THE CITADELLE BRIDGE IN STRASBOURG: A Balancing exercise

Alexandros Giannopoulos
Bridge design project manager
Egis Structure et Environnement
Guyancourt, France
E-mail: alexandros.giannopoulos@gmail.com

Claude Le Quéré
Design Office Director
Egis Structure et Environnement
Guyancourt, France
E-mail: claude.le-quere@egis.fr

Jean Pierre Gerner
Director of bridge department
Eiffage Metal
Vélizy-Villacoublay, France
E-mail: jean-pierre.gerner@eiffage.com

1. ABSTRACT

This paper is going to present, the context of the operation, the conceptual design process, the general description of the structure and his foundations and at the end of it, the final choices made for the construction methods. The Citadelle Bridge is a bridge for pedestrian and tramway traffic. It is formed of a very slender steel box deck of 14 m wide and 163 m long supported by 30 locked coil rope cables and hung from a single semicircular arc. The arch of 180 m chord length spans diagonally across the deck and is made from a variable rhomboid steel box section. The section of the arch varies from 5 m wide and 2.5 m deep at the crown to 2.5 m wide and 5 m deep at the springings. The arch and the abutments of the deck are founded on the granular soil using deep foundations (barrettes) and one of the two abutments has been equipped with a preloaded spring damper for seismic isolation.

2. DESIGN

2.1 Introduction and context of operation

The urban community of Strasbourg (City and Eurometropolis of Strasbourg) decided, after a public consultation in October of 2010, to extend the network of the urban tramway (line D) up into the border town of Kehl in Germany. The chosen alignment of the tram follows a sinuous path on the north side of the route de Rhin, which will serve efficiently the former industrial area of the local port authority with the aim of regenerating the export area and create a high quality urban environment. That project is also expected to be a powerful driving force for developing relations between Strasbourg and Kehl. A timetable of the project is given in table 1.

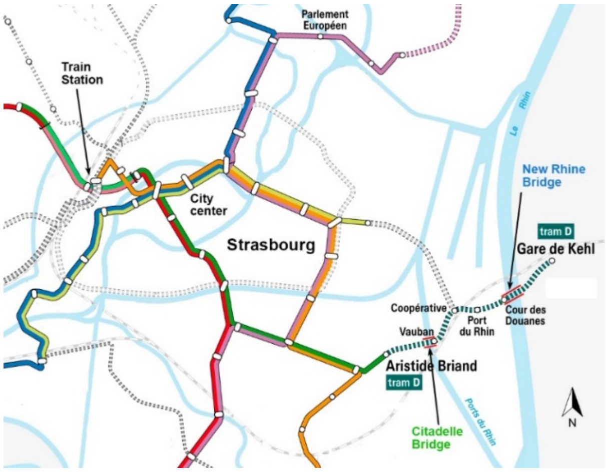

Fig. 1: Map of Strasbourg Tram showing site location © CTS

The implementation of the project needed the construction of four infrastructures: a cut and cover to reinstate the “rue de peage”, a railway bridge to pass over an existing railway line and two special bridges, the bridge over the Rhine and the Citadelle Bridge.

The Citadelle Bridge enables a two-track tramway and “soft” modes of transport (pedestrians and cyclists) to cross a canal and pass over a former towpath and an industrial railway line on the west bank of the canal. It will stand in the heart of the future urban area in the middle of the two constructible zones “Môle Citadelle” and “Starlette”, for which an urban study and development program are also underway.

Mission	**Date**
Architectural proposition	July 2012
Preliminary design	October 2013
Final design	Mars 2014
Public invitation to tender	October 2014
Choice of contractor	January 2015
Beginning of works	July 2016 (17 months)
Inauguration of the tramway	April 2017

Tab.1. Timetable of the project

2.2 Design Concept

Throughout the preliminary design, a global approach had adopted taking into account the technical constraints (optimal geometry for static equilibrium, functional constraints, ground conditions, construction methods) as well as an aesthetic vision for creating a landmark structure (structural form, design and shape of key elements, slenderness, efficient use of materials and efficient structural function, forms that follows the flow of internal forces naturally). The preliminary design done with the use of Inventor© software from Autodesk and the use of a complete 3D model for the definition of the geometry. The same model was served and updated until final design levels and production of drawings. The big challenge of the project was to define the geometry, find the optimum position for the arch and ensure in the same time the safety and serviceability of a tramway-bridge (a low acceptable deformations structure due to the presence of the tracks). The architectural treatment of the bridge has been done in close collaboration with Jean-Bernard Nappi, internal Architect in EGIS. The result was a bridge with qualities of transparency, lightness and harmonious proportions between the different elements.

