, which connects the deck with the arch and, as a great stiffness plane, materialises the latticed web of a variable depth beam, that is, the arch. The diagrid comprises a double plane at each side of the structure's spine, thus creating a four-plane offset mesh that, as well as guaranteeing visual transparency, endows the structure with a dynamic character, generating lights and shadows which reverberate and enrich with different hues the visual perception arising from the diverse perspectives, both during the day and at night, from many points of view.

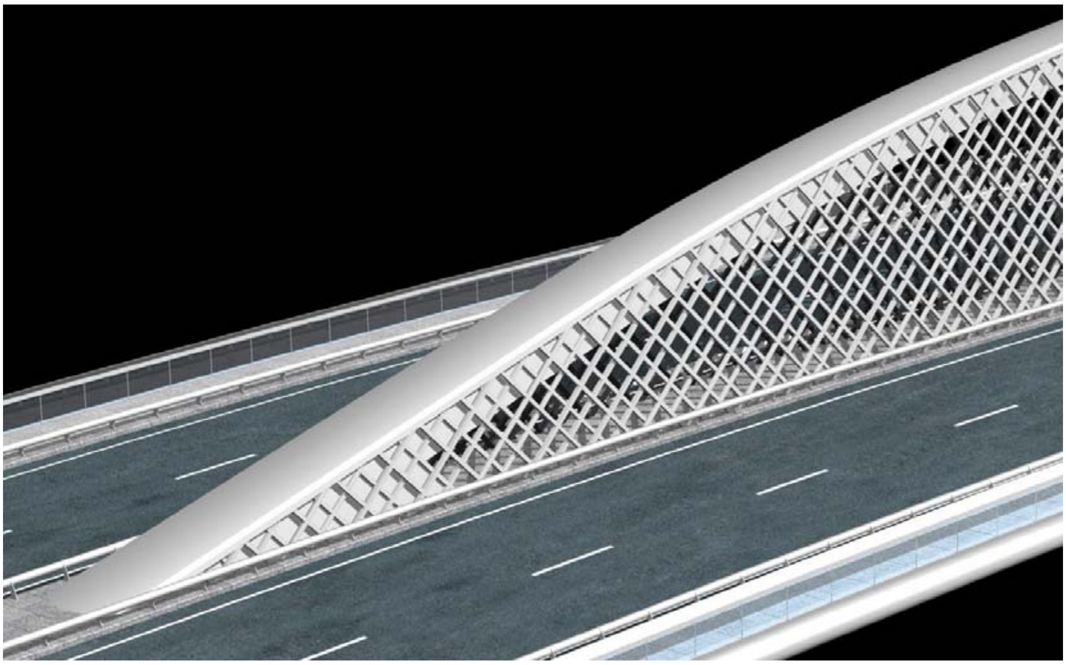

Figure 4. Detail view of double Diagrid at the arch-deck connetion

The meshed structure, diagrid, creates a lateral silhouette like a building's façade. Besides, the shape is entirely efficient, from a structural point of view, without superfluous ornamental accessories. Its structural design is essentially orthodox.

The structure's elevation view is imposing and recognisable, inspired by a classical, orthodox structural typology. As a result of these two streams, an innovative design arises: architectural attractiveness combined with structural efficiency.

The light which, during the day crosses the four-plane diagrid mesh, will multiply, depending on the light intensity and the driver's or the pedestrian's point of view, the rich game of transparencies, lights and shadows cast by the lattice, in an effect which reminds, and is inspired by, Eusebio Sempere's sculpture creations.

At night, the diagrid façade becomes the bridge's reference. The bridge is dimly lit and, the lamps being between the diagrid planes, the light is contained within the cage created by it.

The lighting is enhanced by means of well-designed, high-quality lampposts located along the sidewalks. Besides, several outer light spots will illuminate the deck's lower face and the arch's transition towards the abutment. This ornamental lighting, dim and suggestive, duly gauged in power and orientation, will outline the different volumes, surfaces and lines, thus enhancing the bridge within its complex surrounding (Fig. 5).

Figure 5. Scale model with night lighting

3 THE STRUCTURAL SOLUTION

Despite the proposal's innovative formal design and its architectural approach, uncommon in the field of bridges, this design is the aftermath of an orthodox structural conception in which, as explained, all its elements come from an optimized structural scheme, and where any ornamental or superfluous elements have been eliminated. This proposal's formal incidence and architectural character stem from the order and treatment of the bearing elements'design.

