Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.dimk.rs

doi: 10.5937/GRMK2203115M UDK: 624.21(497.7)
Technical paper

Two new bridges over the river Vardar in Skopje

Goran Markovski*[1)], Marija Docevska[1)], Viktor Markelj[2)]

[1)] *Faculty of Civil Engineering "Ss. Cyril and Methodius" University, Blvd. Partizanskiodredi 24, 1000 Skopje, N. Macedonia*
[2)] *PONTING Ltd., Strossmayerjeva Street 28, 2000 Maribor, Slovenia*

Article history

Received: 23 August 2022
Received in revised form:
03 September 2022
Accepted: 03 September 2022
Available online: 30 September 2022

Keywords

integral bridge,
extradosed bridge,
free cantilever method,
box girder,
construction stages,
stay cables,
pylons

ABSTRACT

This paper presents some aspects of the design of two new bridges over the River Vardar in Skopje.

"Mihajlo Apostolski" is an integral bridge, consisting of two separate structures (22.05 + 50.50 + 21.05 m = 93.6 m length and 15.3 m width). The bridge deck is made up of a two-cell prestressed cast-in-situ box girder with a parabolically variable cross section. The abutments and the piers are wall-shaped and supported on single and double row piles, respectively. The side spans, together with the approaching structures, were proposed to be built on traditional scaffolding, while the middle span over the minor riverbed was built with a free cantilever method.

The extradosed bridge at Ljubljanska Street is 27.5 + 56 + 27.5 m = 111 m long and 24.1m wide. The ribbed deck (two post-tensioned main girders, cross girders, and deck slab) is supported from above by 32 parallel stay cables. The 12.6 m high pylons are located at the intermediate supports. In the base, the four piers have a rectangular cross section that has been rotated 45 degrees. The superstructure is supported by pot bearings. A deep foundation on piles was chosen. Cast-in-place construction of the superstructure was foreseen.

The design of the bridges was done according to Eurocodes and respecting the fib and PTI recommendations. Detailed numerical analysis was carried out in the FEM software SOFiSTiK and additional auxiliary software.

1 Introduction

The Vardar River runs along the longer side of Skopje for about 25 kilometers. Such a river orientation necessitates a greater number of bridges to allow for more efficient traffic communication between the city's north and south sides. Following the catastrophic flood of 1962, the river bed was completely regulated to a total width of about 100 m, depending on the location. In the midst of the major bed, a 50-m-wide and 3-m-deep minor bed was formed. On its left and right sides, there are recreational footways that end with 3-m-high quay walls.

Such a cross-section of the river bed (approximately 25 + 50 + 25 m) along with the quite unfavourable hydrological parameters (a small difference between the finished levels of access traffic lines and the flood water level) create real problems in the conceptual design of bridge structures and inevitably lead to certain mutual concessions.

At present, in the area of Skopje City, nine road bridges are functional. All of these are made of concrete (reinforced or prestressed). Most of them have three spans. Several different static systems are present.

Both bridges presented in this paper were designed in 2019 and 2020, respectively. The investor was Skopje, while the project operator was the Geing Ltd. Company from Skopje. The design solution for the bridges was elaborated based on previously prepared projects on the infrastructure, considering the following defined parameters:

- The finished level of the traffic line;
- The position of the structure on the site plan;
- The width of the traffic line, the cycling paths, and the sidewalks;
- Data on flood waters with a return period of 100 years and the necessary hydraulic opening.

The first bridge has already been constructed, while the construction of the second one started in August 2022. The contractor for both structures is Granit Ltd. Company from Skopje.

* Corresponding author:
E-mail address: markovski@gf.ukim.edu.mk

2 Integral bridge "Mihajlo Apostolski"

The "Mihajlo Apostolski" bridge is part of the ASNOM boulevard extension project.

The traffic solution anticipates that the relatively long access ramps to and from the cross-road located on one side (Fig. 1) are a constituent part of the bridge structure. This poses serious limitations on the elaboration of possible variant solutions.

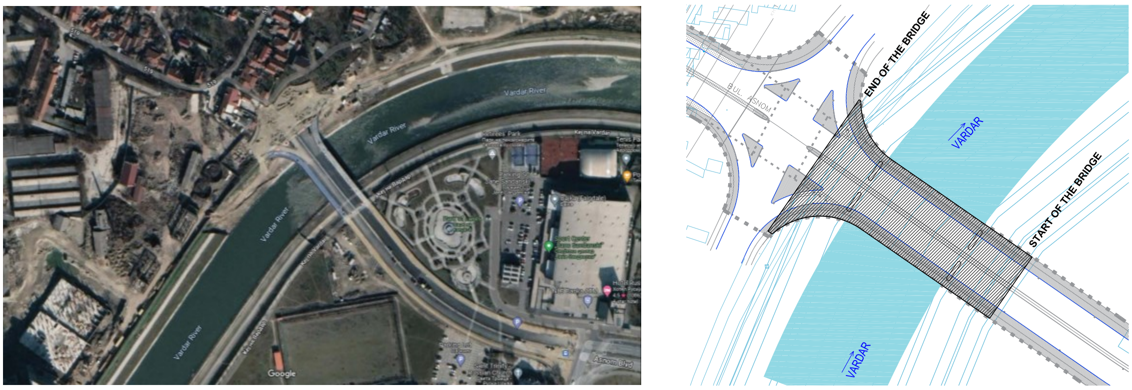

Fig. 1. Position of the bridge on the site plan

A frame with three spans of 22.05 + 50.5 + 21.05 m = 93.6 m (Fig. 2, 3) was selected as the final solution. Such a ratio of spans arose from the condition that the middle piers had to be placed on the slopes of the minor river bed. The bridge consists of two branches that represent separate structural units. The width of each branch is 15.3 m, and it includes: three traffic lanes of 3 m each, 5.2 m for the pedestrian and cycling paths, and two parapet beams for anchorage of the fence systems. The span of the access ramp on the left branch of the bridge is 32.75 m, whereas that of the right one is 25.73 m.

The adopted system is also known as an integral type of bridge. This enables the avoidance of bearings and expansion joints over the abutments that indirectly affect the durability and the cost of the structure. However, on the other hand, the integral solution requires a more detailed analysis of indirect effects as follows: temperature variations, the creep and shrinkage of concrete, and the settlement of supports. Although the standards [1] prescribe this type of bridge for lengths of up to 100 m, lately, such structures have also been constructed to much longer lengths (250-350 m).