Fig. 2 South view of the Citadelle Bridge © EGIS

2.3 General design of the structure

The Citadelle Bridge is a through arc bridge with a curved deck. All the main members are in steelwork. The deck has 163 m span between the abutments and is hung and supported by 30 locked coil rope cables from a single semicircular arch rib. There are 14 pairs of cables in the central zone and a single cable to each end of the deck.

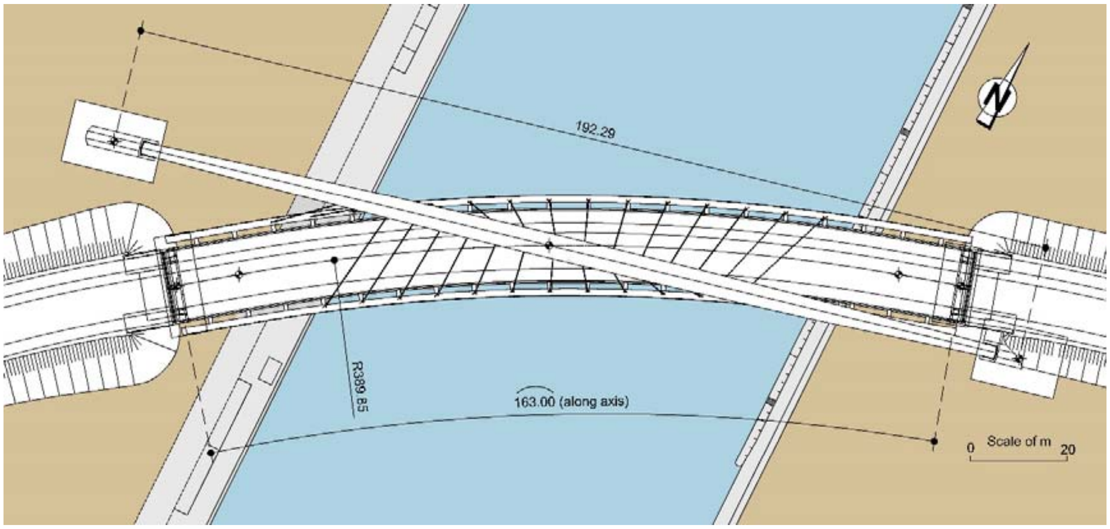

Fig. 3 Plan view of structure © EGIS

The arch of 180.50 m chord length spans diagonally across the deck and is made of a variable rhomboid steel box section. The section of the arch varies from 5.0 m wide and 2.5 m deep at the crown to 2.5 m wide and 5 m deep at its springings. The arc rises about 30 m above the deck level and his rise-span ratio is 0.20. The steel for the arch is S460N grade.

The deck is formed of a very slender steel box section of 1.43 m depth and 15.44 m wide and is fabricated as an orthotropic steel deck. The steel grades for the deck are S355K2+N, S355N (depending on the thickness) and S460N in highly stressed regions such as the anchorage zones of the cables.

The arch and the abutments of the deck founded on a granular soil using deep foundations (barrettes) and one of the two abutments was equipped with a preloaded spring damper for seismic isolation.

The longitudinal profile was specified by the obstacles to be crossed (a towpath and an industrial railway line) and in particular the requirement of the height over the waterway (9.0 m above the extreme water level). On the central zone of the deck, it consists of a circular profile with a radius of 900 m and at the ends two slopes of 4%. The cant of the tramway track has a zero value. The axis of the deck that follows the track alignment is curved in the center with a radius of 389.85 m and has two tangent parts at the ends to allow the installation of the expansion joints for the tramway tracks. These imposed constraints had complicated the design and had a significant impact on steelwork detailing.

