e-mosty

ISSUE 03/2022 SEPTEMBER

PEDESTRIAN AND CYCLIST BRIDGES

LIST OF CONTENTS

Photo on the Front Cover: Sky Bridge 721, Czech Republic — Credit: Denis Pagáč
Photo on the Back Cover: Varvsbron Pedestrian Bridge, Sweden — Credit: Fredrik Rege, Courtesy of PEAB

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Dear Readers

In this issue of the magazine e-mosty, we focus on pedestrian and cyclist bridges.

The first article of this issue brings information about the recently opened footbridge Sky Bridge 721 in the Czech Republic which is – with its length of 721 m – the longest footbridge in the world.

The second article is dedicated to the Varvsbron pedestrian and cyclist bridge in Helsingborg, Sweden. The article was prepared by its architect, Stephen James.

In this connection, we would also like to invite you to read an article about using CATIA software for modelling of this bridge which will be published in our other magazine, e-BrIM, on 20 October. More information about the magazine and the magazines can be found at www.e-brim.com.

The next article was prepared by Ponting Bridges, and brings an overview of already completed footbridges and also the ones currently under construction or being designed by this structural engineering company.

We decided to again publish the article about the St. Elmo Footbridge in Malta which was originally published last year in our magazine e-maritime. This magazine is no longer published (and promoted), and you may have missed this article. We think that the footbridge deserves attention. It was designed by Arenas y Asociados whom I also thank for their cooperation.

The last article of this edition focuses on the utilization of BIM and Allplan Bridge in the design and construction of the new Rize - Artvin Airport bridge located on reclaimed land off the northeastern coast of Türkiye.

I would like to thank our Editorial Board, especially David Collings and Richard Cooke for the review and assistance with the content; and all authors, people and companies that have been helping me to put the content together.

We would also like to thank Peter Collin and Henrik Undeland, Ramboll, for their cooperation on the article about the Varvsbron Bridge in Sweden.

We also thank our partners for their continuous support.

The next e-mosty magazine will be released on 20 December 2022; a part of the magazine will be about the Padma Multipurpose Bridge Project in Bangladesh. The March 2023 e-mosty Edition will be dedicated to the Chenab Bridge in India and will be released on 20 March 2023. The next e-BrIM magazine will be released on 20 October.

Magdaléna Sobotková

Chief Editor

INTERNATIONAL ONLINE PEER-REVIEWED MAGAZINE ABOUT BRIDGES

e-mosty

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The magazine **e-mosty** (“e-bridges”) is an international, interactive, peer-reviewed magazine about bridges.

It is published at www.e-mosty.cz and can be read free of charge (open access) with the possibility to subscribe.

It is published quarterly: 20 March, 20 June, 20 September and 20 December. The magazines stay **available online** on our website as pdf.

The magazine **brings original articles about bridges and bridge engineers** from around the world. Its electronic form enables the publishing of high-quality photos, videos, drawings, links, etc.

We aim to include **all important and technical information** and show the grace and beauty of the structures.

We are happy to provide media support for important bridge conferences, educational activities, charitable projects, books, etc.

Our Editorial Board comprises bridge engineers and experts mainly from the UK, US and Australia.

The readers are mainly bridge engineers, designers, constructors and managers of construction companies, university lecturers and students, or people who just love bridges.

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e-BrIM

In August 2021 we established a new magazine, **e-BrIM,** which focuses on Bridge Information Modelling. Its first regular issue was released on 20 February 2022. The September 2021 edition of e-mosty was also a "zero" edition of e-BrIM.

We follow the concept of the e-mosty magazine; e-BrIM is also an international, peer-reviewed magazine with open access and the possibility to subscribe.

Our plan is to publish it three times a year (20 February, 20 May and 20 October); we believe that with the current development of BIM, there will be plenty of interesting and useful content to share.

Let us introduce and welcome our **Editorial Board Members.** Thank you all for accepting our invitation.

We all do our best to prepare technical, educational and informative content for our readers.

We would like to invite you to contribute with your articles to this newly established magazine e-BrIM:

CALL FOR PAPERS

20 February 2023 Edition:

Deadline for first drafts: 20 November 2022

20 May 2023 Edition:

Deadline for first drafts: 20 March 2023

The text shall be in MS Word, 3 – 5 pages plus relevant images, drawings, 3D models, links and videos and shall be sent to our email address.
You may also send an abstract before starting work on the article or contact us to discuss other options.
All abstracts and articles will be peer-reviewed and also subject to approval by the Editorial Board.

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ISSN: 2788-0540

SKY BRIDGE 721, CZECH REPUBLIC

Václav Röder, Ph.D.

Chief Design Engineer, TAROS NOVA a. s.

Figure 1: Overall View

INTRODUCTION

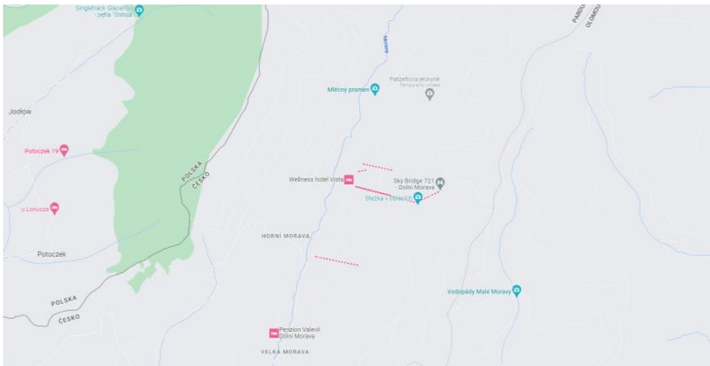
On Friday 13 May 2022, the world's longest suspension footbridge was opened. It is located in the mountain terrain of Králický Sněžník in the area of Mountain Resort Dolní Morava at an altitude of about 1,100 m above sea level.

It was built over a period of about two years and spans the valley between the two mountain ridges Slamník and Chlum with a length of 721 metres.

It is possible to move from one hill to the other in about 15 minutes by ordinary walking.

The main objective was to design a subtle line of the footbridge that would not disturb the silhouette of the mountain massif.

The footbridge is designed entirely in steel, suspended on six main ropes and stabilized by further six smaller ropes.



Figures 2 and 3: Location of the bridge – Mountain Resort Dolní Morava, indicated on the right

ARCHITECTURAL SOLUTION

Challenges

The designers had to take the difficult conditions into account from the very beginning.

This was because of the structural calculations for the footbridge, which can be excessively loaded by snow and ice, especially in winter (temperatures from -35 °C to 55 °C were considered); because of logistical availability (i.e. difficulties to get the material to the site and a limited handling and storage area); and the overall coordination of production and installation.

Transporting construction equipment and materials along the narrow, steep roads was difficult regardless of the season, requiring special vehicles and experienced drivers.

In terms of the design of the footbridge, there were several constraints. It was a real challenge to cross a valley more than 700 m wide and at an altitude of nearly 100 m.

Design & Build / Design, Structural Engineering Design, Statics, Construction (Building)	TAROS NOVA a.s. Czech republic www.taros-nova.cz
Investor	SNĚŽNÍK, a.s. Czech Republic
Design documentation	July 2020 – July 2021
Construction period	Sept 2020 – May 2022
Opening date	13 May 2022
Basic data	
Bridge length	721 m
Height above ground (at the highest point)	95 m
Weight of steel superstructure	234 t
Height of pylons	11.4 m
Weight of pylons	54 t each

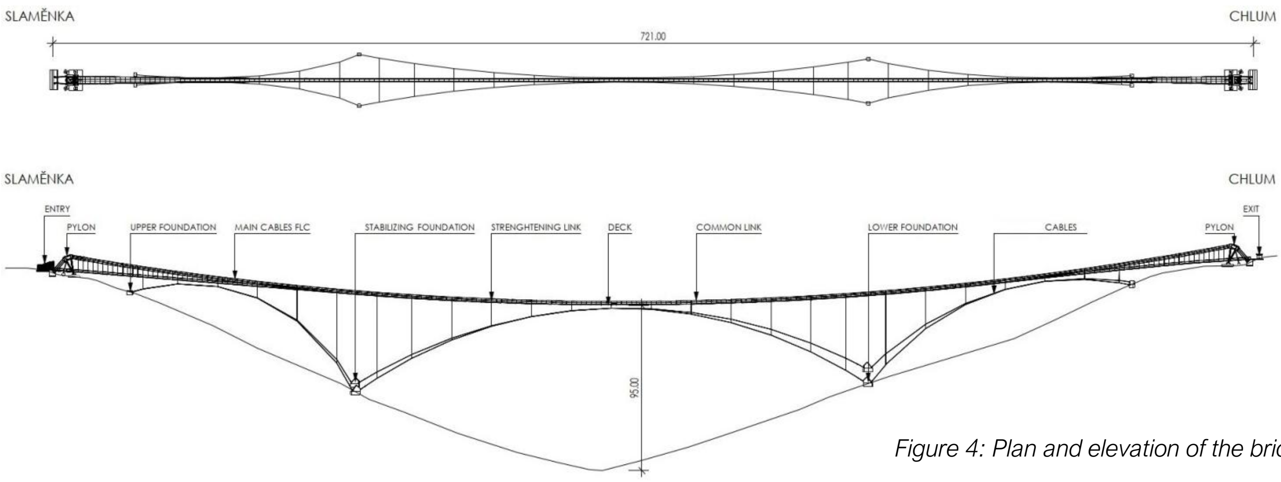


Figure 4: Plan and elevation of the bridge

Click on the image to open it in a higher resolution

The primary task for the engineers, who were also the designers, was to find the most suitable location for entering and exiting the footbridge with the minimum height difference to make the footbridge comfortably walkable.

The next important step was to find the appropriate basic geometry and dimensions of the elements, which were determined by static and dynamic calculations, and the options for manufacturing the parts and assembly.

The original design had to be modified and supplemented several times before the final solution was achieved that coped with all the obstacles.

For example, the main load-bearing cables were modified several times. The original design considered four 100 mm diameter main cables.

However, due to installation and transport, the design was modified to six 76 mm diameter main cables.

Finding the optimum sag of the suspension cables was also crucial due to the slope of the bridge deck, the height of the pylons and the statics of the cables.

A small sag resulted in high forces in the cables and ground anchors, whereas a large sag required high pylons and long bridge deck hangers which would have a negative impact on the stiffness of the footbridge.

DESIGN

The suspension footbridge is carried by six main supporting cables with a sag of 30.7 m in the middle of the span.

The pylons are designed in a 'V' shape with a total height of 11.4 m and a weight of 54 tonnes each, they are knuckle-jointed and inclined towards the slope, and are stabilized against lateral displacement by a system of steel rods.

The height difference between the pylons on the Slaměnka side and the Chlum side is 6 m.

The main supporting cables have the shape of a parabola both in plan projection and in lateral view, thus creating a spatial curve.

From the visitor's viewpoint, the main ropes gradually converge from the pylon towards the centre of the span until they approach a distance of about 2 m.

The main support ropes are fixed to the main pylons so that the tensile forces from the ropes then pass through the pylons to the rear anchor ropes that are finally anchored into the bedrock.

The bridge deck of the footbridge in the side view does not exactly imitate the shape of the supporting ropes, but gradually moves closer to the main ropes until they merge into a single line.

The stiffness of the bridge body thus gradually increases towards the centre of the bridge span.

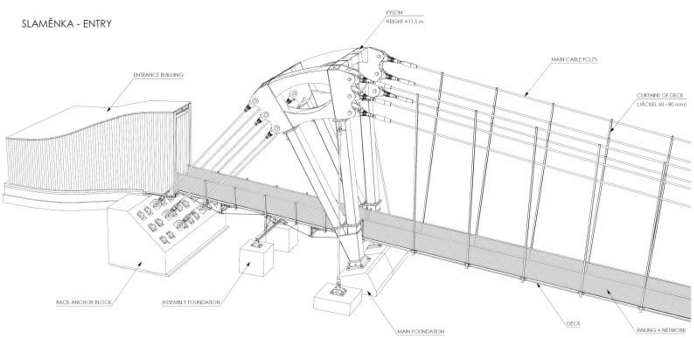


Figure 5: Slaměnka – Entry

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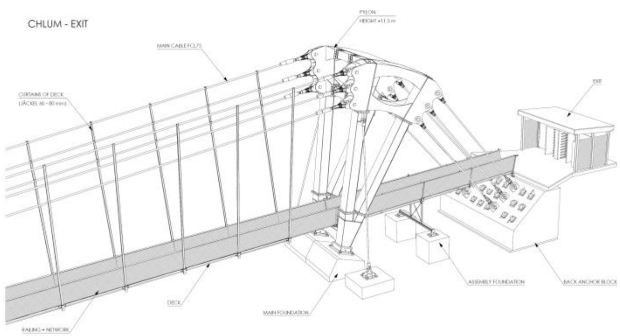

Figure 6: Chlum – Exit

Click on the image to open it in a higher resolution

The bridge deck is composed of two crossbeams with a chamfered leading edge and a non-slip serrated welded steel grating and comprises 244 segments with a length of 3 m and a walking width of 1.2 m.

The bridge deck suspenders are not vertical but are designed at an angle of 11°, which enhances the perspective effect of the footbridge running off into the distance.

The footbridge is stabilized against excessive transverse sway from wind loads and dynamic excitation by walkers by 6 sections of stabilizing ropes.

There are three arches designed to counteract the main cables, tighten the footbridge and at the same time reduce lateral sway.

The central stabilizing arch is connected to a special tensioning device/mechanism that provides tensioning of the wind cables, in which the pretension decreases due to temperature changes and accidental loads.

STRUCTURAL SOLUTION

Footbridge construction system

The 698.6 m long main suspension ropes FLC 76 (Fully Locked Coil) are anchored to two steel pylons via a suspender that allows swaying in both horizontal and vertical directions, thus eliminating bending stresses at the rope anchorage point.

The pylons are designed from welded 720 x 550 mm steel sections of 20 - 80 mm plate thickness S355 grade steel.

The transfer of compressive forces from the pylons to the footing is accomplished through a contact fit that allows the pylon to incline to 1°.

The possibility to tilt the pylons is particularly important for tuning the tension in the rear anchor ropes and minor corrections of the sag of the suspension cables.

The maximum vertical compressive reaction that passes from the pylons to the foundations is 21,000 kN (2,100 tonnes).

The pylons also transfer tensile forces of up to 21,300 kN from the main suspension cables to the rear anchor cables that are anchored to a reinforced concrete sill of dimensions 3.8 x 8.5 x 3.5 m.

The rear anchor ropes are also designed in six FLC 76 pieces. The main concrete footings are rectangular with dimensions 7 x 12.5 x 1.5 m.

The footings are anchored to the bedrock by 24 micropiles 64 mm in diameter with a length of 9 m.

The footbridge is secured against wind along its entire length by a system of ropes anchored to concrete footings in the slope below the footbridge.

The entire bracing is designed in three bays (arches) that are designed at an angle of approximately 15° in the cross-section, to balance

Figures 7 and 8: View of the main Pylons the stabilizing effect in the horizontal direction (wind) and the stabilizing effect in the vertical direction (dynamics from the walkers).

The main central arch is formed by a pair of FLC 56 ropes and the lateral stabilizing arches are designed with FLC 40 ropes.