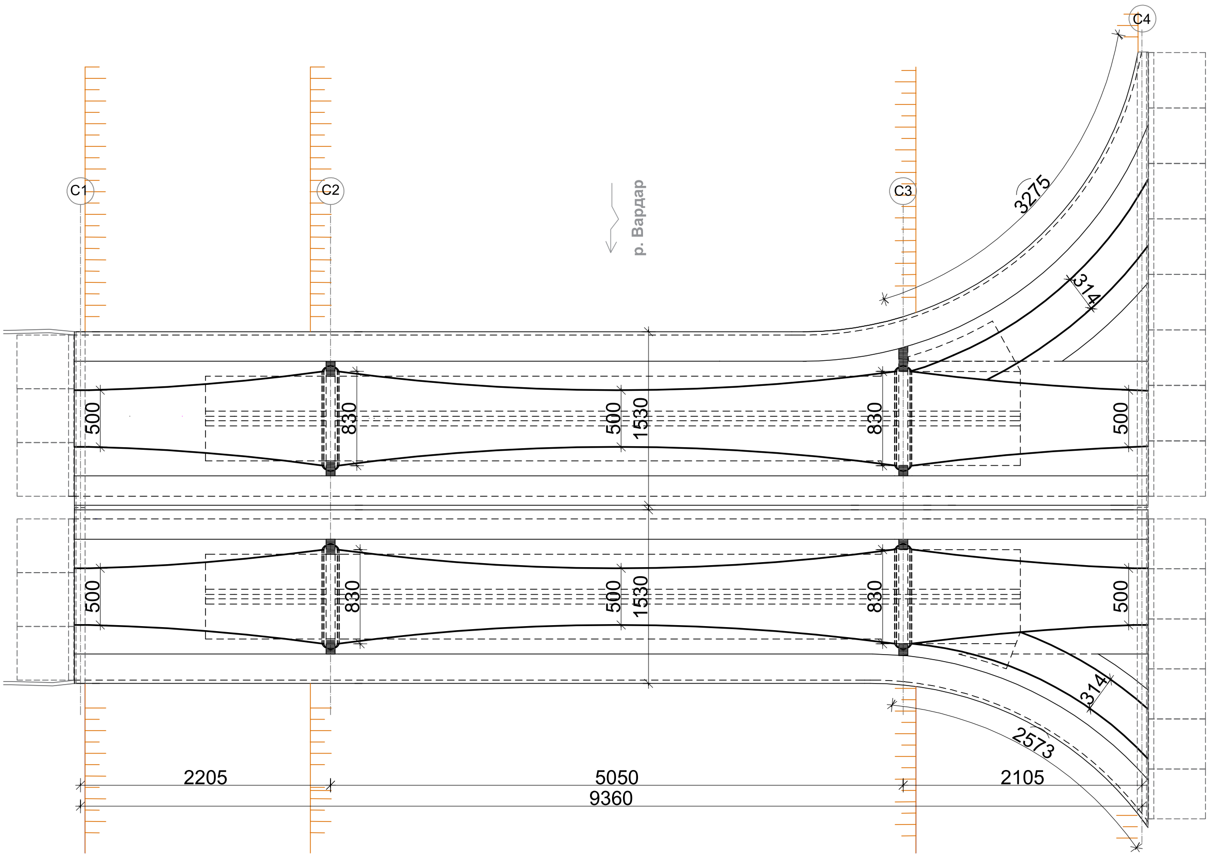

Fig. 2. Bridge plan

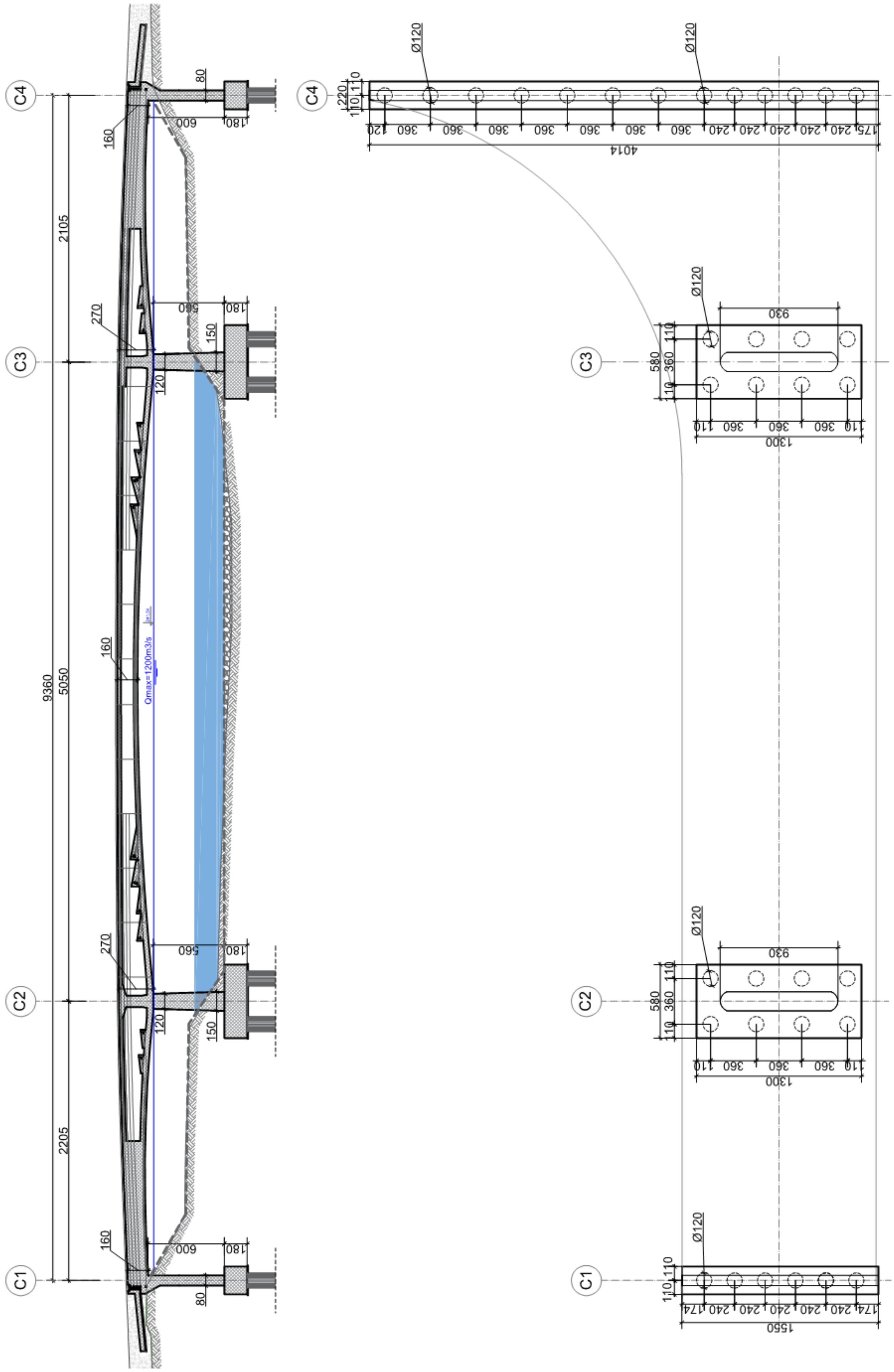

Fig. 3. Longitudinal section (left) and plan of the foundations of the left branch (right)

2.1 Superstructure

The superstructure of the bridge consists of a cast-in-situ, prestressed, double-cell box girder. It has a parabolically variable height and width of the lower deck that also leads to variable inclination of the webs (Fig. 4). The height of the cross-section in the middle of the main span and that over the abutments amounts to 1.60m (L/31.5). Over the piers, it amounts to 2.70 m (L/18.7). The adopted heights are within the recommended limits for this type of structural system. The width of the lower edge of the box girder is also variable, ranging from 5.0 m in the middle of the central span and over the abutments to 8.30 m over the piers.

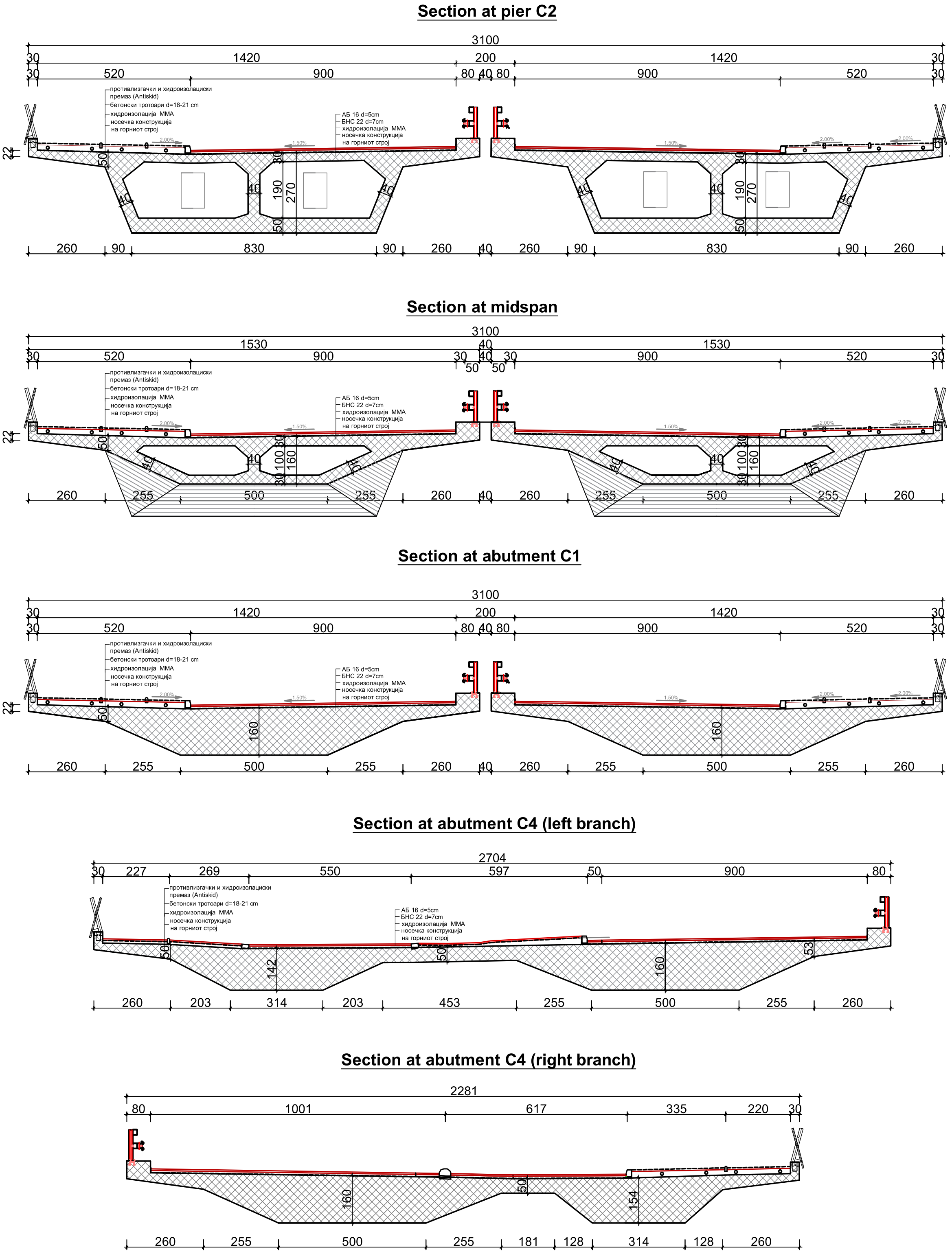

Fig. 4. Characteristic cross-sections of the bridge

The top slab of the box section has a constant thickness of 30 cm along the entire length of the structure, whereas that of the bottom slab starts at 50 cm at the supports and decreases to 30 cm in the midst of the central span. The webs have a constant thickness of 40 cm. The cantilever overhangs are at a span of 2.60 m, whereas their thickness ranges from 22 cm at the parapet beams to 50 cm at the place of fixation into the webs.