The longitudinal structural scheme can be interpreted in two ways which only represent two different approaches to the same structural concept:

- The 156 m apparently (or visually) long span, equivalent to 162 m between the abutments' hidden supports, is dealt with by means of a 124 m long bowstring steel arch with composite deck (or tie beam) (Fig. 6). The suspension hangers are inclined, like in the Network type bowstring arches, but in this case, they are replaced by a quadruple 'diagrid' mesh arranged on two planes with conventional rectangular hollow sections (RHS) at angles of 45° creating a stiff suspension plane which prevents in-plane arch buckling.

  The bow-string's vertical reactions act at the end of the spandrels or cantilevers, 19 meters from the support lines. The reaction can be projected in two directions: a compression strut along the spandrel's lower face (which must be properly connected to a concrete inner bottom head, in double composite action) and a horizontal tension force withstood by the steel upper box girder. This scheme is self-balanced in a traditional triangular cell arrangement: the upper tension force goes on by means of a 25 m long prestressed concrete tie anchored at the end of the composite deck and hidden within the abutments. This force can be split into two: an upward vertical force compensated by the counterweight (anchored at the end of the abutment), and an inclined compressed concrete strut which, heading to the main span support, closes the cell transmitting the vertical resultant force to a deep foundation.

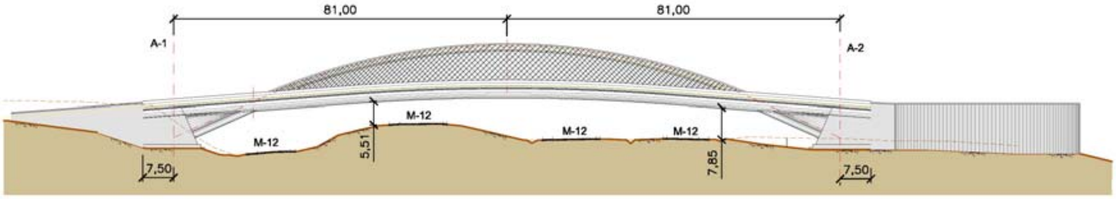

Figure 6. Elevation view of the bridge

- Alternatively, the structural scheme can be explained from a different angle: a 162 m long doubly embedded span is designed. The positive bending area stretches 124 m and is withstood by a variable depth beam with a latticed web (diagrid). The arch acts as the compression chord and the deck, as the tension tie. In the negative bending areas, 19 m long, next to the supports, the composite deck carries the upper tension and the spandrel, with double composite action, the lower compression. The bedding moment, thanks to the triangular cell scheme (Fig. 7), is provided by a short hidden compensation span, whose extreme negative reaction is balanced by a counterweight.