The FLC 56 main stabilizing ropes are connected to a special tensioning mechanism that ensures constant tensioning of the ropes.

Their tension is primarily assured by pre-tensioning. If the footbridge sags (due to high temperature, load, etc.), the ropes are released, i.e. the tension disappears, and the effect of a four-tonne weight in the form of a concrete block and a set of springs comes into play, which loads the ropes, thus tensioning them.

The bridge deck is made up of 3 m long and 1.2 m wide sections composed of longitudinal reinforcement beams, between which are non-slip serrated welded steel grating of high strength, and high bearing capacity.

The longitudinal beams are designed from 4 mm thick bent sheet metal.

The anchorage of the individual bridge deck components is designed to allow free movement of the bridge deck in the longitudinal direction when the main cables are tensioned.

At the same time, the bridge deck anchorage must allow the bridge deck to move slightly so that a variable inclination of the footbridge can be ensured when using the same detail.

The bridge deck suspenders are designed in hot rolled steel rectangular hollow section (RHS) of dimensions 80/80/5 and 60/60/5 in steel grade S355.

A bracing hanging made of closed welded profiles is always placed where the wind stabilization cables are anchored over a distance of 21 - 24 m, see Figure 9.

The connecting elements between the hinges and the main ropes are prestressed stirrups for the transmission of shear forces.

Wire rope structural system

The ropes used in the structure are designed as a dense rope assembly with a core consisting of multiple helically twisted galvanized wires, with outer "Z"-shaped layers of wires which interlock with each other, which makes a rope with high strength and stiffness and smooth surface - FLC (Fully Locked Coil) supplemented with turnbuckles, tapered caps, fork sockets and pins.

A total of 66 ropes of various diameters and lengths are used.

The main and aft anchor ropes are designed from 76 mm diameter ropes (FLC 76).

The stabilizing ropes are designed from FLC 56 - main stiffening arch, FLC 40 - side stiffening arch, and FLC 24 - anchoring (hanging) the arch to the bridge deck.

The ropes are stranded wires, rope grade 1,570 MPa, and a modulus of elasticity of 165 GPa.

The main ropes are ended with a turnbuckle with rectification (adjustment) of ± 200 mm; the rear anchor ropes are fitted with a fixed end cap at one end, and at the other end, which is anchored to the foundation block, a BRC socket by Redaelli (adjustable socket type Bridge) is designed, which allows the ropes to be adjusted by hydraulic cylinders.

The stabilizing ropes are designed with BRC sockets at both ends. For the FLC 20 wind rope hinges, turnbuckles with rectification (adjustment) of ± 65 mm at both ends have been designed for ropes longer than 8 m.

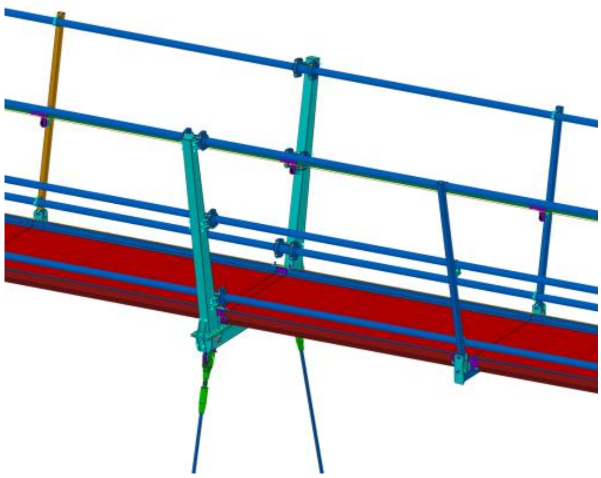

Figure 9: Stiffening hangers are used to anchor the stabilizing ropes FLC 24

Foundation of the footbridge and concrete structure

The lower structure consists of one reinforced concrete footing under the pylon and one reinforced concrete rear block for anchoring the rear main cables.

Both concrete blocks are founded on bedrock. The footing under the pylon is rectangular with dimensions 7 x 12.5 m and a height of 1.5 m.

The anchoring of the footing to the bedrock is done by 24 micropiles, 9 m long and 64 mm diameter.

The rear anchor block for transferring the tensile forces from the cables is designed with a dimension of 3.8 x 8.5 m, anchored by pre-tensioned cable anchors of 12 x 15.7 mm diameter.

The rope anchors have 12 m long roots which are embedded in the bedrock. The size of the prestressing of the rope anchors was designed so that at the worst load combination in the ultimate limit state, the normal force (axial force) from the prestressing in the rope anchors is not exceeded.

The basic element of the anchor block is the steel plates that are welded in a 'T' shape in the anchor area and interlocked/interconnected with the reinforcement of the concrete block to ensure continuous transfer of tensile forces to the prestressed anchors.

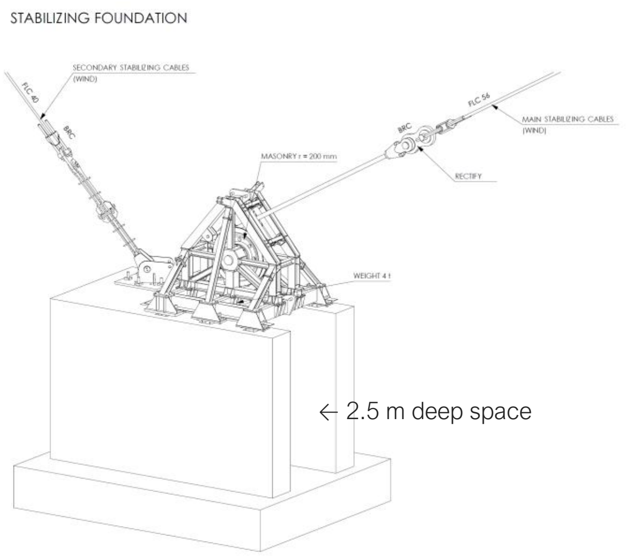

Figure 10: Stabilizing foundation

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The prestressing condition is monitored by dynamometers even during the operation of the footbridge.

The anchoring of the stabilizing cables is also carried out down to the bedrock level using reinforced concrete footings and micropiles.

In the case of the main arch formed by FLC 56 ropes, the footing was made with a 2.5 m deep free space between the anchorage´s sides, see Figure 10, for the free movement of 4t weights of the special tensioning mechanism.

Static and dynamic analysis

In order to find the most suitable conceptual solution for the footbridge structure, a 3D wireframe model was created in a structural analysis program based on the finite element method (FEM).

A total of 16 variants of the computational models were created, which differed in the number of main supporting cables, the sag, and the design of the securing wind cables.

The final concept of the footbridge was further refined on a large number of models, where the loading parameters were already precisely specified and the interconnections, sub-profiles of the structure and the geometry of the wind cables were gradually adjusted.

All the ropes in the structure were modelled using rope-type members that transmit only tensile forces.

Additional models of the footbridge were created for the installation conditions of the footbridge and the mounting structures and ropes.

In addition to the overall wire models, several sub-models of parts of the structure were also created, which were mostly modelled as wall or plane elements.

The sub-models were mainly used for the detailed design of the steel pylon and the joints of the structure.

A nonlinear calculation of the structure on a deformed system was carried out according to Large Deformation Analysis, III. Order.

Loads for the calculation of the footbridge were considered permanent, pre-tension, snow and wind loads according to the valid standards.

The wind load was calculated for a fully frozen structure (including the railing area) with the maximum design wind speed of 48 m/s.

The value of imposed loads in the static model is given as 2.5 kN/m^2. This means that up to 1,000 people can be on the footbridge at any one time – exceptionally dense traffic. The number of people was further adjusted from an operational point of view based on dynamic calculations and it is currently 500 people at one time.

The sag of the FLC 76 main cables in the final state was calculated to be 30.7 m at a temperature of 10 °C with a tensile force in the main cables of 1,500 kN.

The design capacity of the main cables is 3,600 kN.

Static analysis of the structure and basic modal analysis were calculated on the basic wired model of the footbridge.

Detailed dynamic analysis, including fatigue assessment of selected parts, was entrusted to a specialized firm, which performed the calculation using Simcenter STAR-CCM+ and Abaqus software.

Excitation by pedestrians was considered according to the document „Design of Lightweight Footbridges for Human Induced Vibrations“ from JRC Scientific and Technical Reports.

Dynamic load model stands for the excitation forces due to a continuous pedestrian stream used for a capacity of 250 and 500 persons.

The general definition of a harmonic load:

$$(t) = P \cdot (2\pi \cdot f_S \cdot t) \cdot n' \cdot \psi$$

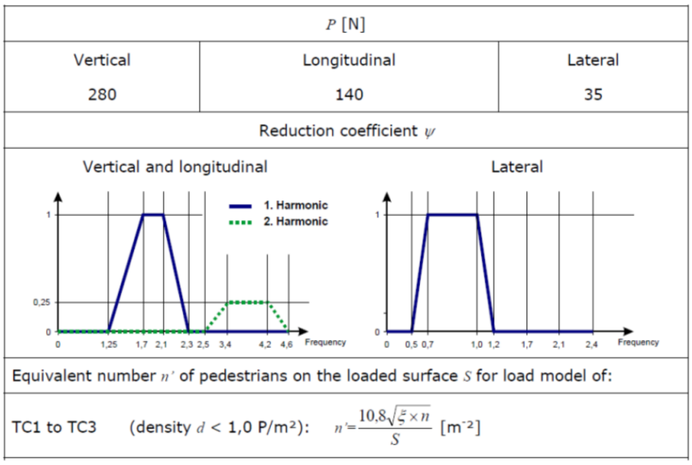

Figure 11: JRC load definition

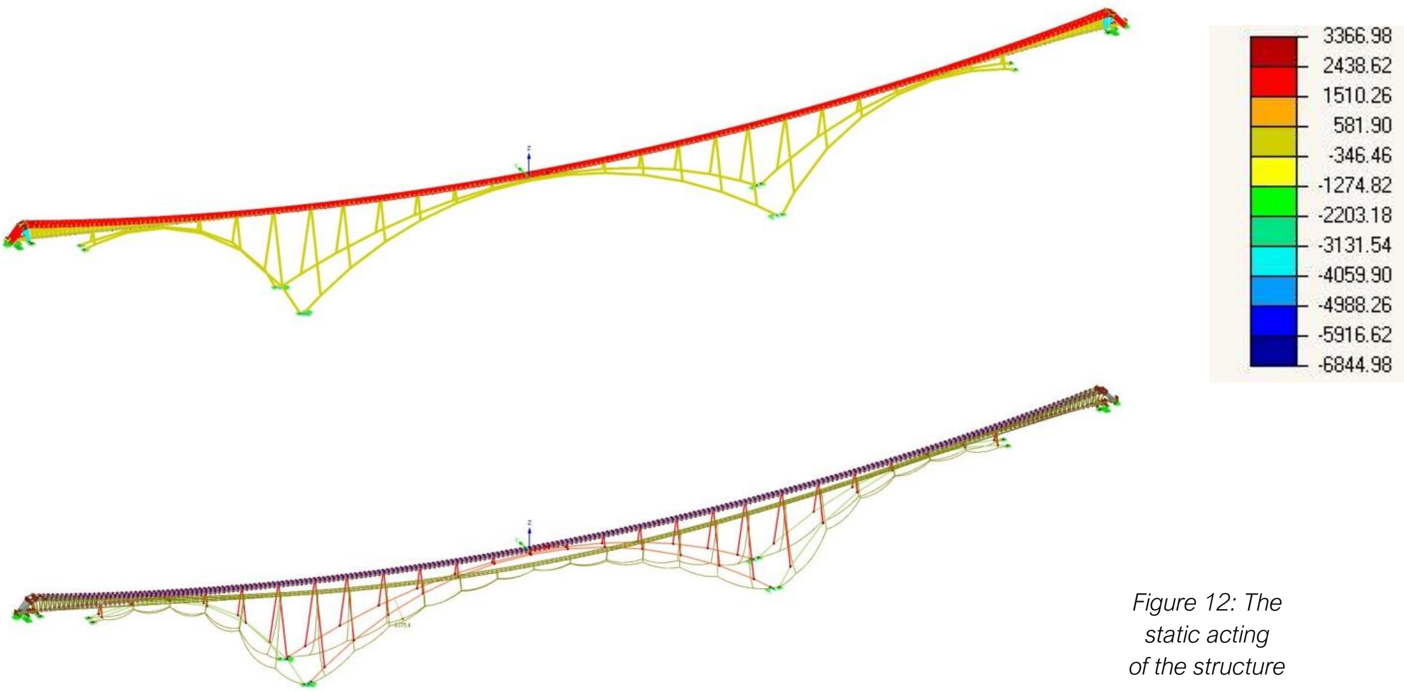

Figure 12: The static acting of the structure

The assessment of the dynamic wind loading is carried out for the range 0 to 30 m/s considering excitation in both transverse and vertical directions.

The analysis of the dynamic response of the structure was divided into three areas:

- The dynamic response and material fatigue of the stabilizing cables as local substructures to transverse excitation due to vortex resonance were assessed;
- The dynamic response of the footbridge to the pedestrian movement was assessed;
- The response of the global footbridge structure to dynamic excitation effects due to wind flow was assessed.

The analysis of the response to dynamic pedestrian loads showed the possible occurrence of a lock-in effect of the transverse response when there is a stream of people.

There is a pendulum effect with the bridge deck body freely suspended from the main supporting ropes.

However, this condition has not been confirmed in practice in operation to such an extent that it would lead to traffic reduction.

In the other parts of the footbridge, in the context of the limits set by the standards, the pedestrian response is compliant.

An analysis of the dynamic aeroelastic response was carried out on a flat frozen bridge deck, where an effect approaching bending-torsional flutter was observed at wind speeds of 15 m/s, 20 m/s and 30 m/s.

The global aeroelastic stability of the structure is compliant if the coincidence of a surface frozen bridge deck and a wind speed load of steady speed greater than 75 km/h are avoided.

This condition is supported by the service rules with regard to maintenance, and snow and ice removal.