At one half of the end spans, the box girder section turns into a solid section to avoid negative reactions at the abutments in all phases of construction and serviceability.

In the part of the access ramps, the girder has a constant width of 3.14 m, whereas its height starts at 2.7 m at the central pier C3 and ends at 1.42 m at the abutment C4 on the left, i.e., 1.54 m on the right bridge branch (Fig.4).

2.2 Substructure

The substructure of each branch consists of two central piers and two abutments. The central piers are in the form of rounded walls with a width of 9.30 m and variable thickness: 1.50 m at the fixation in the pile cap, up to 1.20 m at the top. Their height from the upper edge of the pile cap to the lower edge of the main girder is 5.60 m (Fig. 3).

The abutments are rectangular in plan, with a thickness of 0.80m and a height of 6.00 m (Fig. 3). They are designed without wing walls, which contributes to their greater flexibility.

At the considered location, there are terraced alluvial sediments composed of well-granulated, well-compacted sand and powdered gravel. The foundation below all piers is represented by reinforced concrete piles with a diameter of 1.20 m. The abutments are founded on single-row piles (6 below C1 and 13 below C4) with a length of 12.0 m that are interconnected by a pile beam with a cross-section 2.20/1.80 m. Below the central piers, double-row piles (8 below C2 and C3 each) with a length of 15 m are adopted. The pile cap is 1.80m thick (Fig. 3).

2.3 Equipment

Considering the monolithic connection between the superstructure and the abutments, the adopted expansion joint is placed beyond the bridge, i.e., between the abutment and the transition slab. It enables horizontal displacements of up to +/-40mm and is proportioned for service loads (temperature, braking forces, creep, and shrinkage of concrete). The carriageway expansion joint type is Wd/Wd +80, while the sidewalk expansion joint type is TO 80 (Freyssinet) (Fig. 5).

To make the transition slab remain in a fixed position during horizontal displacement of the structure, a strip-like movable bearing between it and the short element of the abutment has been adopted. This detail has been adopted in accordance with the German Standard [1] and holds for integral bridges with a total length exceeding 50 m (Fig. 5).

For the horizontal bridge surfaces, waterproofing based on methyl methacrylate (MMA) is anticipated. This type of waterproofing consists of a primer layer and a double-layered MMA membrane (Fig. 6). It is applied over the entire bridge surface, where, in the part of the carriageway, there is a double-layered (7 + 5 cm) asphalt, whereas in the part of the sidewalks and cycling paths, monolithic sidewalks (20 cm) are cast, with a finishing anti-skidding, waterproofing layer (Antiskid).

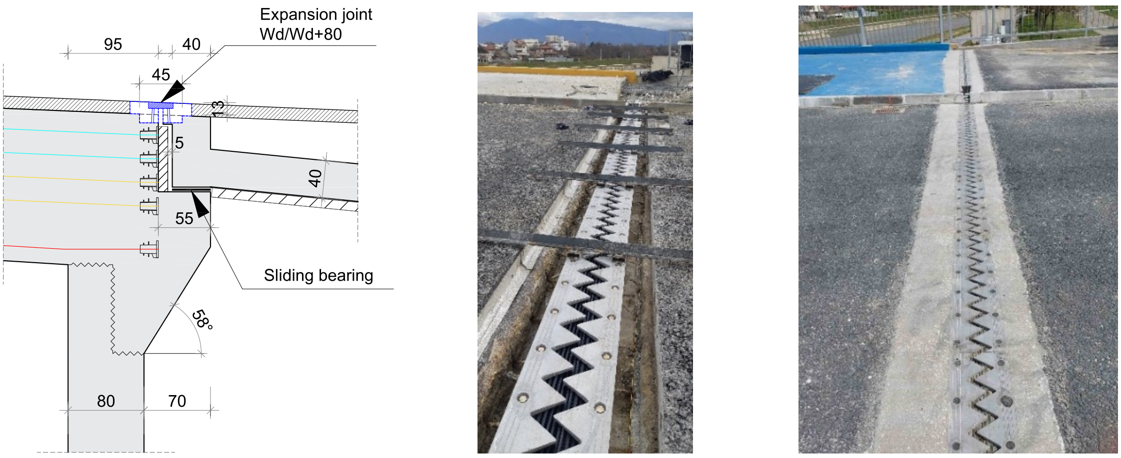

Fig. 5. Detail of an abutment, carriageway and sidewalk expansion joint

Fig. 6. Application of MMA waterfroofing and anti-skidding layer (Antiskid)

On the outside, the box girder is coated with a protective coating called Antikorozin BB. The central piers are coated with granite plates with a thickness of 5 cm.

Anticipated on the side of the footways is a specially designed for that purpose pedestrian steel fence (Prof. Dr.MitkoHadzi-Pulja, grad. architect, Fig. 7), while on the opposite side, an elastic restraint system type H2W4 according to EN 1317 [2] standard is planned.

Anticipated for drainage of atmospheric waters are ACO gullies in compliance with DIN EN 124 [3], pipes of composite material GRP (ISO 25780:2011), and water-purification shafts.

2.4 Methodology of construction

Taking into account the configuration of the river bed, a combined methodology of construction has been selected. The end spans along with the access ramp are proposed to be constructed using the traditional scaffold, whereas free cantilever construction is proposed for the central span that bridges the minor river bed. The central span is constructed in five phases, 4.3 m each from the side of piers C2 and C3. The segment for connection of the left and the right cantilevers has a length of 3.63 m (Fig. 8-10).

From the assumed methodology of construction, the final number and distribution of prestressing cables have emerged. First of all, the cables in the bottom zone of the first and third spans are prestressed (12 cables each), and then the cables in the bottom and top zone of the access ramps (10 in the bottom and 29 in the top zone) are prestressed. For each phase of construction of the central span, 10 cables are anticipated for the top zone, i.e., a total of 50 cables over piers C2 and C3 that are successively prestressed. Following the connection of the two cantilevers, prestressing of the 30 cables in the bottom zone of the central span (the so-called cables for continuation) (Fig. 9) is done.

Fig. 7. View of the constructed bridge

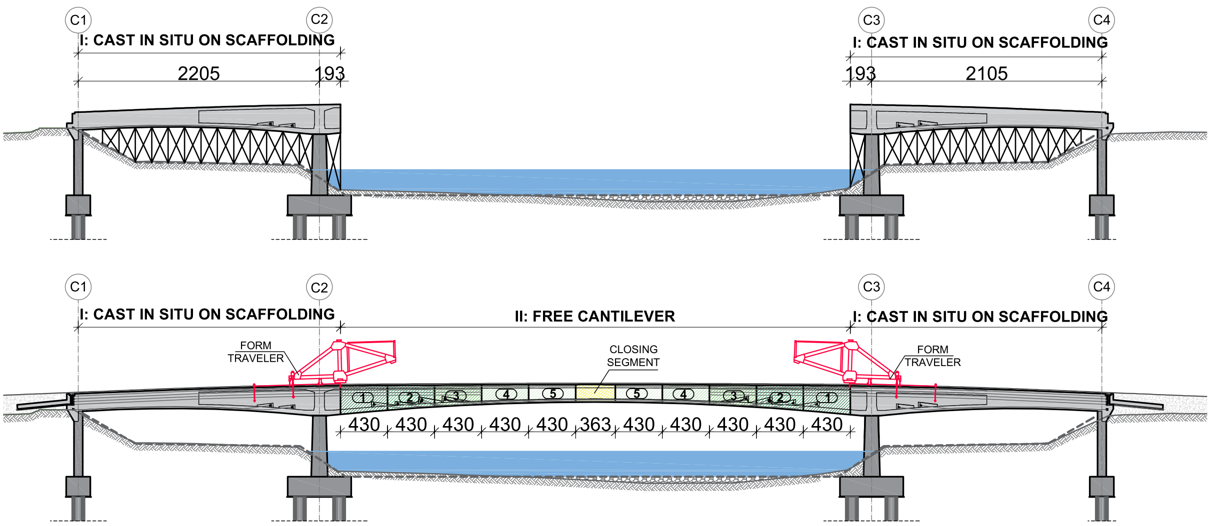

Fig. 8. Proposed methodology of construction

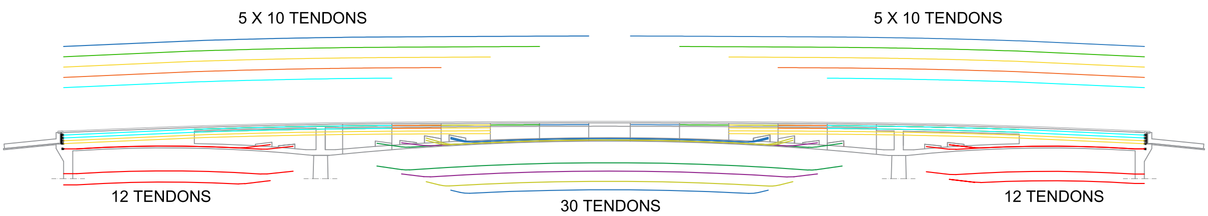

Fig. 9. Prestressing cables in longitudinal section

Fig. 10. Methodology of construction

Anchorage of top cables is done at the end of the constructed segments, while in the case of those for continuation, anchorage blocks are on the bottom slab of the box section.