The traverse profile has a functional width of 14.34 m and includes two footpaths of 2.00 m and 2.40 m respectively, one cycleway of 2.50 m and two tramway tracks for 6.44 m. The separation between tramway and pedestrians was created by aesthetics stones kerbs of 0.50 m width.

The system of the tracks on the deck is the same as that one outside of the bridge including biblock sleepers embedded in slab concrete with the exception that the blocks of the sleepers are in a rubber boot to improve the deformation behavior of the track due to the deflections of the bridge (the two concrete blocks of the sleeper are connected by a steel tie bar in order to build a defined gauge). The slab concrete of the tracks is poured directly on the waterproofing system who covers the top plates of the box girder witch it is not connected with it. The waterproof membrane is a liquid epoxy system sprayed-applied.

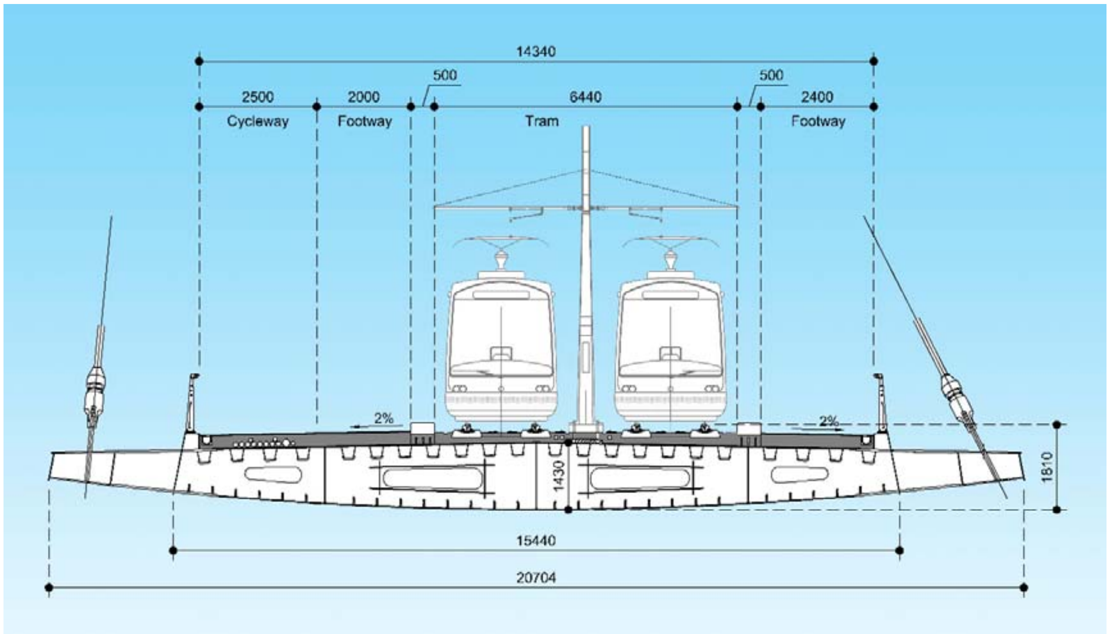

Fig. 4 Transverse section © EGIS

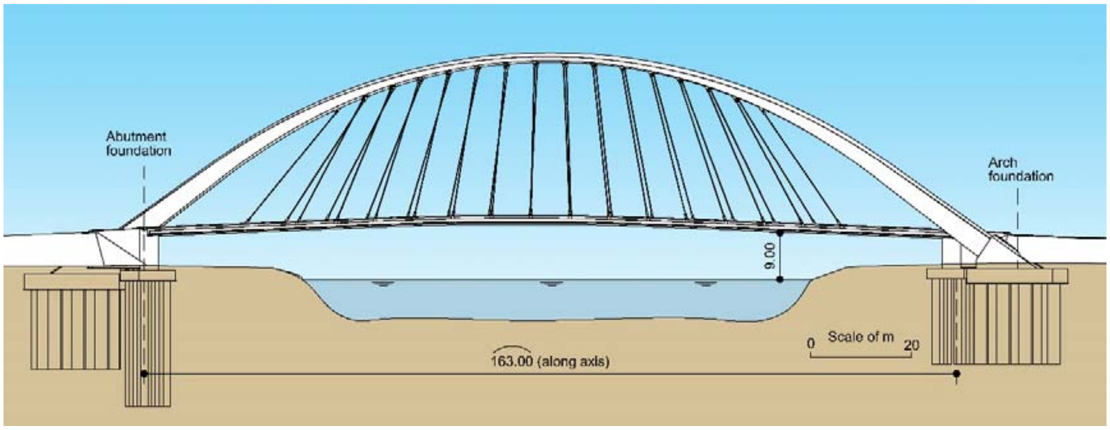

Fig.5 South elevation of the structure © EGIS

2.4 Geometric definition of arch

A reference axis used for the geometric definition of the arch. It is placed at 800 mm from the junction of the two top plates of the girder. It has a chord length of 180.75 m and a rise of 36.60 m. The circular part of the arch has a radius of 120 m and a circular length of 145.45 m, and followed by two tangents parts of 26.70 m each. The vertical symmetry axis passes from the crown of the arch and intersect the centerline of the deck in a way to produce two almost equals areas