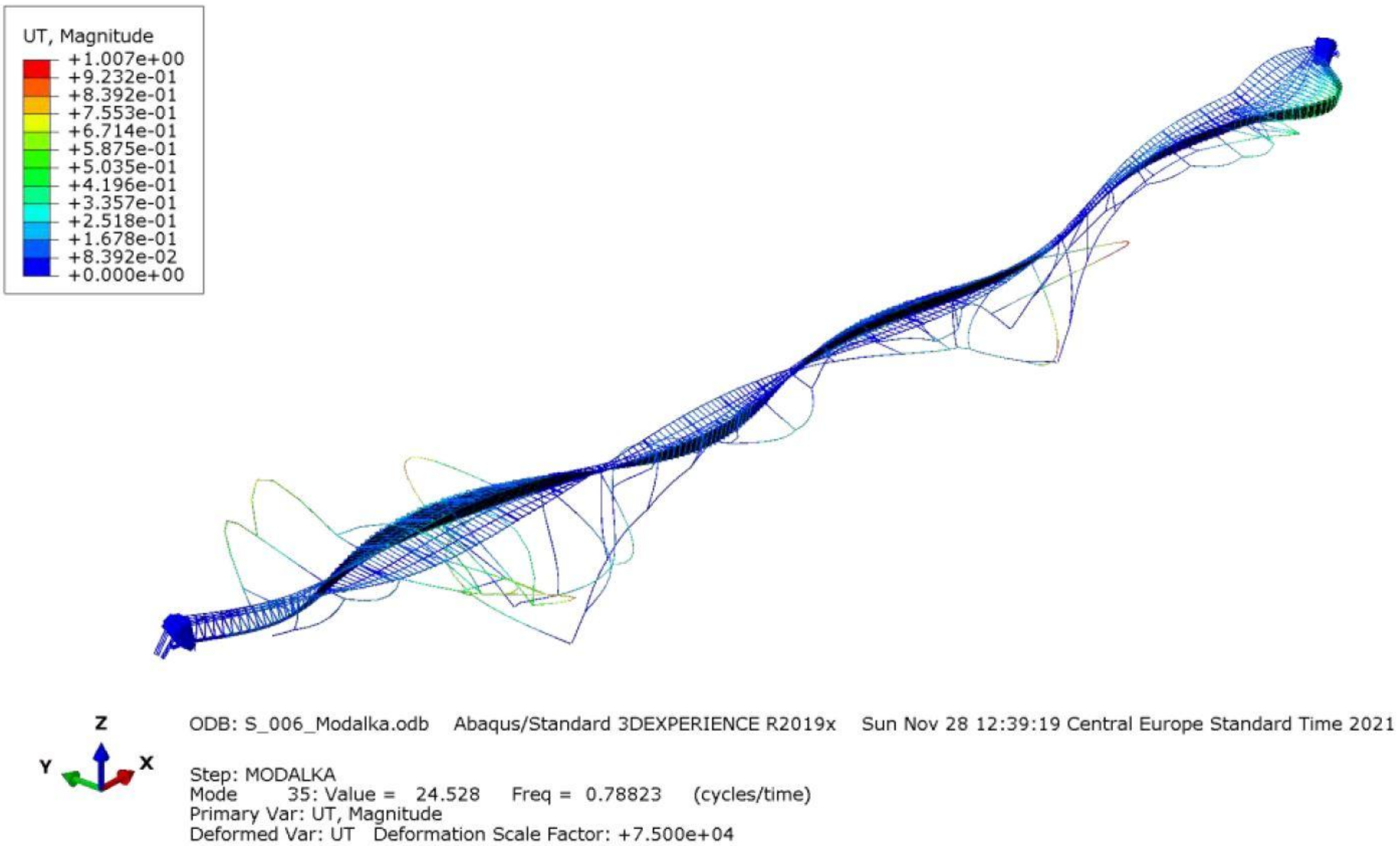

Figure 13: Indication of the stiffness of the structure, the first vertical and first horizontal shape and frequency

INSTALLATION OF THE STEEL FOOTBRIDGE STRUCTURE

First, open slope pits were made.

Particularly at the anchoring point of the main arcs of the stabilizing ropes, it was necessary to take increased caution, as the excavation was located in a steep slope and the bedrock was found only under a large layer of rubble, which led to cutting up to 15 m deep.

Subsequently, the underlying concrete was poured on which micropiles were drilled and reinforcement cages for footings were laid with anchor welds.

This was followed by excavation for the rear anchor blocks, creation of the base concrete, setting of the steel anchor blocks and reinforcement with KG pipes (plastic waste pipe type) in which the rock anchors were routed.

After concreting of the back blocks, the rock anchors were fixed and tensioned.

After the foundation structures were completed, the steel pylons were fitted on mounting supports to ensure the necessary lean of the pylons.

In order to relax the rear anchor ropes, the pylons were tilted approximately 20 mm more towards the slope.

A steel triangle with pulleys and anchor plates was installed on the pylons, which together with the pylon formed a temporary mounting tower for the cableway.

Then, using a drone, a thin nylon wire was transferred to the opposite slope.

Figure 15: Mounting triangle, installed on the pylon

Figure 14: Cableway

Figure 16: Cableway from Slaměnka to Chlum side

Figure 17: Installation of the first main load-bearing cable

Figure 18: Cable installation

The carrying capacity of the wire was sufficient for the subsequent pulling of another wire of a larger diameter, and this process was repeated until the 40 mm diameter auxiliary carrier rope was pulled, which became the basis of the ropeway along which the main ropes for construction were then transported.

The sag of the main ropes just after completion of the assembly is to be approximately 29.8 m (at a temperature of 10 °C), the final sag of 30.7 m being achieved only by creep (the time-dependent irreversible elongation of the rope).

The value of the tensile forces in the main ropes of FLC 76 was approximately 775 kN at installation.

For such high forces, a special pulley block system had to be used to connect the ropes to the pylons.

The bridge deck was assembled continuously from both sides. After the suspension of the bridge deck, the main suspension cables were tensioned by means of wind ropes to bring the structure to approximately the design condition - the tensile force in the main cables rose to 1,500 kN.

The stabilizing ropes were tensioned in the range of 50 - 130 kN. Control measurements during assembly (tension check and geodetic shape check) revealed manufacturing deviations of approximately 100 - 150 mm, which were further corrected by means of tensioning elements.

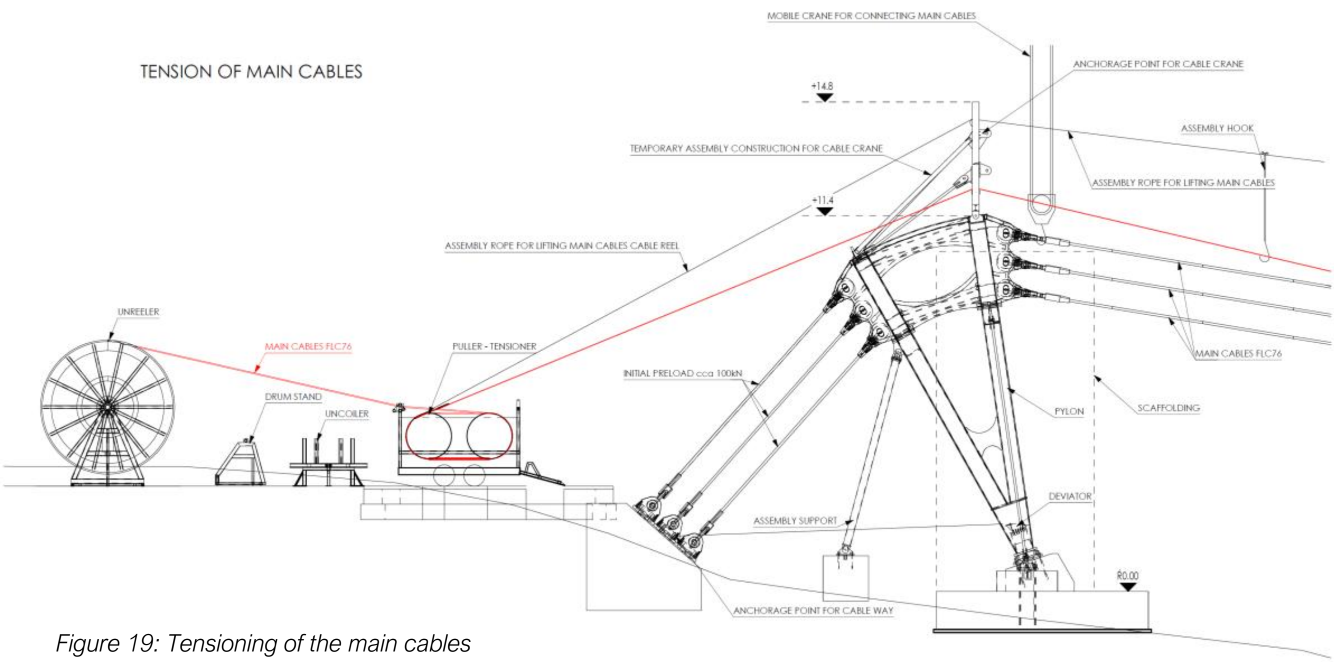

Figure 19: Tensioning of the main cables

Click on the image to open it in a higher resolution

After the installation was completed, the tension in the ropes was again corrected.

The rope installation itself was also affected by the fluctuating temperature - the ropes were exposed to different climatic influences due to their length, with a temperature difference of up to 5 °C between the two sides of the footbridge throughout the day.

At the very end, the railing with stainless steel mesh was installed and the entrance and exit building with turnstiles were completed.

Static and dynamic test of the footbridge

Before the footbridge was launched into full operation, a static and dynamic test was carried out. The static test was carried out by loading sandbags or water with a total weight of 60,000 kg (600 kN).

During the test, the stress in the ground anchors in the rear anchor blocks, the stress in the suspension ropes and the increase in the sag of the supporting suspension ropes were monitored.

The measurements showed high correspondence with the numerical calculation and the behaviour of the footbridge was exactly as predicted.

The dynamic test of the footbridge was carried out in order to verify the damping and to measure the vertical and horizontal response caused by the movement of the walkers on the footbridge structure.

The test showed that the vibration of the footbridge loaded by pedestrians walking normally did not exceed the acceleration limits so that the footbridge could be released for service.

Figures 20 and 21: Tensioning the main ropes with a pulley block system

Figure 22: Deck installation

Figure 23: The footbridge almost disappeared in the foggy weather

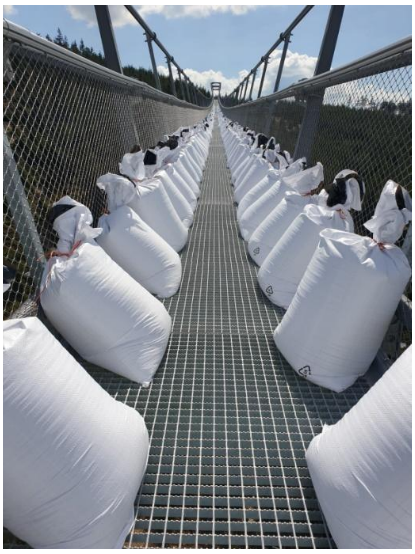

Figure 24: Static test

Figure 25: Trial operation of the footbridge

Only the end sections without stabilizing cables showed increased transverse vibrations when walking through the flow of pedestrians, thus the conclusions of the dynamic analysis were confirmed.

However, the vibration values do not restrict the smooth movement of walkers and, despite being an attraction, the footbridge is very rigid and stable.

CONCLUSION

The project of the footbridge was realized as Design & Build by the general contractor TAROS NOVA a. s., specializing in atypical timber and steel constructions.

The realization of the technologically demanding construction placed extraordinary demands on the design department, which provided not only design documentation itself, but also the project documentation for construction technology.

The construction itself was even more challenging due to the difficult climatic and terrain conditions.

Special tensioning and damping mechanisms were developed to ensure that the footbridge functions properly in all situations.

↘ Figures 26 and 27: Complete Bridge

CABLE-STAYED PEDESTRIAN BRIDGE IN HELSINGBORG, SWEDEN

Stephen James, Architect

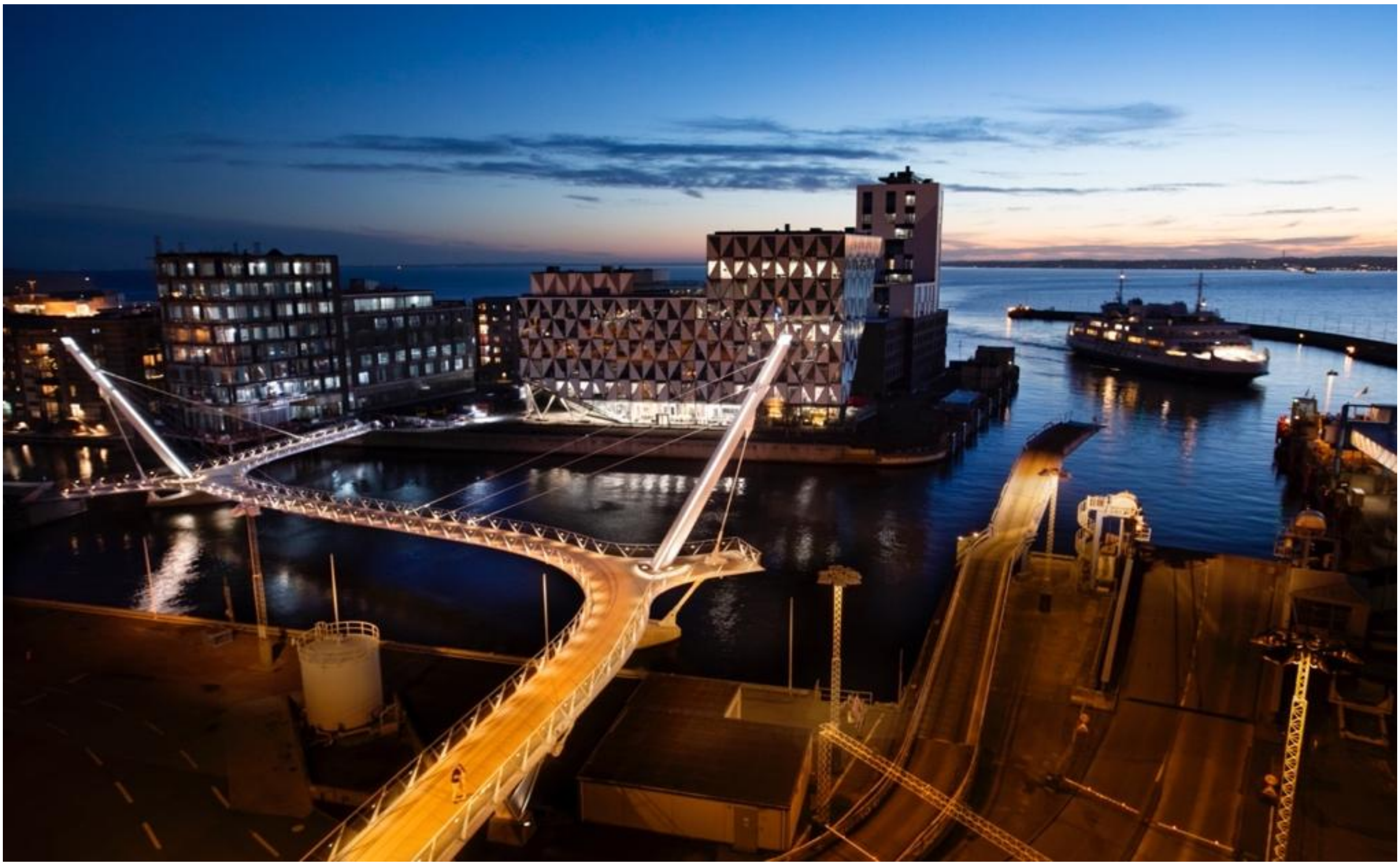

Figure 1: Aerial view of Varvsbron's site with Oceanhamnen development in background and Ferry terminal to foreground and to the right

Credit: Fredrik Rege, Courtesy of PEAB

BACKGROUND

The City of Helsingborg is pursuing an ambitious development programme to create vibrant new neighbourhoods and revitalise its urban fabric.

The urban development project, called H+, proposes four new neighbourhoods in the southern part of the city which, by 2035, will link up with the city centre and provide 5,000 new homes, office space, restaurants, and other businesses.

One of these four areas, Oceanhamnen, the city's new 'urban archipelago' forms part of the harbour, close to Helsingborg's main transport hub, but is isolated by the busy access road to the ferry between Helsingborg (Sweden) and Helsingor (Denmark) that separates them.