Detailed numerical analysis has been done for the adopted methodology of construction.

2.5 Numerical model

Complete static and dynamic analysis of the bridge has been done in accordance with the Eurocodes [4-10] by use of the SOFiSTiK software. For designing the structure in the longitudinal direction, a 3D model was built. In this model, all structural elements have been modeled as beam finite elements (Fig. 11). The model also includes the prestressing cables with their real geometry for the purpose of more accurate computation of prestressing losses. The elements have been divided into groups depending on the construction phases in which they are activated. The change in the static system has also been taken into account.

Due to the specificity of the system (an integral bridge), the piles under each pier position have been incorporated into the model. Their deformability has been included through horizontal and vertical springs placed along their perimeter and a spring at the lower base.

Since the access ramp and the main girder of the third span are monolithically connected, their joint behavior has been simulated through mutual connection with rigid elements (“constraints”).

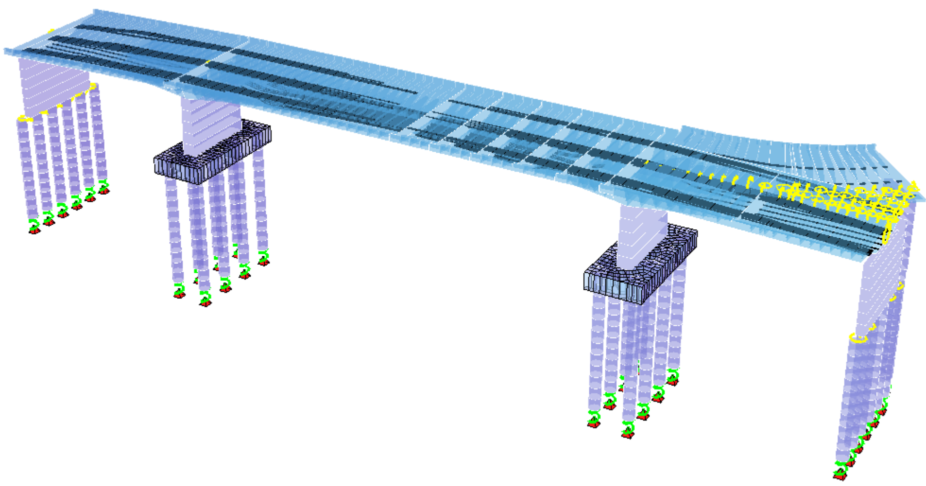

Fig. 11. Numerical model of the bridge in SOFiSTiK

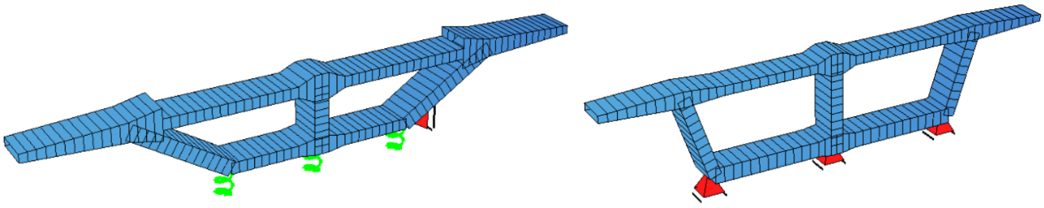

Fig. 12. Numerical model of a single segment in span and above support

Taking into account that this model cannot be used to describe the behavior of the box section in a transverse direction, two additional models of a segment of the box with a unit length have been built. One of these describes the behavior of the box section in span, and it is therefore supported by elastic springs whose stiffness is defined through the vertical deformation at that section. The other model is for the segment above a support, and it rests on rigid supports (Fig. 12). All of the box girder's individual elements are represented by beam-finite elements.

2.6 Analysis

Several different programs were used for the analysis of the structure. The design of the pile foundations was performed in multiple iterative steps between the numerical models built in SOFISTiK and GEO 5. The superstructure was designed separately in longitudinal and transverse directions since the beam model was not sufficient for both. The number, the disposition, and the force in the tendons were defined by the main model and for the most part dictated by the methodology of construction. The segmental construction required analysis of the following construction stages for each segment: casting of the segment, prestressing of top tendons, creep and shrinkage, removing of the traveler formwork, and its placement at the end of the finished segment. The non-prestressed reinforcement in the transverse direction of the box girder was obtained from the analysis carried out on single segments at midspan and at support (Fig. 12). Finally, the load bearing capacity at the cross-sectional level was checked in the auxiliary software CUBUS Fagus 8 using the final dimensions of the box girder and the adopted tendons and non-prestressed reinforcement.

3 Ljubljanska street extradosed bridge

The bridge on Ljubljanska street over the Vardar river in Skopje represents part of the project on the connection of Ilinden Boulevard with Slovenechka Street in Karposh municipality (Fig. 13).

The selected structural solution represents a structure supported from above by parallel stay cables. Considering the configuration of the river bed in the area of the bridge, two variant solutions have been analyzed. The one includes two spans and a higher pylon, whereas the other has three spans and two lower pylons.

Considering that a higher pylon and hence steeper cables limit the line of sight, imposed as the final solution is a structure over three spans (27.5 + 56 + 27.5 m),with two lower pylons and parallel cables. The total length of the bridge is 111 m, while its width is 24.1 m (Figs. 14, 15). It includes 4 traffic lanes of 3 m each, 2 footways and cycling paths of 4 m each, 2 parapet beams for anchorage of the pedestrian railing, and 2 x 1.75 for accommodation of the pylons and the New Jersey restrained system.

The adopted system is known as “extradosed” (a hybrid solution between a traditional girder and a cable-stayed bridge). The main characteristic by which this system is visually distinct from cable-stayed bridges is the small height of the pylons and the mild inclination of the cables. Another specificity of “extradosed” bridges is the higher stiffness of the superstructure compared to that of the cable-stayed bridges and a lower stiffness compared to that of the girder bridges. The higher stiffness contributes to a slight activation of the stay cables under traffic loads that consequently leads to minor changes in the stresses in the cables. Hence, in respect to vertical effects, the cables of “extradosed” bridges mainly sustain the dead loads of the carriageway structure. Therefore, the level of cable stress in these bridges is allowed to be higher compared to that of cable-stayed bridges.