of loading. Therefore, the antisymmetric arrangement of the cables allows the load transfer from the deck to the arch in a similar way for the two half-parts of the arch which as a result the reduction of the out of plane bending moments of a non-uniform load case. The difference between a bowstring (a self-straining arch) and a simple through arch bridge is that the arch in the second case carries all the loads via the cables without any other connection with the deck and produces strong horizontal forces on his foundations.

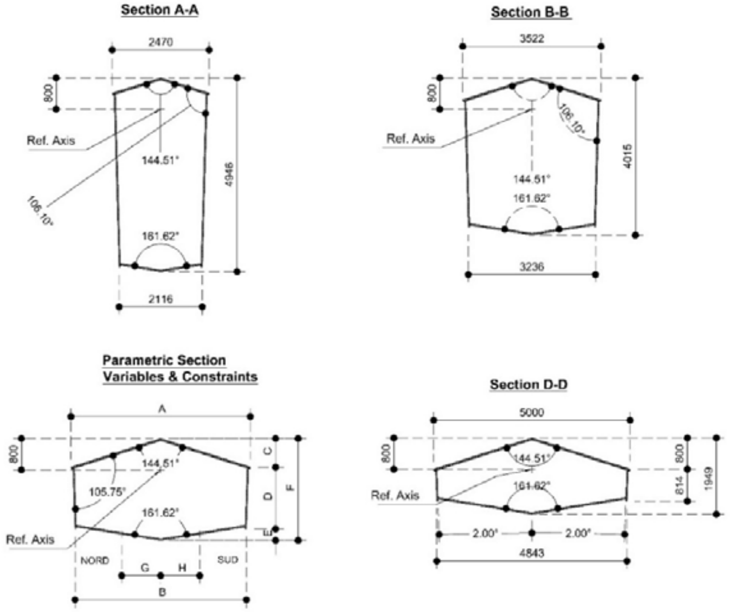

Fig. 6 Sections of the arch © EGIS

The two side faces of the arch are at 2° from the vertical symmetry axis when viewed in section at 90° to the reference axis of the arch. The total width of the two top inclined surfaces of the arch is such that all points at the edges of theses surfaces and in the intersection with the side faces, are in the same plane, so it varies from 5.0 m wide at the crown to 2.5 m wide at springings (this was important to avoid warped surfaces and facilitate the steelwork).

2.5 Geometric definition of cables

The geometric definition of the cables required to have 2.5 m clearance to the footway, 3.6 m clearance for the tramway but also 3 m radius clearance to the overhead contact system. This needed an arch with an important rise but also led to install the cables anchorages out of the main girder, in side box girders, connected every 8 m opposite to internals diaphragms of the main girder. After all, the side girders contribute also to the global rigidity of the deck.