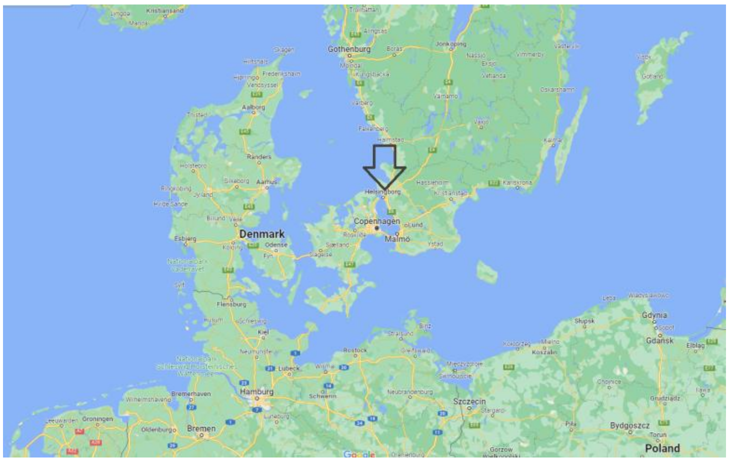

Figure 2: Location of the bridge on the map

Figure 3: Aerial view illustrating complex site context

After spanning the Ferry access road, the bridge must then turn and traverse the waterway of the docks diagonally to connect with a dry dock earmarked as a future public parkland, then turn again and continue to Oceanpiren and the new mixed-use development.

It must do all this whilst negotiating a significant fall of six metres over its total length of 220 m.

A new pedestrian bridge was deemed essential to reduce reliance on cars, promote walking between the site and multi-modal transport, and complete strategic cycle routes through the Helsingborg city centre.

The city called for an efficient, low-maintenance structure that would also become a landmark and the focal point for a new vibrant district.

COMPETITION

In 2014, following a pre-qualification process, three different consultant teams were invited by the City of Helsingborg to submit design bids in parallel.

The team from Ramboll was ultimately successful with an inventive proposal for a gently inclined, snaking form; an innovative variation on a cable-supported bridge, sharing characteristics with both suspension and cable-stayed structures.

The curvilinear alignment effectively resolved the skewed axes of the site and addressed the brief's demanding context with a form that feels both instinctive and natural.

Client: The City of Helsingborg, Sweden with project manager HIFAB

Winning Team: Ramboll
with Team Leader Henrik Undeland

Architect: Stephen James

Structural design: Tore Lundmark, Ramboll

Light design: Ramboll and Luxera

Contractor: PEAB

Construction for the contractor: Centerlöf & Holmberg AB, Malmö, Sweden, LAP (Leonhardt, Andrä und Partner), Stuttgart, Germany, and for modelling VisoPro Sverige AB in CATIA software

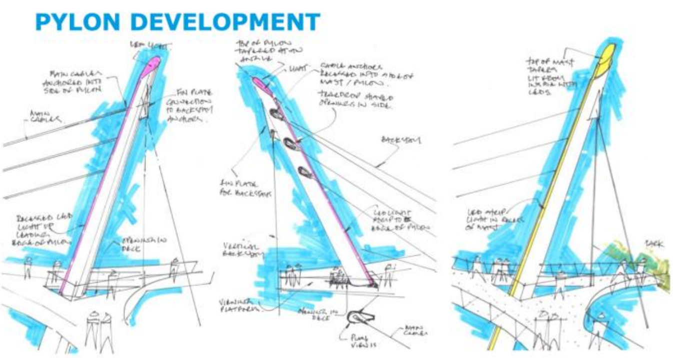

Figure 4: Competition design concept sketch

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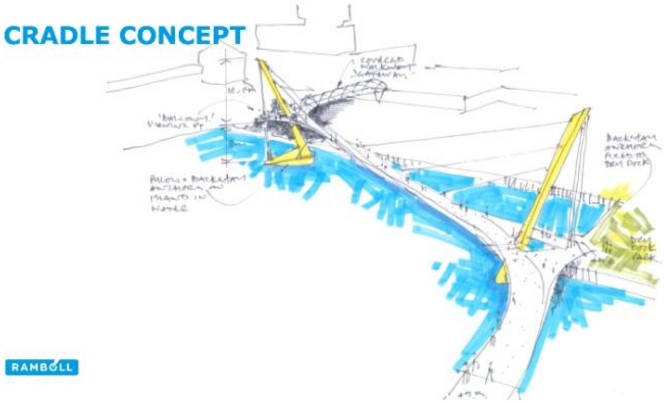

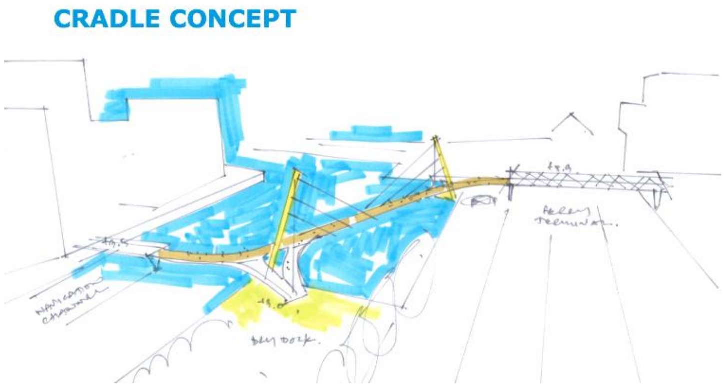

Figures 5 and 6: Cradle concept

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‘CRADLE’ CONCEPT

The deck is supported by three cables strung between two oppositely inclined pylons, which provide the main focal points for the bridge.

The pylons lean dramatically outwards as the bridge deck curves, heightening the sense of movement and lightening the structural appearance.

They are carefully positioned and orientated, one pointing out to sea, the other back to the city such that they are highly visible landmarks within the surrounding area.

The angle of the pylons was carefully studied in Ramboll´s parametric design model.

Rather than simply connect to the deck edge, as is typical for traditional cable-stayed structures, the cables swoop beneath the deck to cradle it from below, emerging on the other side, and rising to the opposing pylon in a dynamic and bold expression of the cable-supported bridge form.

With no cable anchors at or above deck level, typical of cable-stayed structures, the curved lines of the bridge sweep across the dock uninterrupted.

Four further backstay cables, two at each mast, stabilise the bridge and anchor the masts to the ground.

Figure 7: Snaking form of deck

Figure 8: Three primary cables ‘cradle’ the deck

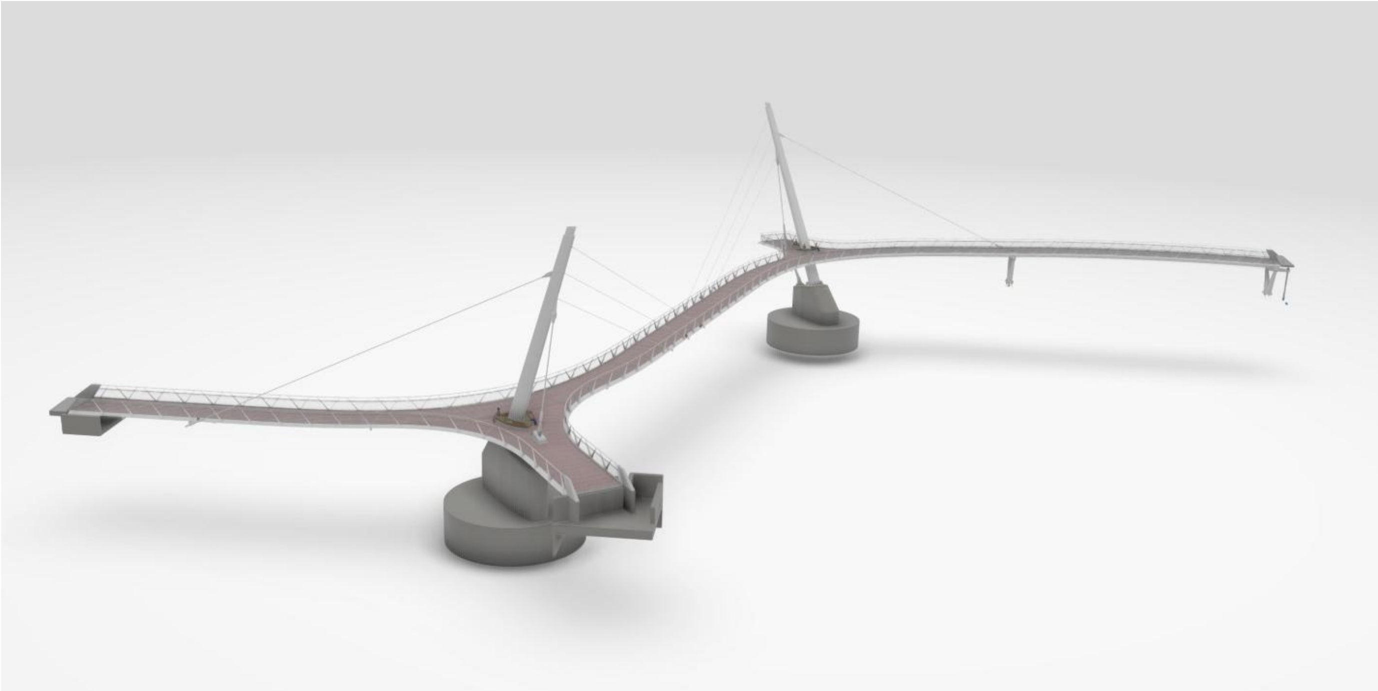


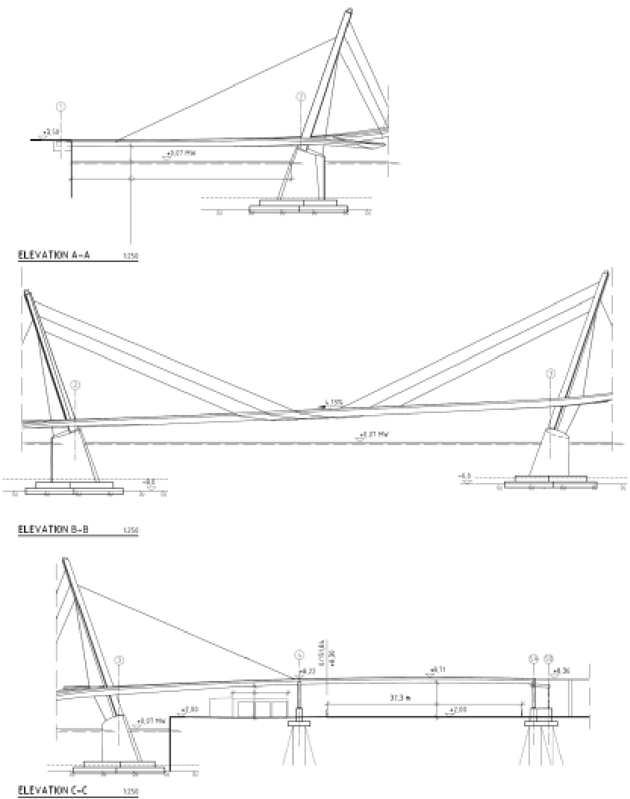
Figure 9: Extract from CATIA model

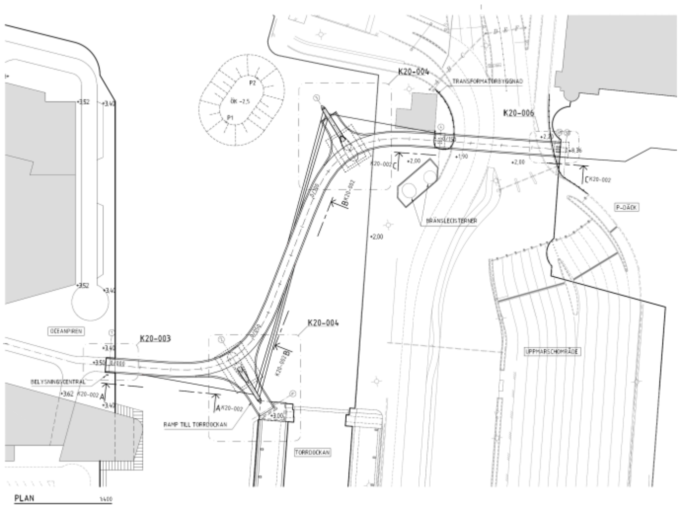
JOINT VENTURE PROJECT

The client, The City of Helsingborg, chose the contractor PEAB for a joint venture project to be able to have an open dialogue between the client with their project manager HIFAB, the winning Ramboll team and the contractor and their construction consultants.

This was a very important draw by the client as this complex bridge demanded positive cooperation between all parts and specialists involved to fulfill the winning design.

The architect and designers were in that way involved all the way till the opening of the bridge in September 2021.





← Figure 10: Elevation from tender document

↑ Figure 11: Plan from tender document

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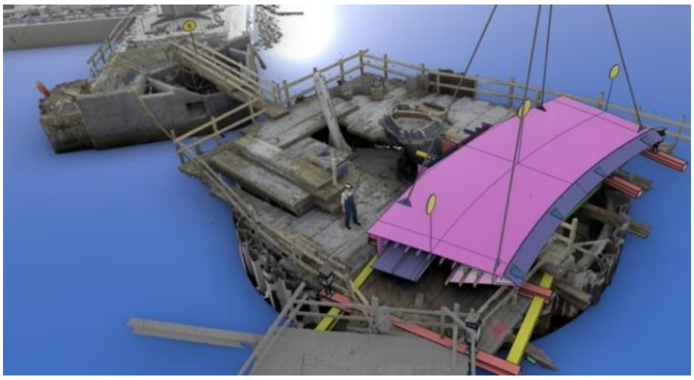


Figure 12: Virtual montage simulation in CATIA

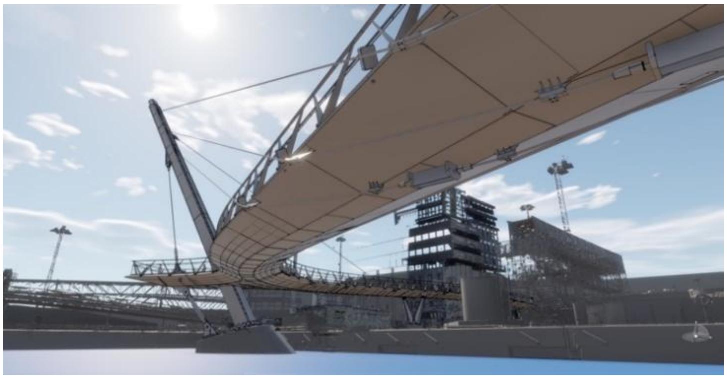


Figure 13: CATIA 3D model with 3D laser scan data

Figures 8, 9, 12 & 13 are taken from models made by VisoPro Sverige AB

STRUCTURAL DESIGN

Post-tender, the swept curvature and complex geometry of the bridge posed a significant manufacturing challenge to the successful construction team.

CAD software commonly used in the construction industry was not felt to be sufficiently nuanced to accurately capture the complexity of the bridge's curvilinear form in full.

The main contractor identified an opportunity to utilise CATIA, parametric modelling software primarily used in the aircraft and automotive industries which have the strictest requirements for accuracy in production and deliver a manufacturable correct 3D model of the bridge for fabrication.