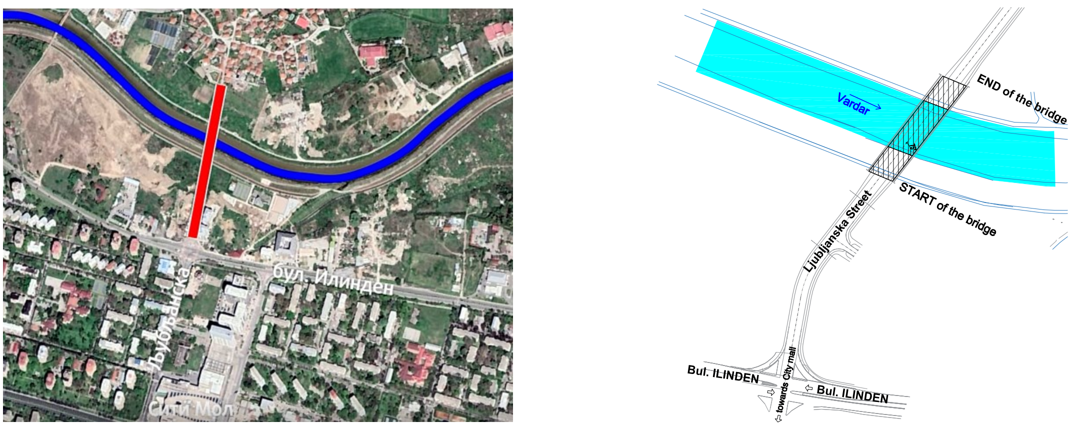

Fig. 13. Position of the bridge on the site plan

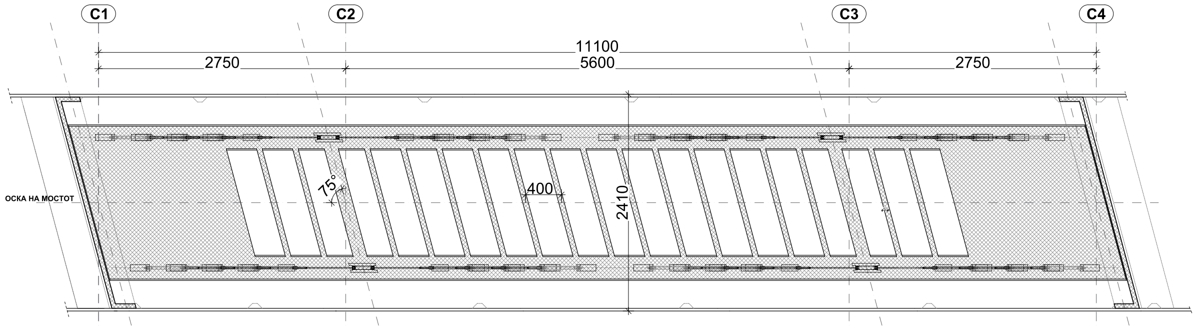

Fig. 14. Bridge plan

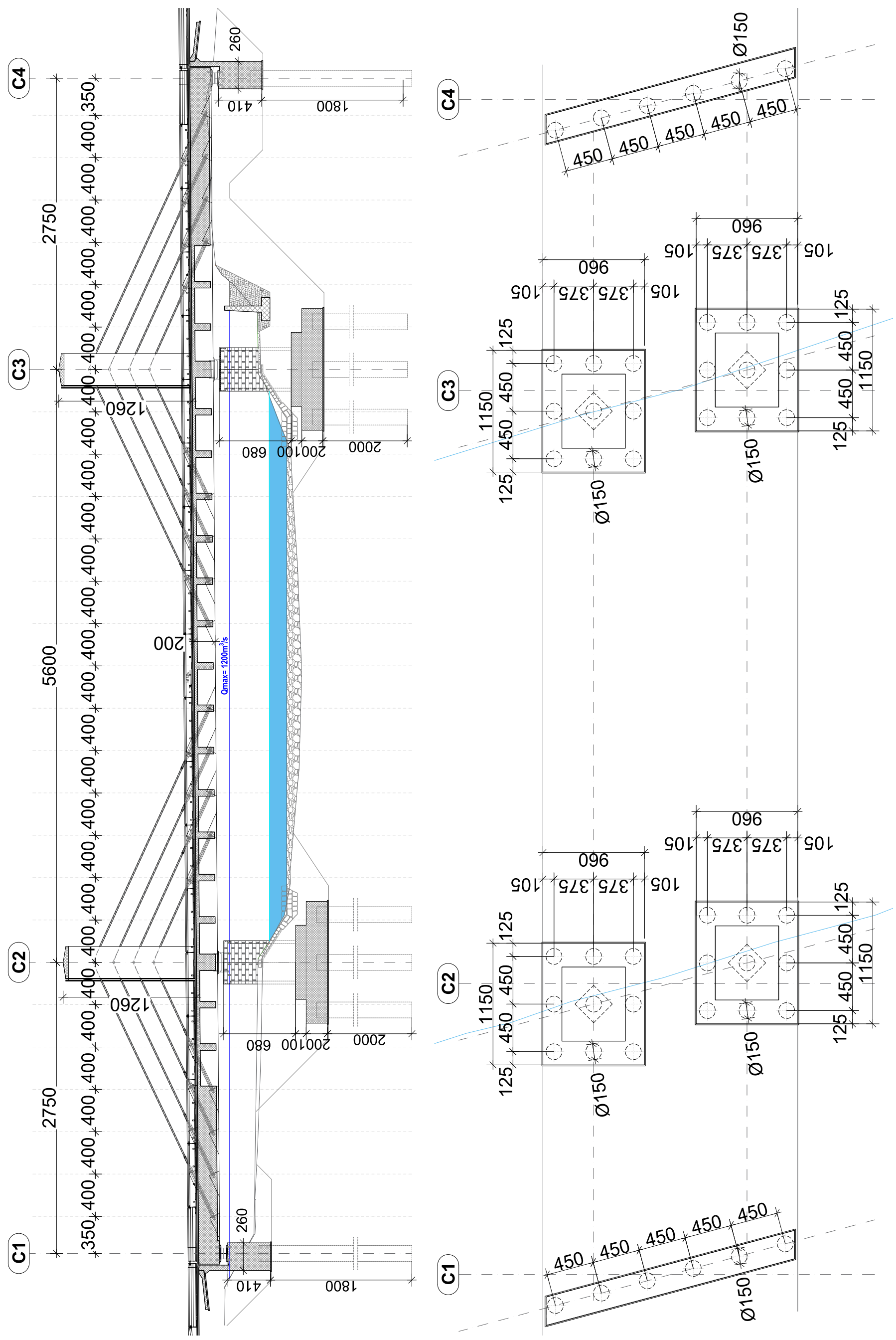

Fig. 15. Longitudinal section of the bridge (left) and foundation plan (right)

Although it is considered that this solution is optimal for bridges with spans of 100 to 200 m, “extradosed” bridges have lately also been constructed for smaller spans, as are the Bergwijk Bridge in Belgium and several overpasses and bridges in Poland [11].

3.1 Structural Elements

The bridge superstructure represents a monolithic ribbed deck “suspended” by parallelly installed 32 stay cables, which is composed of two prestressed main girders, reinforced concrete cross girders, and a bridge deck. The main girders have a constant height of 2 m (L/28). Their cross-section is of a trapezoidal shape with a width of 2.5 m at the lower edge and a width of 2.8 m upwards connection with the bridge deck (Fig. 16). They are placed at an axial distance of 14.5 m.

The middle cross girders have a rectangular cross-section of 0.60/1.80 m and are placed at an interdistance of 4.0 m. They intersect with the main girders at an angle of 75˚ (Fig. 17). The two cross-girders over the central piers have larger dimensions, i.e., 1.5/1.8 m.

The bridge deck has a constant thickness of 30 cm. In the end spans, it increases to 1.8 m (Fig. 17) which enables the avoidance of negative reactions at the abutments in all phases of construction and serviceability. The cantilevers have a span of 3.10 m, while their thickness ranges from 22 cm at the parapet beams to 50 cm at the place of fixation into the main girders. The bridge deck has a constant thickness of 30 cm.

The stay cables are distributed over two parallel planes, where the pylons that are monolithically connected to the main girders (Fig. 16) are positioned over each bearing placed on the central supports. They are designed as reinforced concrete ones with a cross-section of 1.0/3.0 m and a total height of 12.6 m from the carriageway. Due to the limited width of the cross-section, anchorage of the cables is enabled through the so-called saddles (deviators). The height of the pylons to the saddle of the last cable is 9.63 m (L/H=5.8). In the transverse direction, both individual pylons are connected with portal-pretensioned simple supported beams (3.0/0.25-0.5 m).