The deck is hung by 30 full locked cables Galfan© coated (95% zinc and additional 5% aluminum composition) of 50 mm to 75 mm diameter with a minimal breaking load from 238 t to 562 t and a spacing of 8.0 m between them. There are 14 pairs of cables in the central zone and a single cable to each end of the deck. The connecting plates are 80 mm to 115 mm thick and enter into the arch and into the side box girders of the deck. A fan system is adopted to concentrate the anchorage of cables in the circular segment of the arch and consequently decreases the out of plane moment. The structure was designed to resist with the removal of a single cable either accidently either during managed replacement without interrupting the tramway traffic.

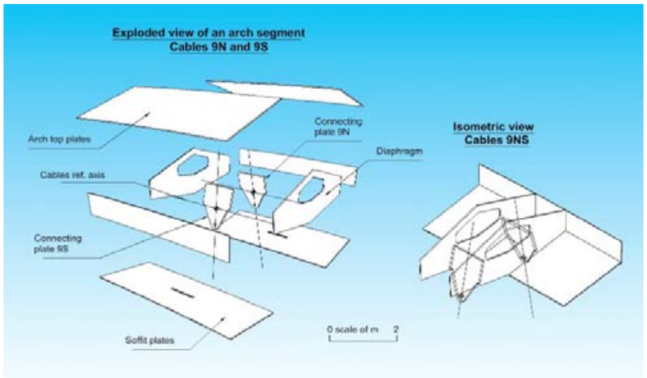

Figure 7: Exploded view showing the anchorage of the cables in the arch © EGIS

For each cable a connecting plate get into the arch and fixed on a double diaphragm that spread the force into the section. The cables are pin-connected on the connecting plates. One in every two diaphragms of the deck (every 8.0 m) are extended till the side box and connected with anchorage plate. The fixed anchors placed in the arch and adjustable anchors in the deck.

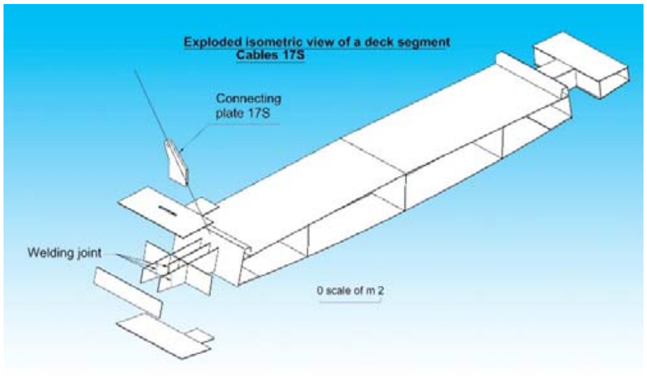

Fig. 8 Exploded view showing the anchorage of the cables in the deck © EGIS

2.6 Bridge deck

The bridge deck was designed as a closed box girder section for its high torsional resistance, suitable for the horizontally curved alignment. The bottom plate is a circular segment with a radius of 80.0 m. The maximum height is 1.43 m in the middle and the minimum is about 0.80 m at the edges, it seems to an airplane wing and make it more slender for the viewer. The top plates are 14 mm thick and the bottom plates are for the most of the part 12 mm except the anchorage zones where it was created a reinforced region with a thickness of 18 mm to 25 mm. The top and the bottom plates are stiffened longitudinally by closed stiffeners for the top plates and open stiffeners for the bottom plates (during the construction phase the open stiffeners were replaced by closed ones since it was easier to manage the curved alignment of the deck with straight segments of closed stiffeners). They are through shaped with the follow dimensions 240 x 300 x 6 mm for the top plates and 220 x 400 x 6 mm for the bottom, and pass through the diaphragms which are placed every 4 m.

2.7 Structural system and foundations

The deck transfer loads via the cables and four special pot bearings placed on the abutments. These bearings are capable of supporting strong horizontal forces combined with weak vertical forces since the arch support already an important part of the vertical loads. In each abutment a central guided sliding bearing and a free sliding bearing are installed to fix the deck in transverse direction. In the longitudinal direction a preloaded spring (PSD with spring function only) is installed on the west abutment. It fixes the deck longitudinally for the service loads and functions as an isolator for seismic loading. In order to be avoided the displacement before reaching a certain force level (ULS horizontal reaction), it is preload with a force of 4200 kN. This choice is taken during the detailed design in order to optimize the foundation of the abutments, seismic energy is dissipated in the PSD unit instead of being dissipated in concrete structure. The seismic loads in transverse direction are transferred by the pots bearings.