The introduction of a specialist consultant with expertise in the automotive industry, transformed the whole construction team's working methods, first converting all engineering 2D data from drawings into a fully parametric 3D model of the bridge.

The bridge comprises multiple curvilinear sections each consisting of unique steel plates.

Surface modelling of every double curvature bent plate was made with the manufacturing process in mind by developing an unfolding tool in CATIA which generated bending data for each individual curved steel plate and exported this for the laser cutting production stage.

These practices made it possible to break down the overall form into approximately 3000 uniquely curved steel plates, all accurately specified for manufacturing, without compromising the desired geometry.

They also 3D scanned the whole harbour and bridge site and combined the scan data with the working model of the bridge.

Combining reality capture and CAD created a new level of depth in modelling and introduced many efficiencies in time, materials, temporary works, and wastage, e.g., virtual verification made it possible to plan and test the complex scaffolding required for precision positioning of bridge and pylon section, considering the camber shape at each stage.

During assembly of the first bridge sections on site, the area was scanned once more to verify the fit of the installed sections at the harbour.

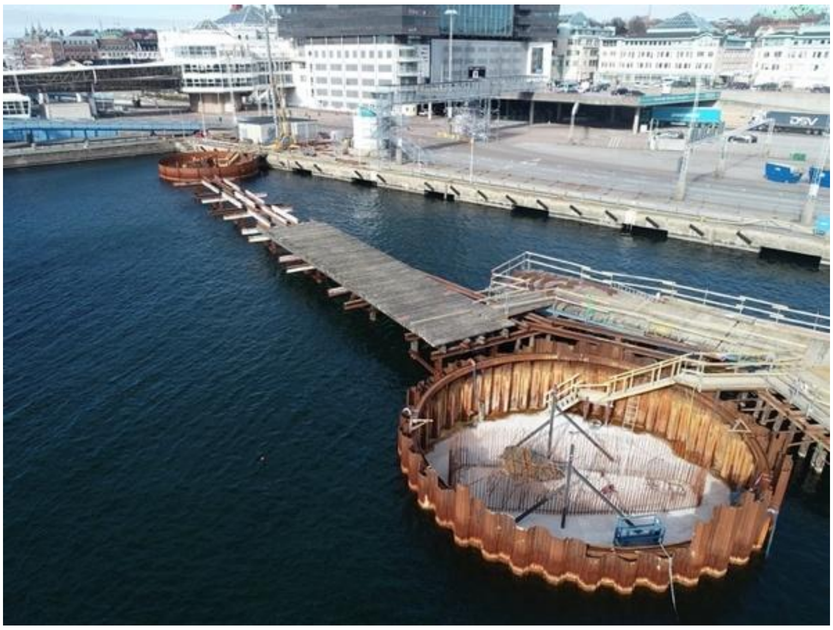
Simulation of the shop section montage sequencing, crane positions and scaffolding helped to shorten the actual assembly time on site and avoided any unwanted issues.

The team's ground-breaking use of parametric modelling merged design and analysis processes and created a seamless transition between traditionally distinct stages of design, fabrication, and installation, which ultimately made this distinctive bridge more sustainable, structurally efficient, and cost-effective.

SUBSTRUCTURE

At an early stage, it was determined that all foundations would be carried out as flat footings, eliminating the need for any piling work and associated emissions.

Shallow foundations in the water were constructed using a unique circular caisson saving 30 tons of steel of a traditional sheet pile cofferdam whilst purpose-designed bags filled with flocculants filtered contaminants from the water.



Figures 14 and 15: Temporary works reused timber and steel where possible. Prefabricated 'Coke can' caisson saved much time and steelwork

The stiff ground in the dock allowed steel frames made completely of reused steel, saving about 100 tons of material, to be positioned in the water and used as temporary support.

All steelwork used on the bridge is locally sourced with 99% produced in nearby Sölvesborg and transported to site by truck.

Long lasting stainless steel and timber were chosen where the public interact with the bridge and where elements are exposed to aggressive environmental conditions to exceed the required design life.

→ Figure 16: Bottom plate illustrated in Catia model

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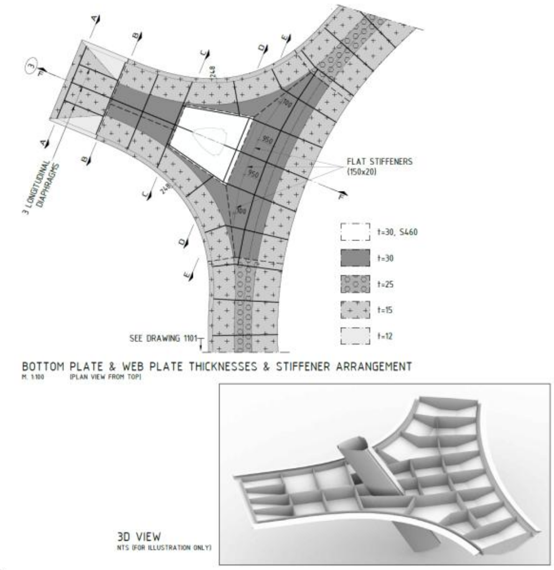

Figure 17: View from the bottom of the pylon

Figure 18: Installation of the deck

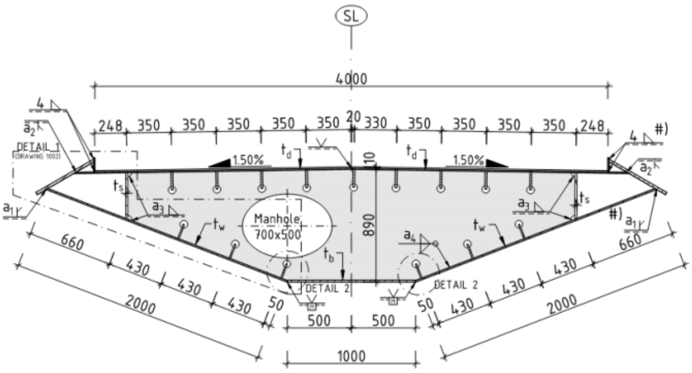

Figure 19: Section through trapezoidal deck

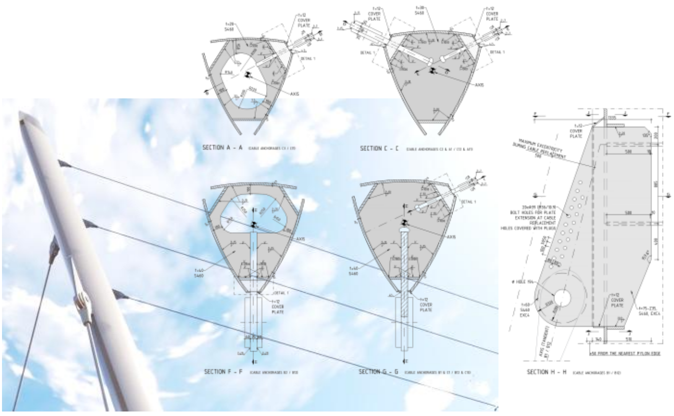

Figure 20: Details of main pylons

SUPERSTRUCTURE

The inclined pylons are fabricated from grade S355 steel coated in accordance with corrosion protection class C5-M. In areas of particularly high stress, grade S460 steel is specified.

The cross-section of the pylons is triangular with convexly curved side plates and tapers towards the top.

Each pylon projects about 23 m above the deck and reaches a maximum height of almost 30 m above the water surface.

Longitudinal niches run vertically along the pylon's vertices which accommodate the sword plates of the cable anchorages and recessed lighting strips.

The deck superstructure is a trapezoidal steel box. Initially designed with a variable height of 900 to 1300 mm, value engineering established a more economic constant height of 890 mm with the optimum cross-section to resist prevailing torsional moments and ensure dynamic stability of the bridge girder, with less maintenance cost.

STAY CABLES

The arrangement of the three fully locked coil 40mm dia. stay cables, forming a single twisted "ribbon" that wraps around the deck at mid-span, was an important feature of the concept design, determining the equal spacing of the joints along the curved edge of the superstructure.

These cables pass under the bridge deck via deflection saddles and emerge on the other side of the bridge where they are anchored to the opposite pylon.

For ease of installation and replacement, the main span cables are also anchored at mid-point beneath the deck.

This special anchorage was made by means of a threaded rod in a steel box, while all other cable anchorages are designed as forked heads.

The available 3D survey data of the bridge site and partially erected structure made it possible to consider actual and projected construction tolerances in the final trimming of the locked coil ropes.

Figure 21: Under the deck during construction

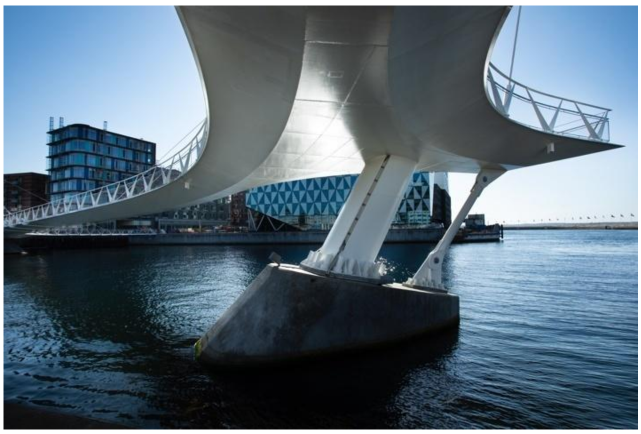

Figure 22: Low level view of curved deck soffit

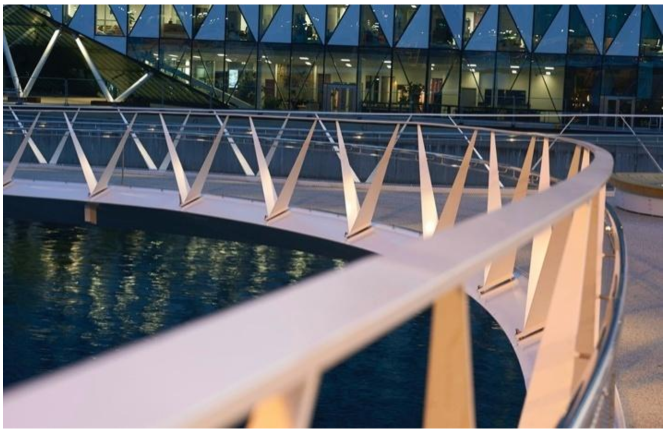

Figure 23: Lightweight parapet comprised of V posts

Figure 24: Night-time view showing bridge lighting

This together with the detailed calculations, close supervision, and experienced workforce enabled a cable installation in a single day.

POSITIVE INTERACTION

A new bridge can help shape public space and even provide a destination itself. Areas on the bridge were designed to promote positive interaction between users.

Coincident with each pylon, the deck branches outward to create two complementary cantilevered spaces: one, a remarkable viewpoint over the busy ferry channel to the north, the second offshoot forms a ramp touching down lightly on the new park to the south.

Each of these creates space, away from pedestrian and cycle movement, inviting the bridge user to stop and linger, to take in the views of the water, park, the surrounding buildings, sea-craft or simply interact with others during one’s day.

A generous bench, timber strip details echoing the decks of boats, wraps around the base of each pylon, further promoting leisurely interaction

Care and a great deal of thought have been devoted to all other details that are experienced close-up, a human scale. One example is the parapets.

Their angular V-shaped posts boldly contrast with the smooth lines of the bridge with a lightweight stainless-steel mesh stretched around the perimeter offering protection from falling without blocking the view of the surrounding water and buildings.

Special attention was also paid to the lighting which was considered an integral part of the concept design from an early stage.

All functional lighting is light and movement sensitive to reduce energy to a minimum. Architectural lighting focuses solely on the cables and pylons.

Low-level, narrow beam spotlights pick up the line of the primary cables.

Two diagonally cut acrylic domes at the tip of each pylon are illuminated from within by an iridescent light, so the pylons act as beacons, signalling the location of the bridge at night.

Recessed lighting along the full height of each pylon, further enhances the presence of the bridge at night.

Other than the usual white colour scheme, these sophisticated lighting strips allow a variety of colours to be utilised for anniversaries, celebrations, or other events.

Figure 25: Balcony emerges from sinuous deck

SUMMARY

The Dockyard Bridge, 'Varvsbron', was ceremonially opened to the public on 30th September 2021, and has immediately become a focus for the regeneration of Oceanpiren and Helsingborg in general.

Users have responded enthusiastically to the new bridge which epitomises a new confidence in engineering that is flowing from inclusive design and fast developing technologies.

It is a highly inventive pedestrian and cycle bridge; the structure represents state-of-the-art design in a location that is rich in Industrial history.

Our proposal took innovative design, world-class engineering, and contemporary technology for bridge analysis, documentation and machine fabrication and utilised them to create a unique form.

AWARDS

In spring 2022, the bridge was shortlisted for the "Architectural Design award" by the Swedish Transport Administration as one of four projects.

In July 2022, the bridge received the international award Eugene C. Figg Jr. Medal at The International Bridge Conference held in Pittsburg, USA.

In July 2022, the bridge was also shortlisted for the IABSE Award for Pedestrian and Cycle bridges as one of six projects from all over the world.

Figure 26: Completed Bridge opened to the public in September 2021

Credit: Fredrik Rege, Courtesy of PEAB

DESIGN OF FOOTBRIDGES & CASE STUDIES

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Dušan Rožič, Project Manager, Ponting Bridges, University of Maribor
Rok Mlakar, Project Manager, Ponting Bridges, Slovenia

I. INTRODUCTION

In the field of bridge design and construction footbridges (bridges for pedestrians and/or cyclists) represent a very special and characteristic branch of the profession.

Technically speaking, they have to take much lower loads than road and rail bridges, which makes them much lighter and more diverse in concept.

This allows and calls for greater creativity and makes footbridges the subject of research also within other disciplines (architecture, urban planning, landscaping, etc.), not only in sense of strict structural design.

Sociologically speaking, the experience of slowly crossing the footbridge is much more personal, through direct contact with the structure, then it is when passing by in a moving vehicle at a higher speed.

Therefore, the engineer has to devote more attention to details and equipment design of a footbridge than is usually prescribed and standardized in practice for road and rail bridges.

II. MAIN DIFFERENCES COMPARED WITH ROAD AND RAILWAY BRIDGES

The main differences between footbridges and other bridges can be summarized in the following categories:

- Loads
- Geometry
- Materials
- Finishing, detailing, and equipment
- Costs

Loads

The loads are defined by different national regulations, laws and specifications, which also in the field of footbridges differ from each other.

Footbridges are typically loaded with a characteristic uniformly distributed load q_{fk} = 5 kN/m^2 which applies for short spans up to 10 m; for longer spans, the characteristic load is smaller and is calculated according to the relevant equation[1].

Geometry

Road and railway bridges are part of a complex and mostly continuous infrastructural network and have to comply with the geometry set on a larger and wider scale and meet the strict and fully determined geometric standards and regulations for road/rail layout and alignment.

The main criterion for the geometry of these bridges (roads and railways) is the characteristic travel speed, which is, in general, higher than 50 km/h, and it makes road and railway bridge geometries more aligned to the route and often less curved.

The travel speed for footbridges is not really relevant but one must consider, especially in urban areas, geometric rules for physically handicapped people and people in wheelchairs, which is often appointed as a Barrier-Free Construction.