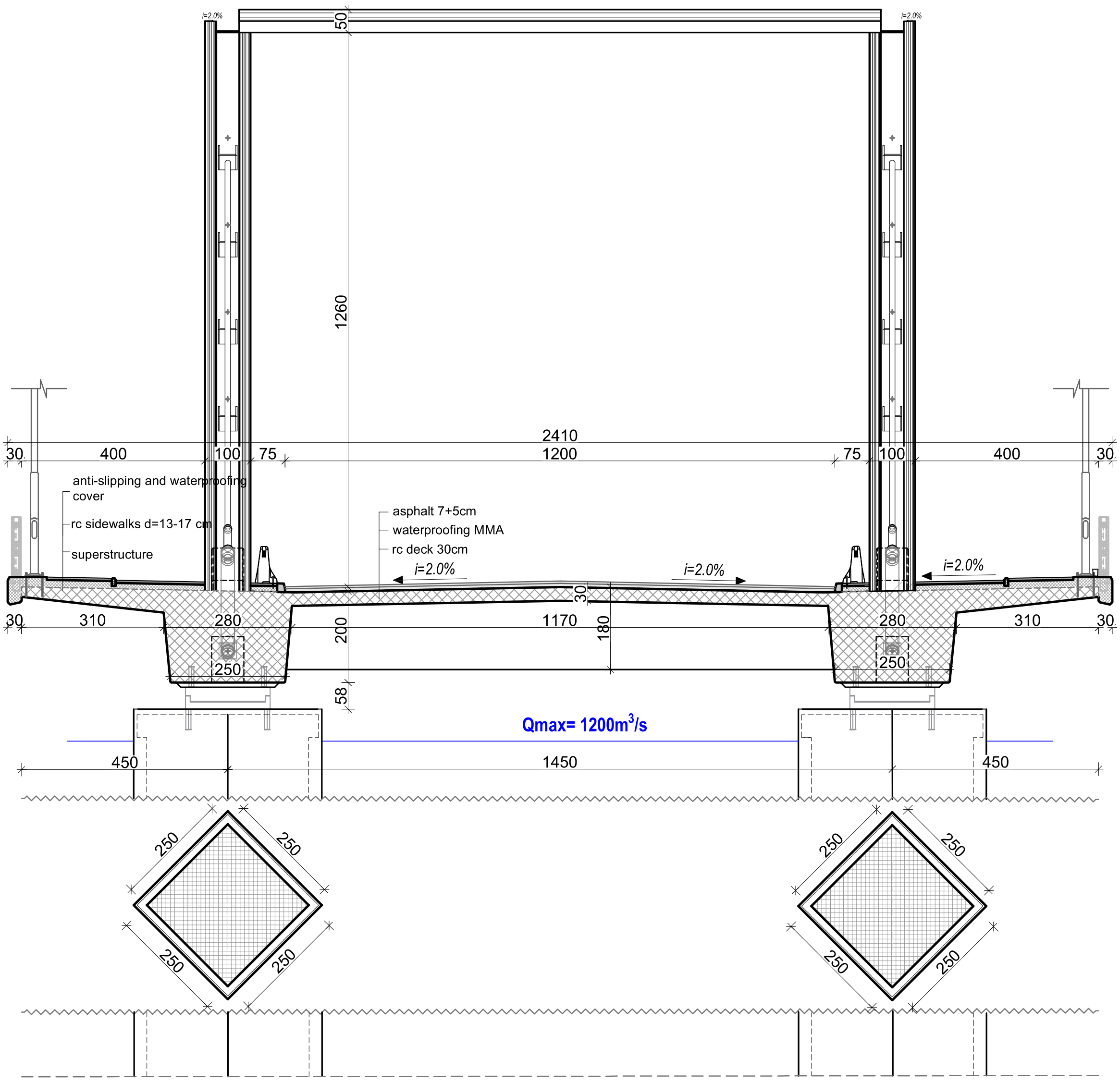

Fig. 16. Characteristic cross-section of the bridge

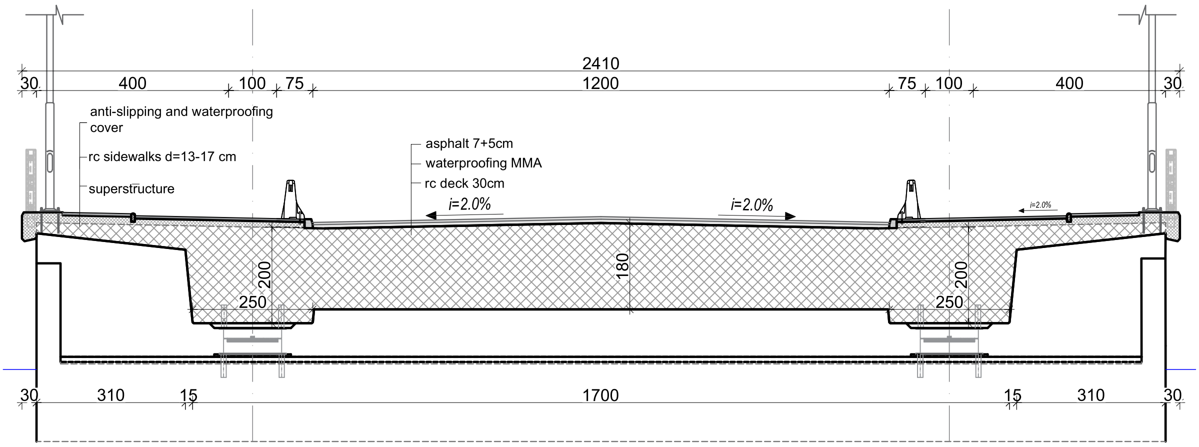

Fig. 17. Characteristic cross-sections in end spans of the bridge

The cable system is composed of a total of 32 mutually parallel stay cables, 8 at each pylon. Passing continuously over the pylon saddles, they are anchored into the superstructure on both sides, at places where main girders are connected with cross girders. The detail of the anchors and anchorage of the cables into the pylon and the main girder is shown in Fig. 18.The adopted type of cables has a three-layer anticorrosion protection, which is of great importance for the durability of such systems. Each strand of a cable is galvanized, and upon it, an external barrier of a polyethylene coat of high density (HDPE) filled with paraffin wax is directly extruded. The cable composed of such protected strands is housed in individual HDPE external protection tubes. Additionally, antivandal tubes are anticipated for the lower part of the cables.

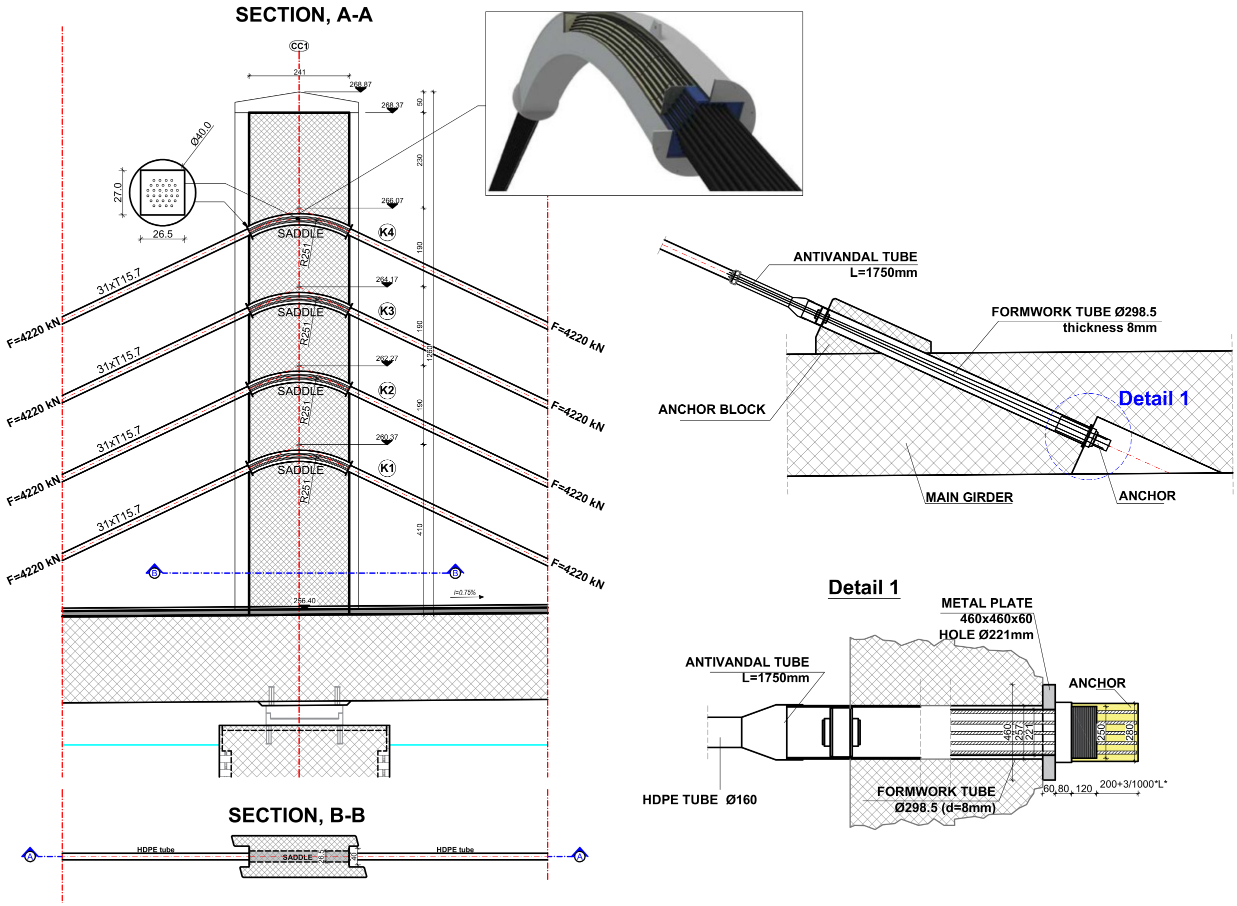

Fig. 18. Detail of a pylon, saddle and anchorage of a cable into the main girder

The hinged connection between the superstructure and substructure is provided through movable and fixed pot bearings. Over the central piers, a total of four fixed bearings are placed. Four longitudinally movable bearings are placed over the abutments. The distribution of movability of the bearings has arisen from the dimensioning of the substructure for the effect of horizontal forces. Their connection to the super- and sub-structure is through steel anchors.

The bridge substructure consists of two abutments and two central piers placed parallel to the Vardar River bed. The abutments that, at the same time, have the role of a pile beam, have a constant thickness of 2.6 m due to the relatively small height (4.1 m). They are designed without wing walls.

The middle piers have a square cross-section that, due to hydraulic and aesthetic reasons, is rotated 45˚ with respect to the longitudinal axis of the bridge. Each middle pier consists of two individual piers proportioned to 2.5/2.5 m (Fig. 16). Their height from the upper edge of the pile cap to the lower edge of the bearing is 6.80 m. In the upper 50 cm, widening of the cross-section for 15 cm is anticipated on all sides. This is necessary to provide the space necessary for accommodation of the hydraulic jacks during replacement of the bearings.

On the surface of the considered location, there are shallow terraced alluvial sediments composed of gravels, whereas in the deeper layers, there are Miocene sediments classified as marlstone. Deep foundation by application of piles with diameter of 1.5 m has been adopted. Considering this, the deeper layers, specifically the marlstone, play a dominant influence in the behavior of the pile foundation. The abutments are founded on single-row piles (6 below C1 and C4 each) with a length of 18 m. Below each central pier, 3 x 3 piles with a length of 20m are anticipated. They are interconnected by a cascade pile cap, whose thickness amounts to 2.0/3.0 m (Fig. 15).