The arch is fixed to his springings without any hinge joints. The connection between the arch and each foundation is made with 48 prestressed bars of 58 to 66 mm diameter each. The bars are placed inside the arc section to avoid external exposition and to limit maintenance. The arch is connected to a massif concrete block that has the same form and inclination with the arch. This block is about 6.0 m high (4.0 m outside of the ground) 4.0 m width and has angle of 40 degrees with the ground. It resists on large horizontal forces in an area where the ground condition is poor (alluvium deposits containing sands, silt-sands and gravels), for that reason is supported by a big footing of 3.0 m high and 16.0 x 7.0 section that diffuse the forces in 3 barrete piles of 6.0 m x 1.2 m section disposed with the large side in the transverse direction. They are 20 m deep to reach a layer of dense gravel. This rigid system for the foundation is necessary to limit the horizontal displacement of the arch and ensure his stability.

In preliminary design, abutments of 8 m high are a full height type abutments with a cantilever front wall that are strengthened by three T beams and supported by ten circular piles via a pile cap. In the detailed design and due to the usage of the PSD and the decrease of the forces to transfer, the constructor proposed and replaced the piles by three barrettes-columns of 3.6 m x 0.8 m section connected directly to the cross beam that supports the deck. The front wall reserved to retain the backfill material and to support the architectural decoration, gabions filled with local granite from Vosges with rose color.

3. CONSTRUCTION

3.1 Foundations

The construction of the foundations took place in three stages: construction of the foundations at the west side, transfer of construction equipment from one side to the other, construction of the foundations at the East side.

The ground of the site is characteristic for the Rhine valley, it consists of pebbles, sands, silt-sands and gravels (along the depth of the excavation). The drilling is conducted with the use of a KS hydraulic grab and bentonite mud. However, when the first panel is opened, the ground turned out to be much more permeable and spongy than expected. In order to guarantee the safety of the staff and the drilling equipment, the method of excavation are adapted due to the total loss of excavating fluid (bentonite) and collapse of the soil around the trenches. The technique used to overcome this difficulty is a pre-impregnation of ground with grout. A first excavation carried out with grout and then backfilled. The grout then diffused into the permeable ground, consolidated and reduced the permeability. This technique allowed to have sufficient resistant of the soil around the trenches during the re-excavation and thus to limit the loss of bentonite.

3.2 River work

Two temporary supports (auxiliary piers) were necessary into the canal for the erection of the deck and the lifting of the central segment of the arch. Tubular steel piles of 1200 mm dia. were used and driven over ten meters deep in the canal-bed. In order vessel collision to be avoided on the supports four dolphins (rectangular shaped sheet pile walls) were installed using a vibratory hammer. These works was executed using a mobile crane set on a barge (Figure 10).