This field is covered by local, national and also international regulations (e. g. ISO 2008).

In practice for footbridges, this means restrictions in longitudinal inclination are mostly set at 5% although this may be steeper over short distances.

Bridge accesses only by stairs are not allowed, there must be an alternative present in the form of ramps and/or elevators.

Footbridges in a natural environment on hiking trails can be designed and built around these restrictions, here stairs and longitudinal inclinations also over 20% are not problematic or prohibited.

The most important geometric parameter for footbridges is the clear width of the bridge deck, which depends on the bridge's basic function, traffic type and volume, and prescribed conditions for passing and meeting of bridge users (wheelchairs, cyclists, pedestrians).

Most guidelines agree that a minimum clear width for combined traffic on footbridges (walking and cycling) can be considered from 2 to 2.5 m (fib 2005).

At the higher density of traffic in urban areas, larger deck widths (3 - 7 m) are required, while footbridges on hiking trails can easily be much narrower (1 m).

Most of the footbridges shown in the literature (Baus and Schlaich 2007, Idelberger 2011) have a clear width between 3 and 4 m.

The bridge railings' heights can also vary depending on different national legislations. A trend of raising the height of the railings, following the increase in the average height of the population, can be noticed.

In general, the minimum height of the bridge railings is set at 1.1 m for mainly pedestrian traffic and 1.2 to 1.4 m for cycling traffic.

Materials

For road and railway bridges, reinforced and pre-stressed concrete is considered to be the most commonly used construction material, while steel dominates long-span bridge construction.

Footbridges are a bit different. As these bridges can be constructed of almost any material, the most noticeable structures are made of steel and wood because these materials allow better and more appropriate pedestrian detailing.

Besides those mentioned, there are also other materials (composite materials, various fiberglass, glass, aluminum and other stainless alloys) used for footbridges that are not suitable for heavy road and railway bridge construction.

Concrete structures are widely used within footbridges with thinner cross-sections, that is, with the use of HPC (high-performance concrete) or UHPC (ultrahigh performance concrete) in combination with microfiber reinforcement.

Also, various material combinations are used more and more often.

Finishing, detailing and Equipment

Footbridges are felt closer by pedestrians and cyclists who can see and feel the details and even touch them. Therefore, details, accessories, and finishing of footbridges are very important.

The experience of walking over the footbridge is affected mainly by the selection of the walking surface, bridge railings concept and lighting of the structure.

The bridge deck must meet the load-bearing criteria (possible concentrated wheel loads), it must be safe against slipping, and it shall be able to drain the surface water and provide structural durability. With regard to the implementation, we can distinguish between watertight bridge decks and decks where a proper separate draining system is needed.

Open water-permeable bridge decks:

- Open wooden bridge deck
- Bridge deck of steel gratings
- Bridge deck of different sections or lamella (steel, plastic, laminated, etc.)

Watertight bridge decks:

- Concrete or composite bridge deck slabs
- Steel orthotropic plates with epoxy- or asphalt cover
- Wooden laminated or glued panels

Railings, lightning and other details provide the ultimate experience of the footbridge. Detail guidelines and recommendations are given in different literature sources, e. g. Sterling 2005 or Keil 2013.

III. SOME CASE STUDIES – FOOTBRIDGES IN SERVICE

STUDENCI FOOTBRIDGE IN MARIBOR

In principle, the new footbridge over the river Drava in Maribor, Slovenia, is a reconstruction of an existing old bridge where the supports (concrete/stone piers) were preserved and strengthened while the old superstructure was entirely replaced with a new, completely different one.

The history of the Studenci footbridge is very colourful. Originally it was constructed in 1885 with three simply supported truss girders and wooden supports in the riverbed, see Figure 1.

Figure 1: Bridge from 1885 - 1946

After severe damage during the flood in 1903, the bridge got new stone intermediate supports.

During WW II the bridge was destroyed and reconstructed by the army.

In 1946 it was swept away by a flood again and two years later rebuilt again, the superstructure was replaced with a new one – with two welded-plate girders, see Figure 2.

Figure 2: Bridge from 1948 - 2007

After the completion of a hydropower plant in 1968, the water level was raised by about 5m.

In 2007 the final reconstruction was carried out according to the winning design solution of a design competition in 2004.

Design of the new footbridge

Due to the construction economy, it was necessary to use the existing supports of the old footbridge, thus dictating the spans of 3 x 42 = 126 m; at the same time, it was necessary to enlarge the clear opening of the existing navigation height under the bridge from 3 to 3.6 m.

Besides common requirements such as safety, durability and economy, the city of Maribor also wanted to have a unique and attractive new bridge, yet in harmony with the environment.

The new structural design is a triangular steel truss as a primary longitudinal bearing structure (spine) along which a secondary transverse structure is raised (ribs).

On both banks where there was insufficient static height, the structure was raised upwards in relation to the bridge deck surface which is here divided into two parts.

By a gradual rise of the deck the structure is disappearing under the floor, both walkways join and over the middle of the river raises a common surface for an unimpeded view to all sides and invites a peaceful conversation with friends.

Description of the footbridge and structure

The footbridge axis is straight, the longitudinal alignment is in a convex vertical curvature R = 1,045 m with a maximum slope of 5%.

Figure 3: New bridge, 2008

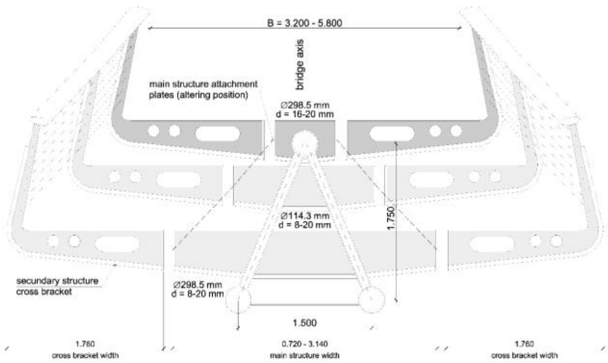

Figure 4: Cross section

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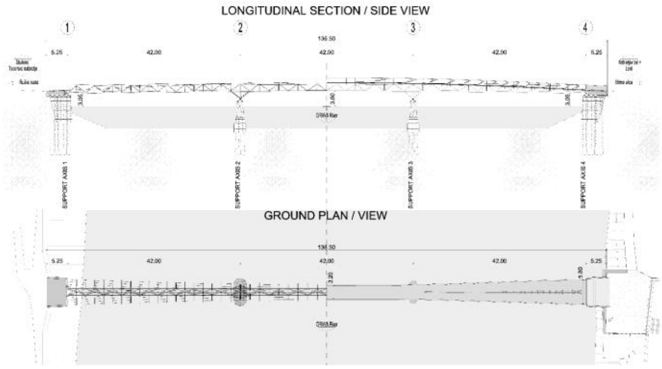

Figure 5: Longitudinal section and ground plan

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In the middle of the footbridge, the deck width is 3.2 m, at both ends it is split into two parts of 2.4 m each, divided by a visible 1 m wide main structure, breaking through the deck.

The variation of the structure and deck alignment was solved by dividing the structure into two systems:

<u>The spine – the main steel structure</u> is a centrally positioned triangular truss of a constant structural height and width.

Such geometry simplified the workshop production and erection. It consists of three longitudinal tubes – one for the upper flange and two for the bottom flange.

The triangular cross-section is constant on the outside, only the tube thickness and the position of the accessory piece for attaching the secondary structure (ribs) change.

The axial distance between the upper and bottom tubes is 1.75 m which gives a total structural height of 2.05 m, and the axial distance between the lower flanges is 1.50 m.

The longitudinal tubes are ∅ = 298.5 mm, wall thickness 8 – 20 mm; the diagonal and cross tubes are ∅ = 114.3 mm.

Elevation of the main structure has a constant hog curvature of R=4,000 m.

The struts of the truss are not vertical but radial, so the element lengths and mutual angles are equal along the total bridge length, which made the construction a lot cheaper and simpler.

The structure was made of structural steel S355 and protected with anticorrosive coatings.

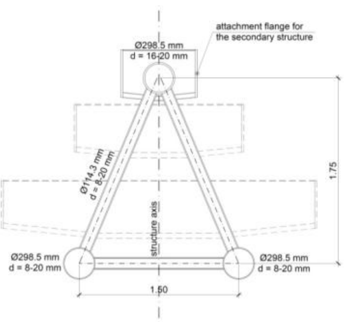

Figure 6: Spine cross section

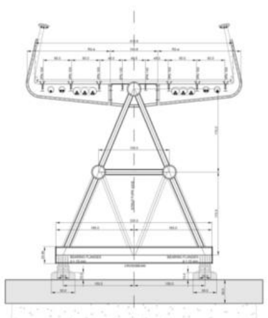

Figure 7: Medium support cross section

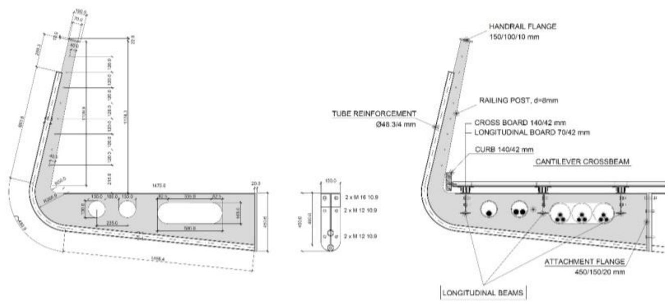

Figure 8: Rib cross section

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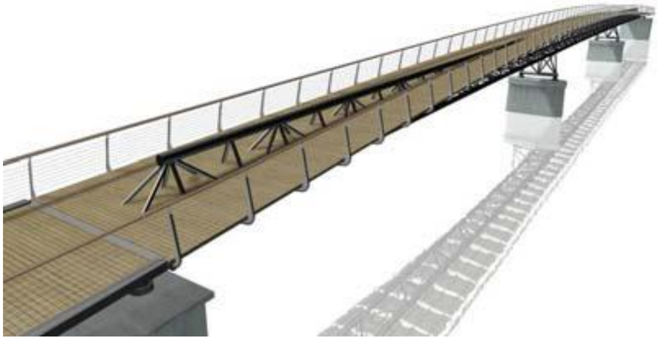


Figure 9: Model of the bridge

Figure 10: Complete bridge

Ribs – the secondary steel structure rise along with the main structure which carries the bridge deck surface.

It was erected by screwing after the erection of the main structure and was protected by hot galvanizing.

It is composed of transverse cantilever girders (ribs) and longitudinal stiffeners.

The transverse cantilevers are at the same time railings balustrades and exactly the same throughout the whole length of the bridge.

The deck is made of transversely placed profiled Bangkirai wooden boards.

Discreet footbridge lighting of LED diodes with only 1,350 W is placed in a wide and comfortable handrail.

Construction

The footbridge construction was also innovative and for a very competitive price, as it used the existing structure as a support for erection.

The main structure – triangular truss - was welded from segments and progressively launched over the existing structure.

After launching the new structure was supported through the partly removed existing structure.

Truss elements above the intermediate supports were erected and the bearings grouted. The old footbridge was hung from the new structure which also enabled dismantling.

Figure 12: Partial disassembly of the existing structure

Figure 13: Launching of the new structure on the old one

Figure 11: Assembly of the bridge deck

Figure 14: Complete bridge

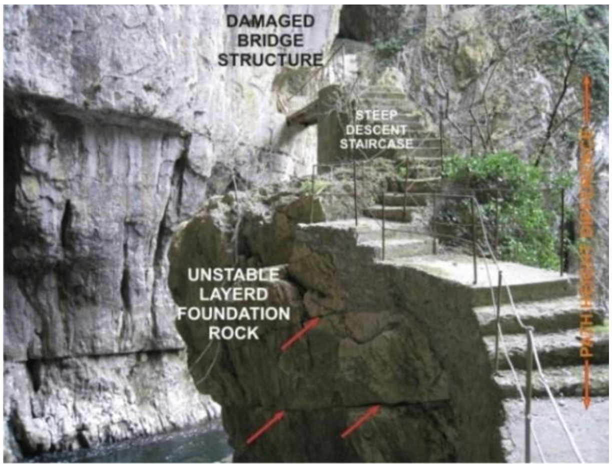
MARINIČ FOOTBRIDGE, ŠKOCJAN CAVES, SLOVENIA

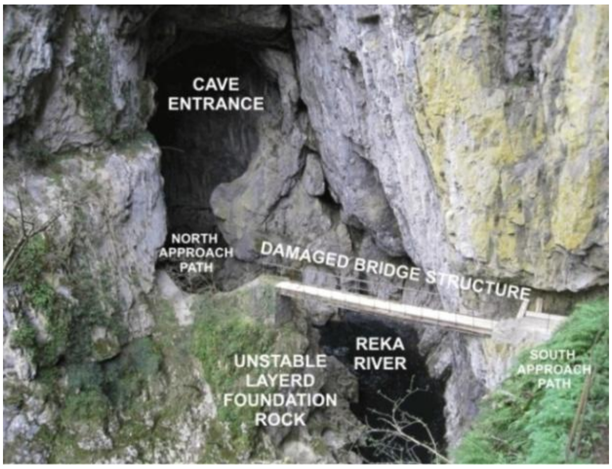
The Marinič Footbridge in the Škocjan Caves Park, Slovenia, together with associated footpaths and other cave infrastructure, was rebuilt in 2010 on the initiative of the Public Service Agency Škocjan Caves Park to expand their tourist activity and enable visits to the eastern parts of the caves, which had been closed to the public since 1965 when much of the existing cave infrastructure was destroyed by devastating floods.

The bridge was originally built in 1891 as Concordia Bridge (under Austria) and between World Wars (under Italy) renamed Bertarelli Bridge.

The new bridge replaced the existing bridge of two steel I-sections and a wooden deck, worn down, with unstable support and partially heavily damaged by falling icicles and rocks from a vertical, over 100 m deep, rock wall above the cave entrance, see Figures 15 and 16.

The new bridge was designed as a curved, lightweight, rock-anchored and transparent steel structure, see Figure 17.