3.2 Equipment

Based on the computed horizontal displacements of the superstructure due to the total service and seismic loads, two expansion joints over the abutments are anticipated. These enable displacements of up to +/-115 mm. For the carriageway surface, an expansion joint type Wd/Wd + 230 has been adopted, whereas type PL 230 (Freyssinet) has been adopted for the sidewalks. While adopting these expansion joints, the inclination of the bridge at plan has been taken into account.

With the resulting ultimate responses and horizontal displacements of the superstructure, the following types of pot bearings have been adopted (Fig. 19):

- Over the abutments: type GG (movable in longitudinal direction and fixed in transverse direction) with proportioned A/B/H = 1210/1030/550 mm, maximum vertical bearing capacity of V_{ULS} = 20 000 kN, horizontal bearing capacity ofH_{ULS} = 6 000kN and maximum capacity for horizontal displacement of 200 mm.
- Over the central piers: type FX (fixed in all directions) proportioned D/H = 1850/481 mm, with maximum vertical bearing capacity of V_{ULS} = 45 000 kN and horizontal bearing capacity of H_{ULS} = 13 500 kN.

For the vertical elements that are in contact with the external environment, waterproofing in the form of bitumen-based coating is anticipated. For the horizontal bridge surfaces, waterproofing based on methyl methacrylate (MMA) has been adopted. This type of waterproofing consists of a primer and a double-layered MMA membrane. It is applied to the entire bridge surface by way of a cold procedure, where in the carriageway part, there is a double-layered (7+5 cm) asphalt, whereas in the part of the footways and cycling paths, monolithic sidewalks (13-17 cm) are cast, with a finishing anti-skidding and waterproofing layer (Antiskid). The central piers are lined with granite plates with a thickness of 5 cm.

On both sides of the bridge, between the carriageway and the sidewalks, a New Jersey restrained system is planned to be constructed according to the EN 1317 standard [2]. The primary role of this restrained system is the protection of the cables and the pylons against direct impact by vehicles. Additionally, it separates the motor traffic from the pedestrian traffic on the bridge. The shaping of the pedestrian steel fence, the pylons, and the central piers as well as the line illumination of the pylons are works of Prof. Dr. MitkoHadzi-Pulja, grad. arch. (Fig. 20).

ACO gullies in accordance with DIN EN 124 [3], pipes made of composite material GRP (ISO 25780:2011 [12]), and water purification shafts are anticipated for drainage of atmospheric waters

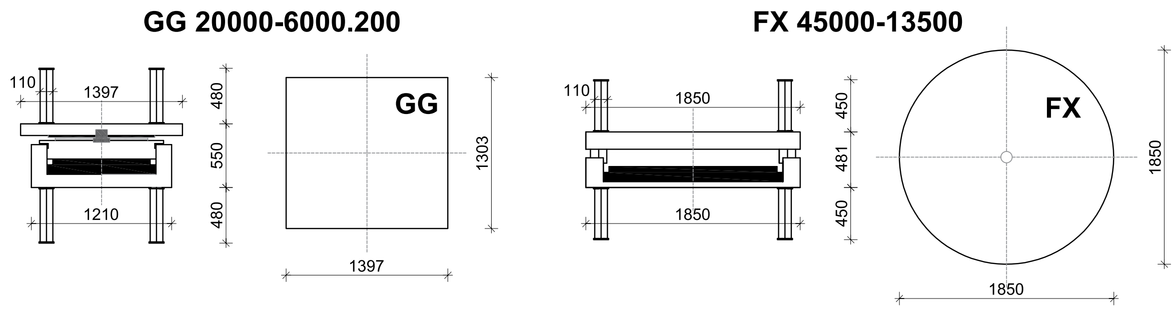

Fig. 19. Detail of the adopted pot bearings

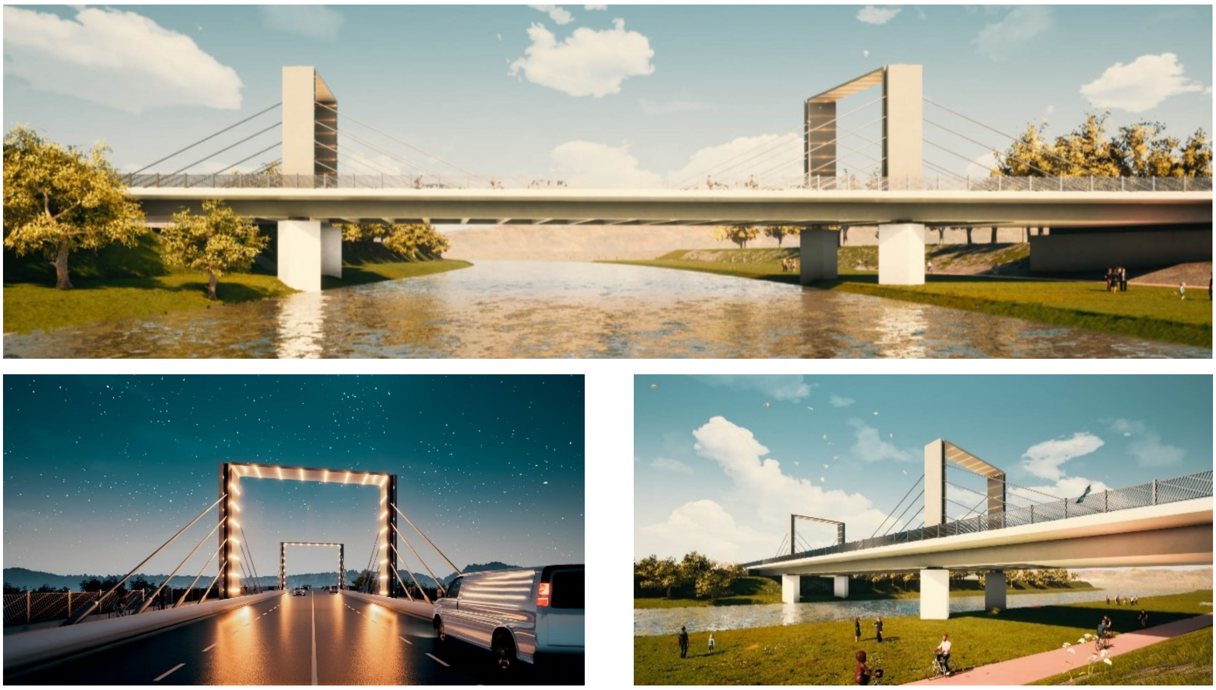

Fig. 20. 3D View of the bridge (Nikola Strezovski, grad. arch.)

3.3 Methodology of construction

Monolithic construction of the superstructure and its simultaneous concreting are anticipated to be done by use of an integrated scaffold. Anticipated for the central span is the so-called “heavy” scaffold that can entirely bridge the minor river bed, resting on temporary supports placed immediately next to the central piers. After the sub- and superstructures are constructed, the following phases start to be realized (Fig. 21):

- Prestressing of all internal tendons by the full amount of the anticipated prestressing force (14 cables on each main girder) from the side of the abutments;
- Partial tensioning of the second (according to length) external cable K3;