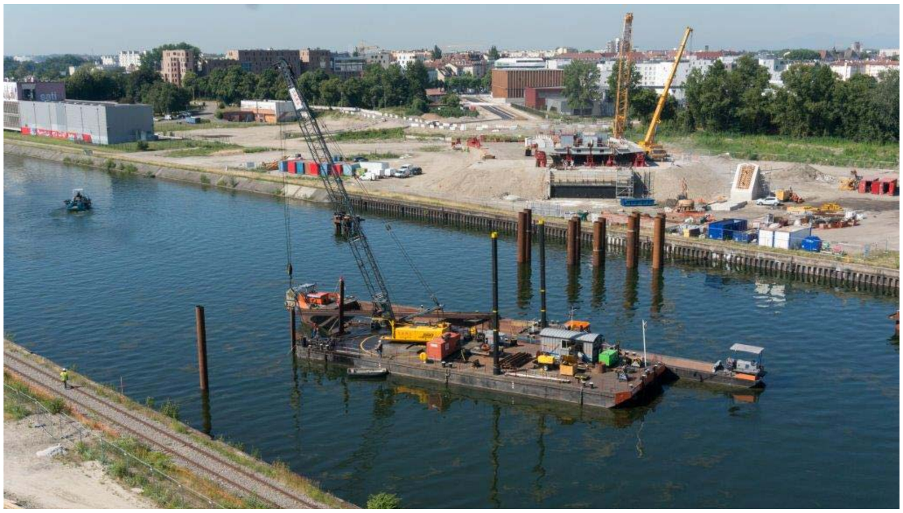

Fig. 9 View on the river work © EIFFAGE METAL

3.3 Abutments and Arch springings

A GTMR crane used for the construction of the abutments and anchorage blocks, first on west side and then transferred to the east side of the canal. Two teams were working simultaneously on each side to respect the short schedule and deliver the supports on time for the erection of the steel structure. The geometry of the supports are already described above. The wing walls were designed as a free standing independent structures of the abutment wall and founded on spread foundation. However due to poor ground condition especially on the east side, the ground was reinforced using Controlled Modulus Columns (CMCs) to improve the soils characteristics and reduce imposed settlements. C35/45 concrete used both substructure and foundation. Steel formwork covered by wood panels was used for the erection of substructures. Attention was given to anchorage block of the arch for the concreting of the inclined surfaces as well for the accurate integration of the anchorages bars. For that reason, a special steel framework was cast in the block incorporating the 48 bars and two tapered dowels to guide the arch into the final position

(Figure 11). A trial assembly performed in the fabrication shop before the final assembly on site and the integration of a very dense reinforcing steel cage (Figure 12).

Fig. 10 Support of the arch anchorage © EIFFAGE METAL

3.4 Steel works

The arch was shop-fabricated in fifteen segments. The deck was divided in 7 longitudinal segments and 4 transversal, thus in total 28 elements. The size of elements was: for the deck about 26 m long and 6.20 m width, for the arch 15 m long 4.0 width 4 m high for a weight of 100 ton max. All these segments were prepared in the fabricator's workshop (including painting) at Lautebourg workshop of EIFFAGE METAL and then transported to the site via 43 exceptional convoys (for 60 km a full day trip needed).

The first 100 m of the deck was assembled behind the west abutment and then pull out by incremental launching until the first temporary support situated into the canal. In a second time the last 60 m was assembled and welded to the already erected part of the deck.

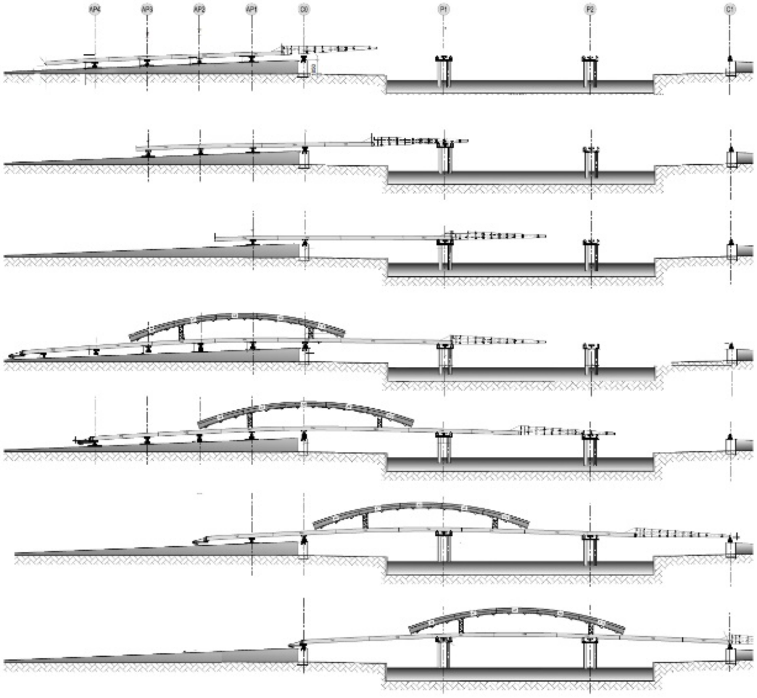

Fig. 11 Incremental launching of the deck © EIFFAGE METAL

The assembly of the first sections of the arch started at the same time on the both sides of the canal regarding the following stages:

- Erection by crane of the two first sections of the arch, placed on the anchorage blocks and on temporary supports and then welded together.
- Filling the space between the block and the back plate of the arc by two-component non-shrink grout.
- Pre-assembling on the ground of the sections 3 and 4
- Prepressing the connection bars
- Placing of the pre-assembled segments on the ground on the temporary supports and on the segments that have already been built up and the welding them together.