↑ Figures 15 and 16: Original damaged and unsuitable bridge

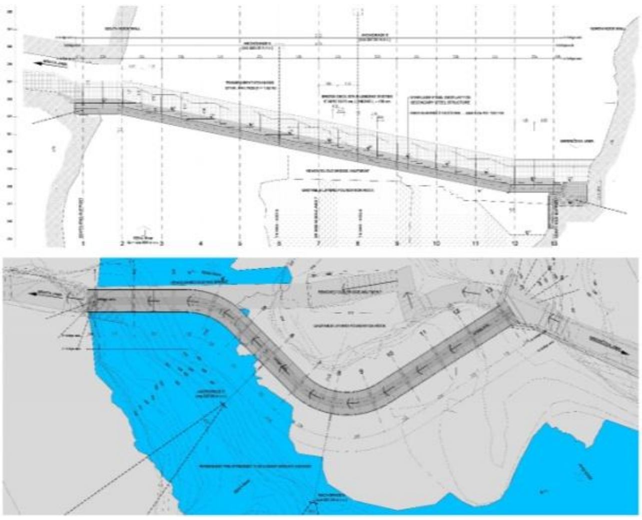


Figure 17: General scheme

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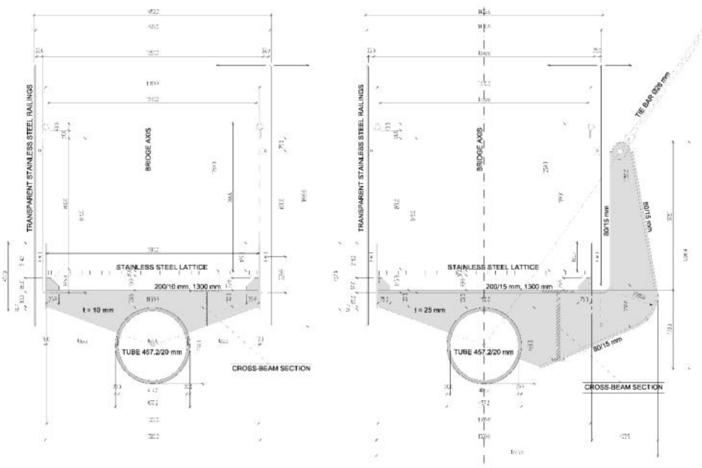

Figure 18: Characteristic cross sections of the bridge

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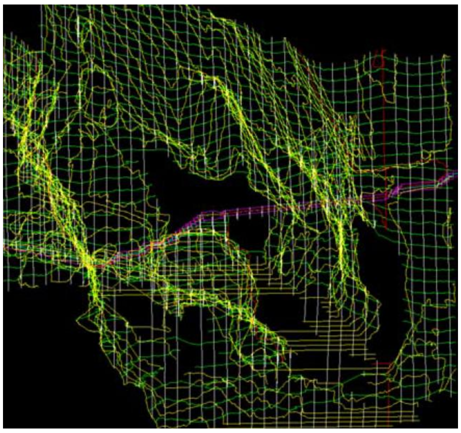


Figure 19: 3D scan of the cave entrance

Figure 20: 3D printed cave scan and initial work model of the bridge

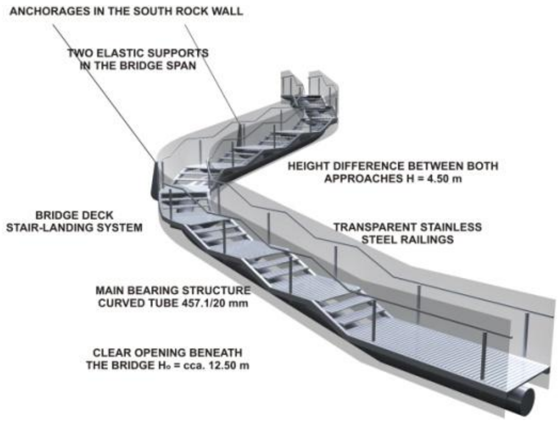


Figure 21: 3D design model

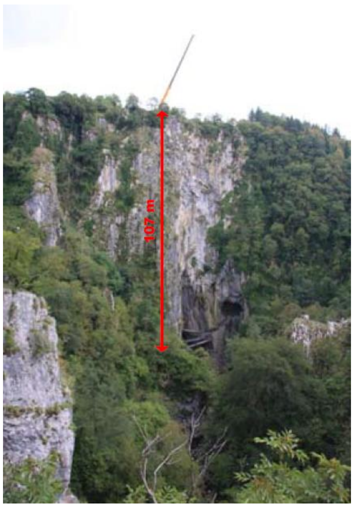
The footbridge is almost 30 m long (span 27 m) and overcomes a height difference of 4.5 m between both end supports.

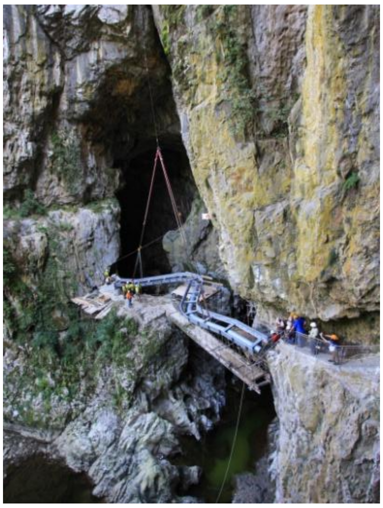
Structural design and shape of the new bridge respond to all conditions given by the distinctive natural karst environment.

The bridge deck is only 1.50 m wide and equipped with stainless steel footpaths and railings.

The total weight of the bridge structure amounts to about 11,300 kg.

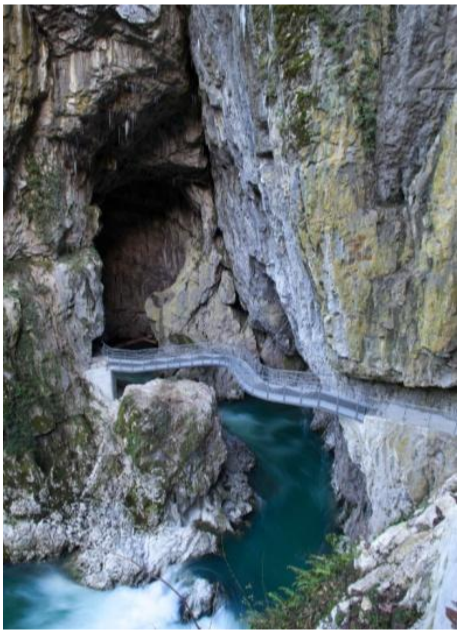
With its curvature, towards the cave entrance, the bridge avoids falling debris and unstable support conditions, and with its lightness preserves the fragile, natural, UNESCO protective ambiance.





Figures 22 and 23: Installation of the bridge

↗ Figures 24 and 25: Complete bridge



SCENERY FOOTBRIDGE FOR "CHRONICLES OF NARNIA"

In the summer of 2007, the Walt Disney production company filmed the second part of the blockbuster movie Chronicles of Narnia - Prince Caspian near the small mountain village of Bovec in Slovenia.

For the attractive final scene, the producers needed an ancient-looking wooden bridge across the emerald green river Soča.

The location was chosen due to the exceptional natural features of the Soča River Valley which were consistent with other outdoor scenes, mostly filmed in New Zealand.

Here the concept and technical characteristics of the temporary wooden bridge and its structure, which served as a scenic element in the movie, will be briefly explained.

The bridge was used for about 1 month and was then demolished and partly used for further sequence shoots in the studio.

The bridge was 7 m wide and had 7 spans of 7 m, together with the abutments it was 60 m long.

The bridge was constructed of wooden logs 46 cm in diameter and squared wooden beams 30/40 cm.

The basis for the idea of the bridge was the drawings showing Caesar's Bridge over the Rhine River, which Caesar built on his imperial quest some years BC, see Figure 26.

The bridge basically consisted of cross-frame supports and longitudinally laid, simply supported spans of wooden logs.

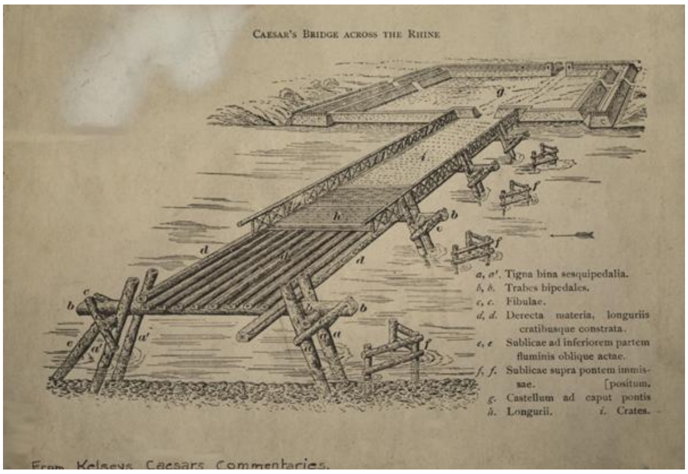


Figure 26: Caesar's Bridge over the Rhine (in year 55 BC)

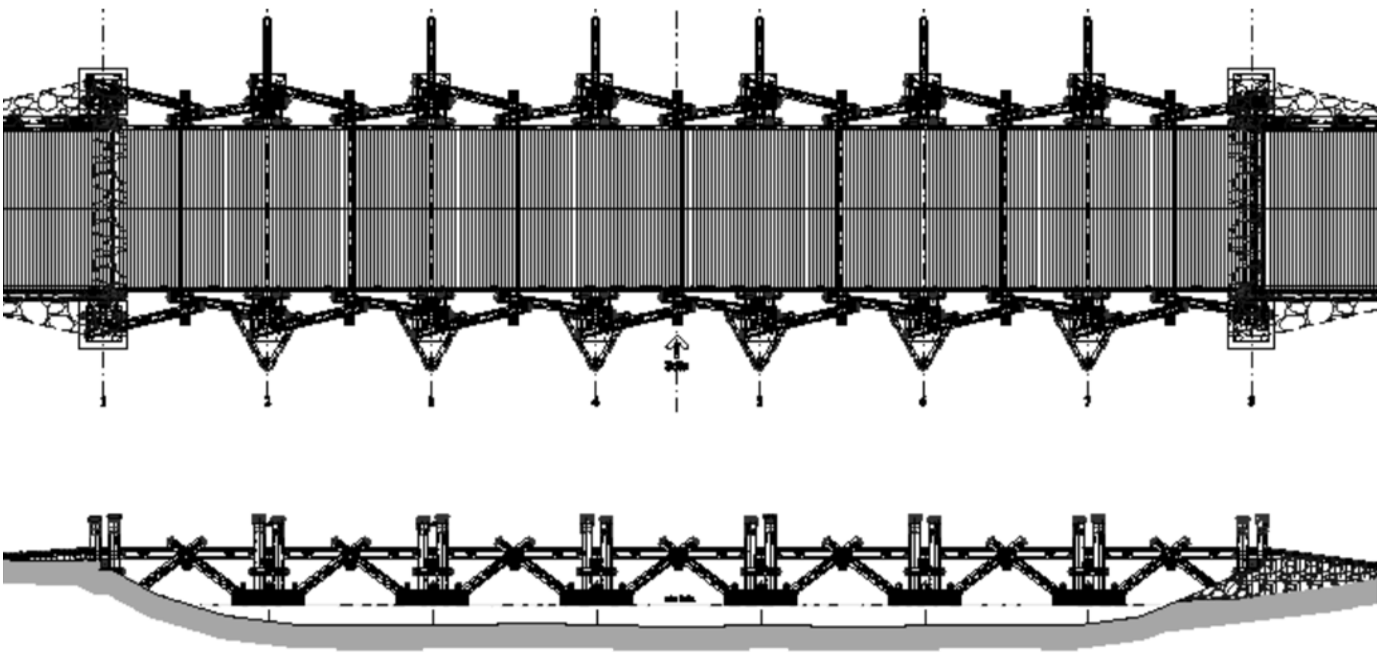


Figure 27: Design Concept – 7 spans of 7 m length and 7 m width

Interesting here were mainly the cross frames, which used a system of shorter logs over the corners and driven beams to embed the longitudinal girder into the cross frame.

In our design only supports shields and additional supports for the water pressure were added.

The original design had to be modified a bit; partially due to the film screenwriter's demands and also for constructional reasons and needs.

The foundations were adjusted to the existing ground conditions of the Soča River bed (gravel with rocky solitaries) and construction deadlines.

That is why prefabricated concrete foundations 2 x 2 m with pier sockets were specially designed, two for each support.

Due to the high level of the groundwater and the risk of underflow, the foundations were set rather high and additionally supported with driven 3 – 4 m deep piles.

The piles were at first designed as wooden piles, later, due to construction difficulties, the piles were substituted with old steel rail tracks.

Screenplay anticipated filming on the finished bridge, followed by partial removal of the bridge and filming of the final scene of the bridge destruction.

These scenes were filmed during the construction of the bridge.

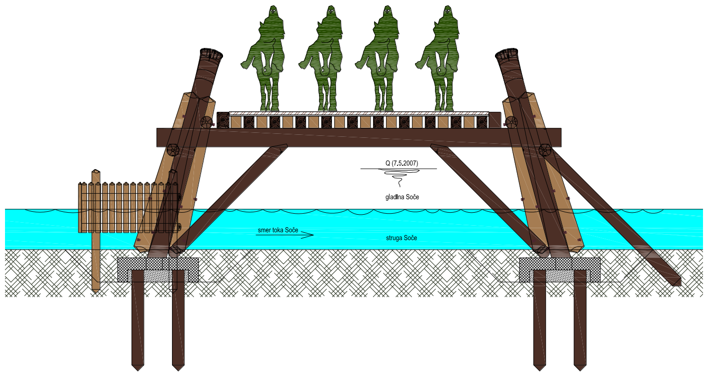


Figure 28: Cross section of the scenery bridge

The reverse order of the filming sequence was logical since the demolition was much faster than the erection of the bridge.

The design, coordination with the Client and the Authorities as well as gathering of permits took more than 6 months (November 2006 – May 2007), the construction then took a month (May 2007 – June 2007), and the filming took place in the first half of June.

Just at the time of the filming, the bridge was exposed to a high-water test as the flow rate on 7 May 2007 was 97.4 m^3/s - considerably over the usual flow rate of 35 m^3/s. The normal water level of 0.5 m rose to almost 2 m.

Figures 29 and 30: Scenery footbridge for "Chronicles of Narnia"

FOOTBRIDGE IN THE OLD CENTRE OF LJUBLJANA

The greatest modernist influence on the historical centre of Ljubljana, Slovenia, was given to the city by a famous Slovenian architect Jože Plečnik.

When arranging the banks of the River Ljubljanica, he even left an opening in the masonry for a future footbridge.

For some period of time, there stood a temporary wooden structure (1991 - 2014), which was no longer useful.

Therefore, in the year 2012, the city of Ljubljana announced an international design competition for a new footbridge, and the winning solution was built in 2014.

The design is based on the principle of minimalism, with an extremely slim structure, as thin as possible.

The concept of minimalism, in its limitation, raises the question of how far can we go with the slenderness ratio and still keep the structure suitable for use in the city centre with heavy pedestrian traffic.

To maximise its slenderness, the structure was fastened or continued over the existing retaining wall with an additional span and tensile pile support on the right bank.

This was not possible on the left bank, where a protected building is located, and the structure was simply supported on the bearings, see Figure 31.

The main span of 25 m in length is a slender steel deck that continues, on the right bank, into a concrete pile cap with two tensile piles of 1.20 m in diameter.

The transition from the steel to the concrete part is created by an intermediate composite part, where shear studs transmit forces.

The steel deck is trapezoid-shaped with a structural height of 25 cm at the edges and 50 cm in the centre of the cross-section, see Figure 32, resulting in a high slenderness ratio.

The footbridge deck is 3.60 m wide.

The basic material is S355 quality steel.

The edges of the structure that serve to anchor the glass railing and drainage are made of stainless steel due to potential problems with maintenance.

The upper sheet layer is 12 mm thick and the lower 10 mm respectively.

Longitudinal ribs on a 0.5 m raster and transversal ribs on a 2 m distance are both 10 mm thick.