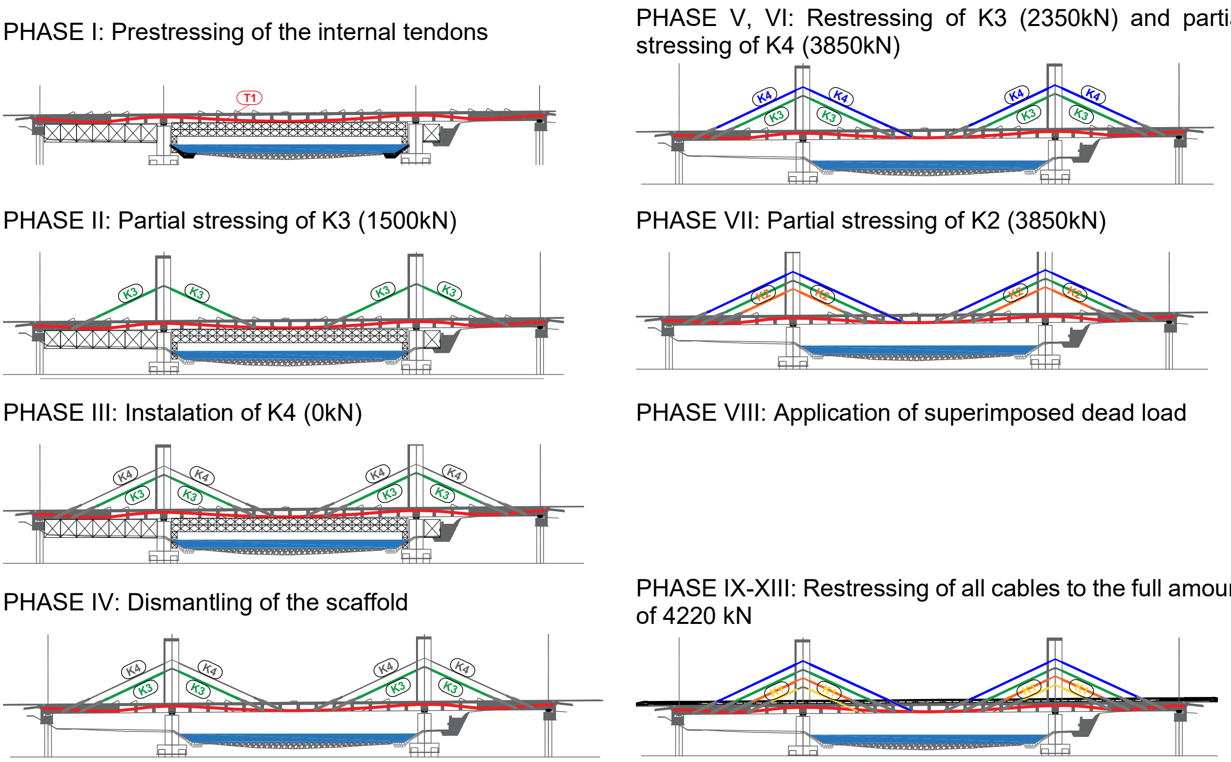

Fig. 21. Proposed methodology of construction

- Placement of the longest external cables K4;
- Dismantling of the scaffold and activation of the entire dead weight of the superstructure;
- Additional external cable tensioning K3 and partial tensioning of K4 and then K2;
- Partial tensioning of K1 after application of the superimposed dead loads (asphalt, sidewalks, railings and alike) and additional tensioning of all cables up to the anticipated force of 4220kN.

The proposed construction methodology is preceded by a detailed numerical analysis that controls the stresses in the bridge superstructure throughout the construction process.

3.4 Numerical model

Using the SOFiSTi software, a complete static and dynamic analysis of the bridge was performed in accordance with Eurocode. For the proportioning of the structure, a 3D model has been formulated. In this model, all structural elements with the exception of the bridge deck have been modeled by linear (beam) finite elements (Fig. 22). The main girders are modeled in T-section and include the effective bridge deck in longitudinal direction. The variation of the effective width along the length of the girders has been taken into account in accordance with EN 1992-1-1 [13]. Since one part of the deck is already included in the flange of the main girders, for these parts, the shell elements by which the bridge deck is modeled are defined without dead weight (γ=0 kN⁄m^3). To prevent doubling of the deck stiffness in longitudinal direction, the shell elements have axial and bending stiffness only in the transverse direction. Beam elements with a rectangular cross-section are used to model the cross-girders. At places where they enter the main girders, they are modeled without dead weight.

For the external cables, linear (cable) elements are used that sustain axial forces only. The pot bearings through which the superstructure rests upon the substructure by way of a hinge, are modeled by spring elements with corresponding stiffness. In the model, the internal prestressing tendons are included through a resultant cable with a sinusoidal run.

The elements are divided into groups depending on the phases of construction in which they are activated. For cable-stayed structures that are constructed monolithically by using the traditional scaffold, it is of particular importance to simulate the separation of the structure from the scaffold and the gradual activation of the dead weight during the phase tensioning of the cables. In the analysis, this has been simulated through nonlinear springs placed below the entire surface of the superstructure that are able to sustain compressive forces only.

To simulate a deformable pier, the model also includes the piles and their interaction with soil. For that purpose, horizontal and vertical springs along the perimeter of the piles as well as a spring on the lower base have been modeled. The stiffness of the springs has been defined by means of the GEO-5 software.

3.5 Analysis

The final type of stay cables (31T15) and 14 internal tendons per girder (19T15) were adopted based on results from both, analysis of construction stages and the analysis of service life of the bridge. The sequences of stay cable stressing, as well as the moment of scaffold dismantling, arose from limiting the stresses in the superstructure during the construction and its service life. Having in mind the sensitivity of the structural system, two additional checks were carried out: replacement of one stay cable and brakeage of the cable due to the vehicle impact. Due to the applied system for anchoring the stay cables in the pilon through the so-called saddle, the maximum allowable differential forces in the cable on two sides of the pilon were controlled. This check was performed in accordance with fib89 [14] and the recommendations of PTI [15] for such structures.

4 In lieu of a conclusion

Bridges are undoubtedly considered among the most impressive works of construction, a synonym for structural engineering. A fruit of primeval creative exaltation, ample engineering knowledge, and spiritual love for the profession. Indicators of the vision of rulers, the intellectual and technological power of nations, the maturity of cities, the importance of states, the development of civilizations. A symbol of human unsubmissiveness to obstacles. A victory of connection over separation.

The design of the “Mihajlo Apostolski” bridges and Ljubljanska street over the Vardar river in Skopje was a challenge to create something new, moving away from destructive iterativeness, encouraging the self-confidence of builders. Each step, no matter how modest, creates faith in the dialectics of the human being, nurtures love toward creation, and initiates hope for new achievements.

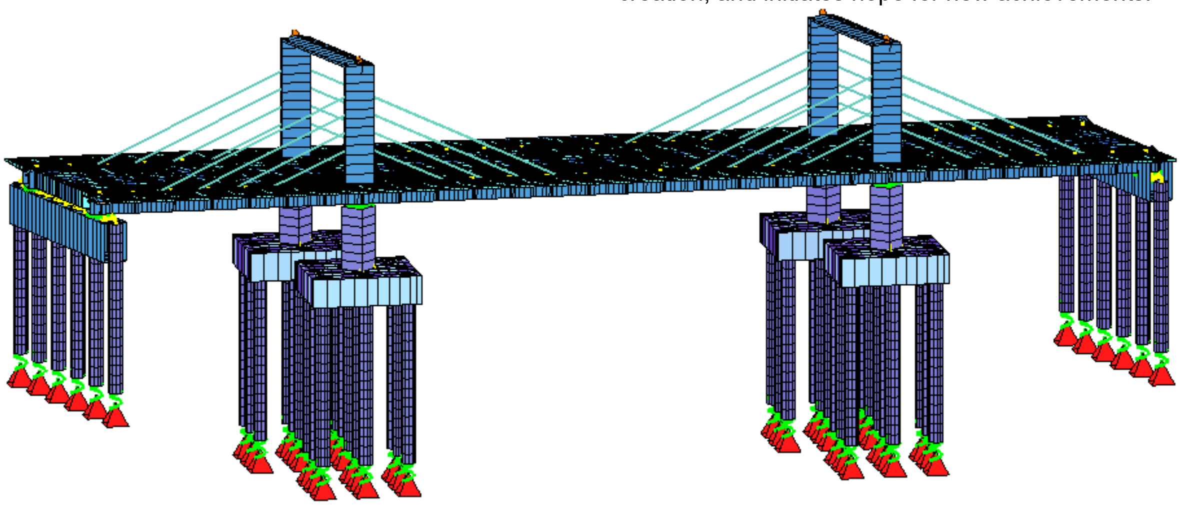

Fig.22. Numerical model of the bridge in SOFiSTiK

Acknowledgement

The authors would like to thank Ponting Ltd., Maribor, Slovenia, Freyssinet Macedonia, and VenMises/SOFiSTiK, Italy, for their unwavering assistance in the bridge design process.

References

[1] Richtlinien für den Entwurt und die Ausbildung von Ingenieurbauten, 10/2013.
[2] EN 1317 – Road restrained systems.
[3] DIN EN 124 – Gully tops and manhole tops for vehicular and pedestrian areas, Part 1: Definitions, classification, general principles of design, performance requirements and test methods.
[4] EN 1991-1-1 (2002). Eurocode 1 – Actions on structures, Part 1-1: General actions – Densities, self-weight, imposed loads for buildings. Brussels, Belgium
[5] EN 1991-2 (2003). Eurocode 1 — Actions on structures, Part 2: Traffic loads on bridges. Brussels, Belgium.
[6] EN 1991-1-5 (2003). Eurocode 1 — Actions on structures, Part 1-5: General actions – Thermal actions. Brussels, Belgium.
[7] EN 1991-1-4 (2005). Eurocode 1 — Actions on structures, Part 1-4: General actions – Wind actions. Brussels, Belgium.
[8] EN 1998-2 (2005). Eurocode 8 — Design of structures for earthquake resistance, Part 2: Bridges. Brussels, Belgium
[9] EN 1992-2 (2005). Eurocode 2 — Design of concrete structures – Concrete bridges – Design and detailing rules. Brussels, Belgium.
[10] EN 1990 (2002). Eurocode - Basis of structural design. Brussels, Belgium.
[11] Biliszczuk J. et al. (2017). Extradosed bridges in Poland – design and construction. Frontiers in Built Environment vol. 2, pp. 1-9
[12] ISO 25780:2011 – Plastics piping systems for pressure and non-pressure water supply, irrigation, drainage or sewerage – Glass-reinforced thermosetting plastics (GRP) systems based on unsaturated polyester (UP) resin – Pipes with flexible joints intended to be installed using jacking techniques
[13] EN 1992-1-1 (2004). Eurocode 2 — Design of concrete structures, Part 1-1: General rules and rules for buildings. Brussels, Belgium
[14] fib Bulletin 89 (2019). Acceptance of cable systems using prestressing steels.
[15] PTI Post-Tensioning Institute (2007). Recommendation for stay cable design, testing and installation.