The central segment of the arc, consisting of 5 sections, was assembled and placed on the deck in vertical alignment with his final position, before the second launching (Figure 13). At the end of the second launching, additional temporary supports were partly installed on the deck and partly on the existing supports into the canal. At the top of these supports (40 m above the deck), four jacks were installed and equipped with cables of 200 t capacity each, in a few hours, the central segment of the arch of 400t and 80 m length arrived at the almost-final level launching (Figure 14).

During the same week, the following operations were accomplished:

- Lifting of the central segment of the arch,
- Erection by crane of the west arch’s last element and temporary connection,
- Tolerance adjustment of the arch,
- Erection by crane of the east arc’s last element and temporary connection.

Fig. 12 Lifting the central part of the arch © EIFFAGE METAL

After the welding of the two last elements, the two structures - arch and deck- separated the one from the other, were ready to be connected by the cables. As soon as there was a difference between the current erection’s levels than the expected final level, an adjustment of the deck had to be done and reach the final longitudinal profile.

The installation of the bridge accessories was able to start after removing the temporary supports. Subsequently, it’s validated the achievement of the corrosion protection, the waterproofness, the placing of the different sheaths and gutters, the installation of the separated border between the tramway area and the pedestrian zones, the concreting of the pavements, the placing of the asphalt and finally the installation of the guardrails.

4. DATA BLOCK

Main contributors and material quantities are presented in table 2 below.

Data block	
Owner:	Eurometropole de Strasbourg represented by « Compagnie des Transports Strasbourgeois »
Designer :	EGIS
Main contractor:	Eiffage Metal - GTM Halle
Steel (t) :	2350
Concrete (m^3) :	3200
Reinforced steel (t):	480
Cables (m):	920

Tab.2. Data block

5. ΠΕΡΙΛΗΨΗ

Η γέφυρα Citadelle επιτρέπει στην προέκταση της γραμμής B του τραμ της πόλης του Στρασβούργου να διασχίσει το κανάλι Vauban στα ανατολικά όρια της πόλης και στη συνέχεια περνώντας πάνω από τον ποταμό Ρήνο να φτάσει στην γερμανική πόλη Kehl. Γεωμετρικά βρίσκεται σε χάραξή με καμπυλότητα σε κάτοψη και σε μηκοτομή. Αποτελείτε από ένα μεταλλικό τόξο με άνοιγμα 180 μέτρα και μεταβλητή ρομβοειδή διατομή. Το κατάστρωμα αποτελείται από κιβωτιοειδή μεταλλική διατομή και είναι αναρτημένο από το τόξο μέσω μιας σειράς μεταλλικών καλωδίων. Το τόξο διασχίζει διαγώνια το κατάστρωμα Το έργο μεταφέρει τα φορτία στο έδαφος μέσω βαθιάς θεμελίωσης στις αμμώδης αποθέσεις του Ρήνου. Είναι εξοπλισμένο με ένα προεντετατεμένο αποσβεστή για την βελτιστοποίηση της σεισμικής συμπεριφοράς του φορέα. Η μεταλλική κατασκευή τοποθετήθηκε μέσω μιας περίπλοκης διαδικασίας και διαδοχικών φάσεων κατασκευής : αρχικά με προώθηση του καταστρώματος από το δυτικό βάθρο, στην συνέχεια τοποθέτηση ενός μέρους του τόξου στο κατάστρωμα, έπειτα ξανά προώθηση μέχρι την τελική του θέση με χρήση προσωρινών στηρίξεων μέσα στο κανάλι και τέλος ανύψωση του τόξου με τη χρήση προσωρινών πυλώνων.