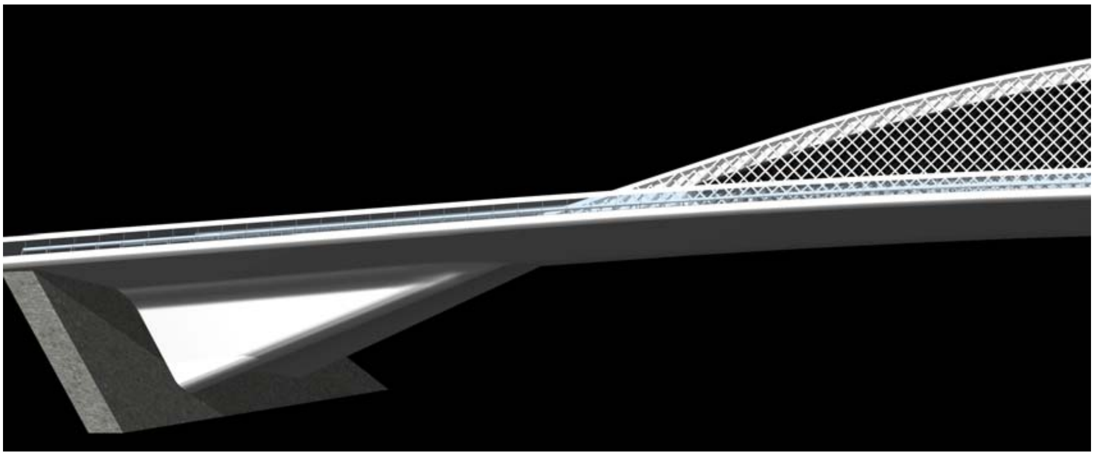

Figure 7. Detail view of the triangular cell, partly hidden behind the abutment

Even though both structural approaches to the design's conceptual explanation are correct, the second one (embedded beam) is better to describe the bridge's behaviour against live loads. The behaviour as bowstring arch with network hangers between the zero-moment points and a deck supported on triangular cells assumes that the arch-deck structure is articulated at their intersection or that the zero-moment point of the three-span beam (22.5+162+22.5) is located right there. The arch and the deck are connected and even though the zero-moment point of a variable stiffness beams is located at the weakest section for uniform loading, live loads alter that situation. This peculiar aspect does not appear in conventional Nielsen bowstring arches, which behave as simply supported beams. This feature enhances the structure's beam behaviour.

In order to optimize the structure's behaviour during the erection process, once the bridge is continuous and before placing the dead loads, jacks will be applied to readjust the reactions. By doing so, it is possible to control the position of the zero-moment point of the three-span beam, taking it to the intersection of the arch and the deck (approximately) and reducing bending in the structure's weakest sections. A time-dependent analysis was also made to obtain the redistributions forces and reactions after an infinite period of time.

Four main structural elements should be highlighted:

- Arch: the whole deck is suspended from the arch, with a structural rise of 10,30 m and a span of 124 m (considering only the arch above the deck), yielding a 1/12 rise/span ratio, which indicates this is a shallow arch. The arch's cross section (Fig. 3) is almost rectangular, with two ledges jutting out at the top in order to attach the 'diagrid' planes. The arch has a constant depth of 1,50 m and variable width ranging from 4,0 m at the start to 2,0 m at the crown. It is made of S355J2 steel, with maximum thickness at the crown and minimum at the start. Seen in elevation, the arch follows a circular curve of approximately 150 m of radius and continues at a tangent up to the start. Below the deck, it goes on up to the supports as it becomes wider and remains linked to the deck, creating a volumetric triangular spandrel, of great formal incidence. The spandrel's geometry contributes to distributing the compression stress transmitted from the arch to the supports.
- Deck: It consists of a multicellular steel hollow box girder 3,0 m deep (at its center) on top of which a 0,25 m thick concrete slab rests (Fig. 8). S355J2 steel is used, with a yield stress of 355 N/mm2. The section's bottom follows a circular curve 21,65 m of radius which goes on at a tangent up to the abutments. The deck's cross section comprises 5 cells by means of using 4 webs. In order to easily handle the section's elements and to attach the 'diagrid' to the inner webs, the latter have the same inclination as the diagrid.

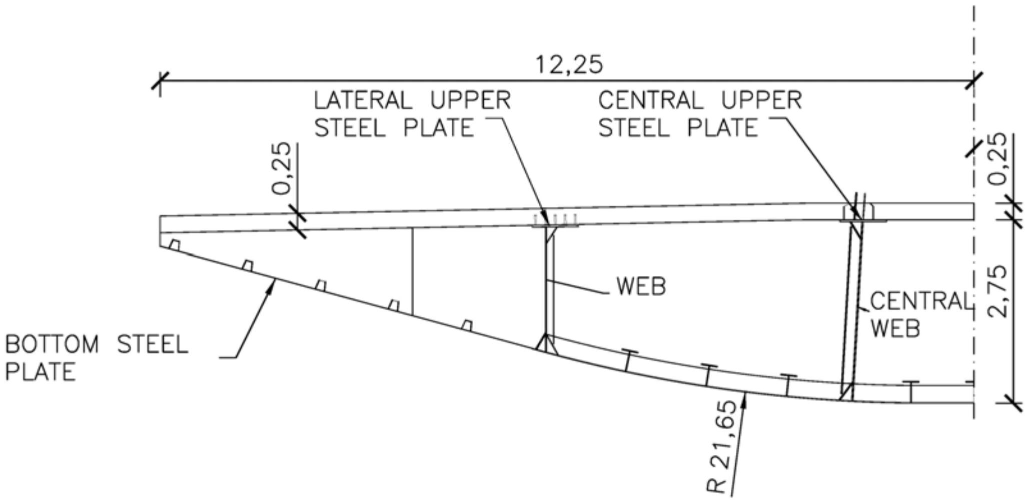

Figure 8. Deck cross section

Within the section and every 5,0 m, transverse trusses are located so that torsional effects derived from eccentric actions can be transferred to the 'diagrid', which acts as a plane of inclined hangers which divert the loads along the arch. Torsional moment, quite important owing to the bridge's width, is withstood in the intermediate 124 m thanks to the high torsional stiffness of the deck's composite section.

The deck's twisting stiffness was evaluated, on the safe side, taking into account different cracking hypothesis due to the tension carried by the tie that constitutes the composite deck of the bridge.

- Deck suspension system or diagrid (Fig. 9). The deck is linked to the arch by means of a mesh or lattice of S355J2H steel tubes termed "diagrid". Its structural mission is to transfer the vertical loads acting on the deck from it to the arch. Therefore, it basically responds under tension, since the shear stress which might have to be withstood acting as a web of an inverted T-section is dramatically reduced by the arch's compression inclined component as well as by the deck's (or tie beam's) flexural stiffness. Each 'diagrid' mesh consists of two coplanar, mutually perpendicular families of tubular profiles arranged at angles of 45º with respect to the horizontal plane. There are two 'diagrid' planes at each side of the arch, one in each direction.

Diagrid's stiffness within its own plane suppresses any in-plane arch instability problem. Likewise, the two 'diagrid' planes at each side of the arch are braced together by means of trusses in order to prevent any wind-induced vibrations. These trusses are parallel to the 'diagrid' tubes' direction, thus preventing visual and inner lighting interference.

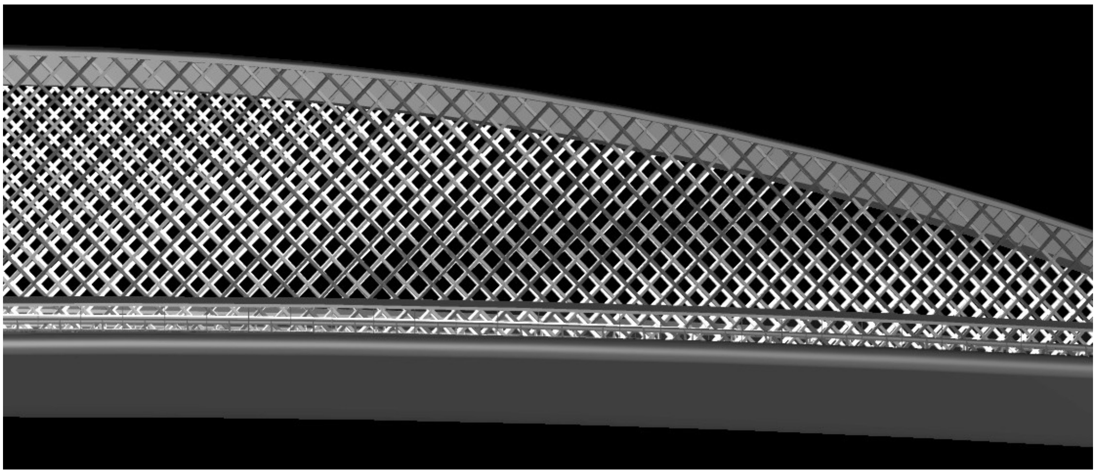

Figure 9. Double Diagrid view

- Abutments and counterweights: The bridge is in equilibrium at its end by placing a concrete counterweight across the deck's width. Equilibrium is achieved at the top of the counterweight. The acting forces are the deck's tension, the counterweight's vertical force and the compression along the concrete strut which links the counterweight to the arch's support section. In order to facilitate the stress transmission, the deck's final meters, hidden within the abutments, were conceived in prestressed concrete, in such a way that the steel deck (where the prestressing cables are connected) transfers its tension adequately. Besides, a massive node is created at the counterweight's head.

  The deck's upward lift is withstood with a stopper and 6 spherical bearings (or similar devices). Since abutment 2 is longitudinally fixed, stoppers are also placed along that direction.

Figure 10. Render with elevation view spanning over M-12 motorway

Figure 11. Structure scale model including accesses

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