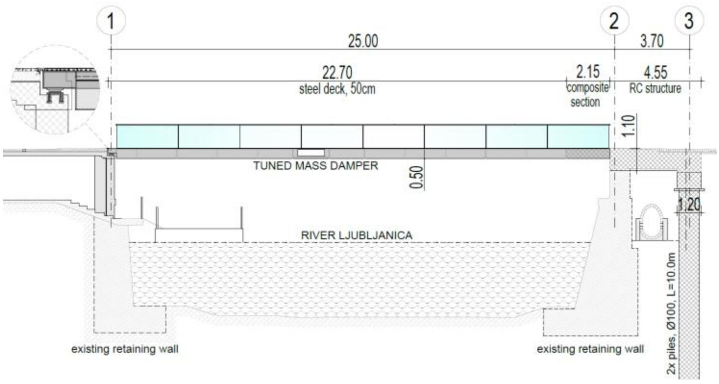


Figure 31: Asymmetrical footbridge structure - longitudinal section

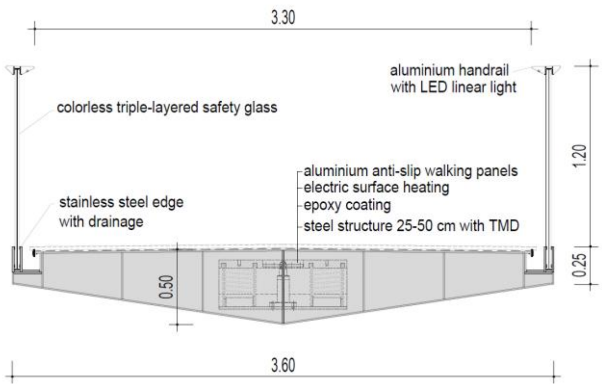


Figure 32: Footbridge characteristic cross section

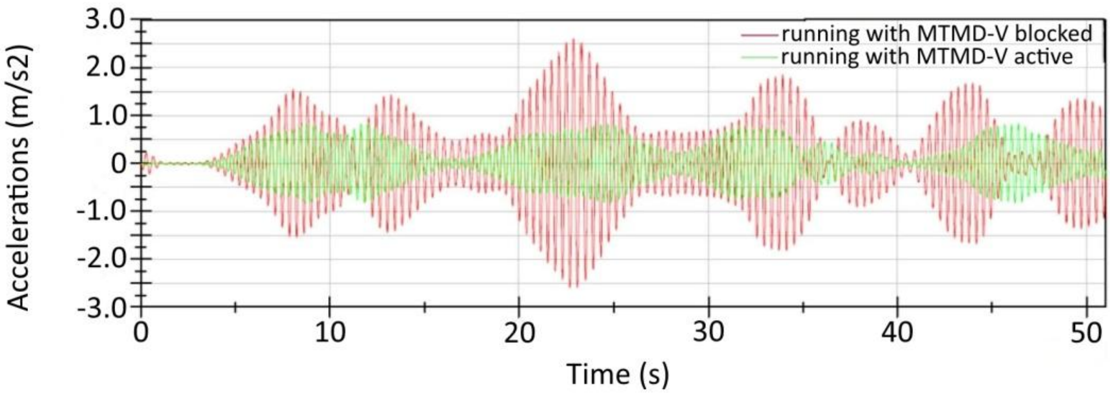


Figure 33: Vertical acceleration, 6 people running

In view of the high slenderness of the structure, a lot of attention was paid to the dynamic behaviour of the structure.

The first natural frequency (vertical) was 2.76 Hz, which could be critical for excitation caused by pedestrians, therefore tuned mass damper (TMD) was foreseen from the very beginning.

We used Maurer MTM-V damper with an oscillation mass of 1,500 kg, stiffness constant of 397 kNs/m and damping constant of 6.9 kNs/m.

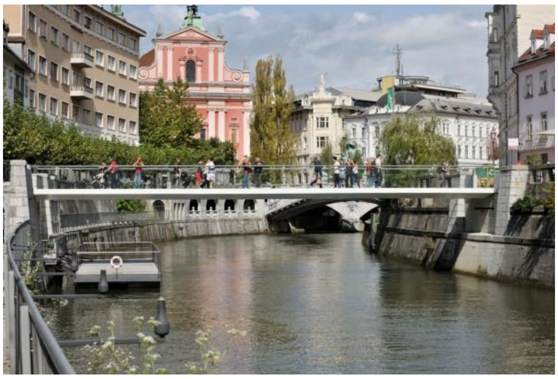
The tests showed excellent results, as the accelerations of 6 people running decreased by a factor of 3.14, see Figure 33, and 4 people jumping even by a factor of 7.17.

The steel structure of 25 m in length and 26 tons in total weight was constructed in a workshop in one piece, transported to the site and installed into its final position.

The footbridge was officially opened to the public in September 2014.

The total contract value was EUR 660,000.

The new footbridge in the very centre of Ljubljana was well-received by locals and tourists alike.



Figures 34 – 37: New footbridge in the centre of Ljubljana (with the local name Ribja brv)

DRAW FOOTBRIDGE IN GDANSK

The draw bridge is located over the river Motława to Ołowianka Island in Gdansk, Poland, in the historical centre – an extremely sensitive ambiance due to its historical significance and cultural heritage under the high protection of various authorities.

The footbridge is 62.2 m long and 6 – 8 m wide.

The main structural parts of the bridge are:

- Integral concrete structure on the left bank (Old Town); L = 15 m
- Movable steel structure in the middle of the river; L = 41 m
- Concrete caisson as foundation and engine room (on the Ołowianka Island side); L = 8 m
- Control building on the top of the engine room

Concrete structures and the control house are quite standard.

The movable part of the footbridge is a single-leaf bascule bridge.

This is, due to its reliability, shortest operation times and easy maintenance, the most often constructed type of movable bridge.

The span with the weight of the cantilevered flap can open the bridge without additional counterweight which makes the structure very simple.

The rotation is powered by an electro-hydraulic lifting mechanism, which is considered the most reliable drive for modern drawbridges.

Due to a limited depth, a special type of structure was adopted.

Figure 38: Rendering of the winning concept

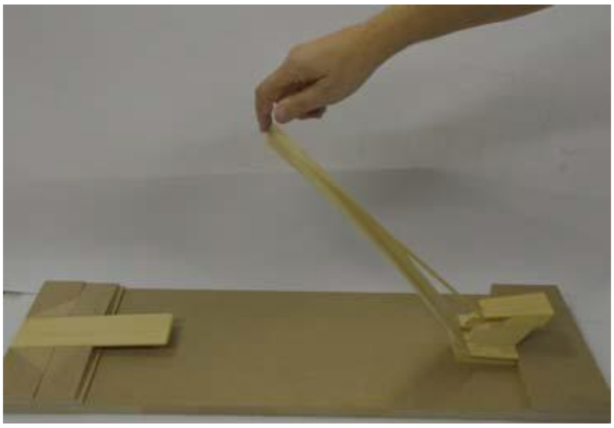


Figure 39: Model of the bridge

The steel triangular-shaped structure has a span of 40 m and a maximum structural height of 1.9 m (L/21), positioned partly above the deck (from 0 to 1.50 m) and partly underneath (constant 0.40 m).

Pathways are on both cantilevered sides of this longitudinal torque girder.

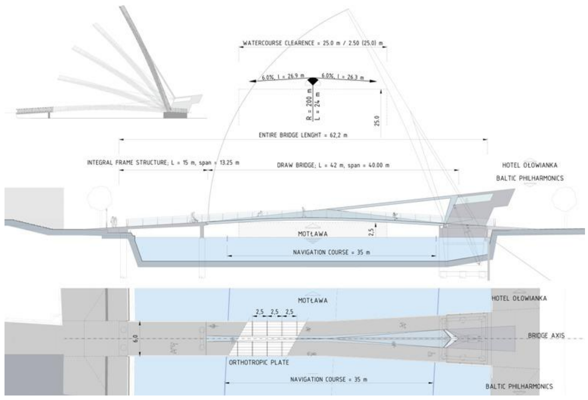


Figure 40: Bascule Footbridge in Gdansk - general layout and alignment

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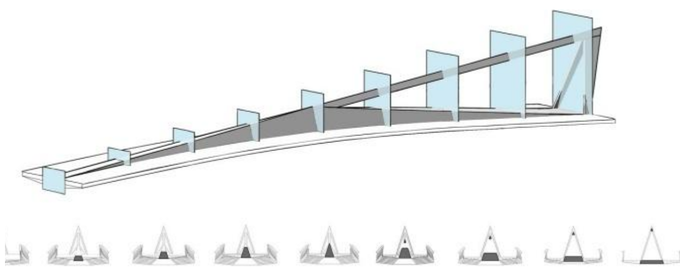


Figure 41: Main girder - cross sections

Figures 42 and 43: Construction of the bridge

The bridge deck is designed as an orthotropic 10 mm thick steel plate with longitudinal ribs connecting the cantilevered cross girders.

Both the main steel girder and deck were made of steel S355 or fine-grained steel S460.

The structure was welded in a shop, transported and erected on site.

In a horizontal position (the bridge in function and hydraulic off) the structure acts almost as a simply supported girder, while in the lifting stage it is a stayed bascule bridge.

From calculations, it can be seen that the footbridge, though with an extremely slender body, would have enough damping for the comfort of pedestrians with just one TMP device (G = 10 kN) in the middle of the span.

The control building is set on an axis of the bridge, directly on top of the foundation caisson with the engine room.

This provides undisturbed communication between control and maintenance (down and up).

The operator's room on the top provides excellent direct visual control of the whole traffic on the footbridge as well as the river area nearby.

In appearance the control building is some kind of reminiscence of the old port crane in Gdansk or poop deck on the stern of old Baltic ships, adopting historical and implemented shapes of the old Baltic town and connecting them with the future.

Figure 44: Rendering of the draw footbridge

Figure 45: Complete Bridge

SONCE OVERPASS IN ROGAŠKA SLATINA, SLOVENIA

The Sonce overpass, for cyclists and pedestrians, serves as a direct link between the Rogaška Slatina promenade and the P+R (Park&Ride) system with additional tourist capacities and facilities (observation tower ˝Kristal˝, organ museum, ...) under construction, at the foot of Tržaški Hill.

The footbridge crosses the access road to the senior citizens' home ˝Pegaz˝, the Ločnica stream, a parking lot between the stream and the R3-685 regional road, the R3-685 regional road, the Grobelno - Rogatec railway line and the road to Tržaški Hill, landing aside the P+R parking lot at the foot of Tržaška Hill.

The curved geometry of the Sonce Overpass link is the result of local, technological and technical conditions as well as the client's wishes, taking into account all local features of the surrounding area.

The characteristic span, tied-arch over the regional road and the railway, is 43 m, the approach spans are arranged at 13.50 + 17.50 + 15.50 = 46.50 m (from the northern promenade side) or 17.00 + 17.50 + 13.50 = 48.00 m (to the southern side towards Tržaški Hill) respectively.

The northern approach is yet extended by a 36m-long ramp along the parking lot in front of the Sonce Restaurant.

The total length of the overpass, together with the northern approach ramp amounts to 173.50 m.

Figure 46: Areal view of the Sonce Overpass link

Figure 47: Visualisation of the Sonce Overpass link

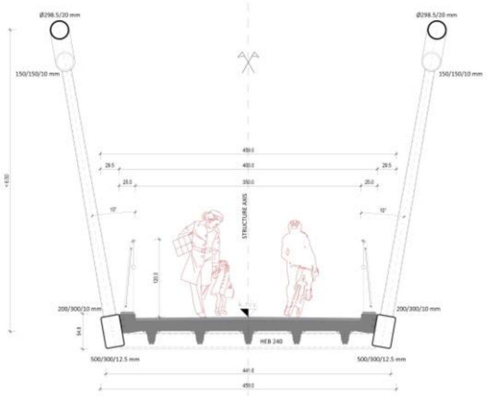


Figure 48: Characteristic cross section

Click on the image to open it in a higher resolution

Figure 49: Arrangement scheme longitudinal section

Click on the image to open it in a higher resolution

Figure 50: Bridge deck – pedestrian view

Figure 51: Structural detail

On both sides of the characteristic span, additional accesses to the bridge are provided by elevators, to connect the existing bicycle paths, parking areas, retail and restaurant capacities and pedestrian traffic areas underneath the overpass.

In concept, the bridge is an integral steel structure with bearings and expansion joints only at both abutments.

The main girder is assembled of standard RHS, CHS and I-sections, while only the ties of the arch are welded hollow sections with variable cross sections.

The longitudinal slopes of the bridge (levelling) are dictated by the obstacles to be bridged; the regional road R3-685 Tekačevo – Rogaška Slatina – Ranjkovec and the railway line Grobelno – Rogatec.

The rather steep levelling of the bridge is carried out at a constant slope of 5%, except at the elevator accesses, on both sides of the characteristic span, where the longitudinal slope is levelled to 0%.

The longitudinal gradient on the northern approach ramp is 6%.

Figure 52: Finished Sonce Overpass – regional road driver view

TREMERJE FOOTBRIDGE OVER THE SAVINJA RIVER

Tremerje footbridge for cyclists and pedestrians is part of the 1st phase of the national public cycling route between Celje and Laško, Slovenia.

Due to the torrential nature and frequent floods of the Savinja River, the design conditions of the Slovenian Environment Agency (ARSO) required a bridge without support in the riverbed itself.

Consequently, the footbridge is designed with a single span of 80.0 m length; the total length of the construction is 92 m.

On the other hand, the client wanted the structure to have an innovative and distinctive design.

The main idea during the design process was to build a footbridge that would be light and transparent above the riverbed, where the view of the river is most beautiful.

Therefore, we designed a lightweight spaceframe superstructure from a circular hollow profile in one span of 80 m, which is connected by massive abutments on each side of the river.

The main steel structure was designed as a space truss structure consisting of two longitudinal circular hollow profiles ∅ 406.4 mm at the top and the bottom, connected with diagonals 244.5 mm.

The deck structure is a composite concrete plate, and the clear width is 3.50 m.

The length of the main span of the bridge is 80 m, and the total length of the structure is 92 m.

Before the production of the steel structure in the factory, a 3D BIM model, see Figure 53, and shop drawings for the whole structure were produced.

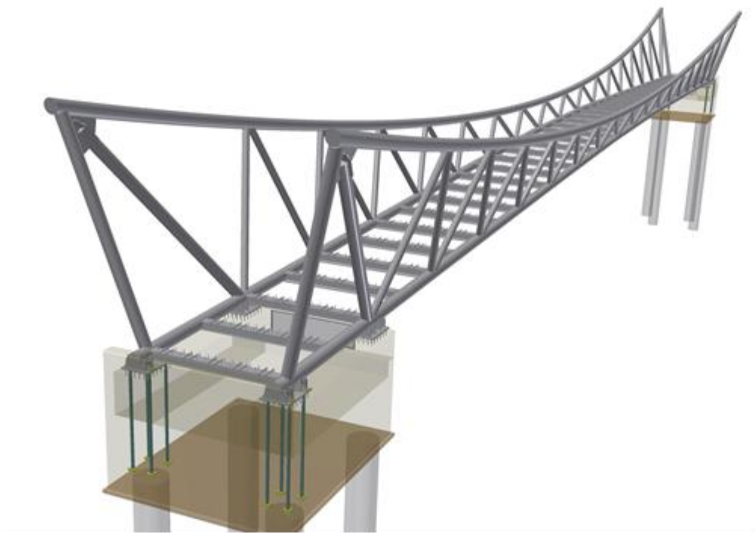


Figure 53: 3D BIM model for fabrication

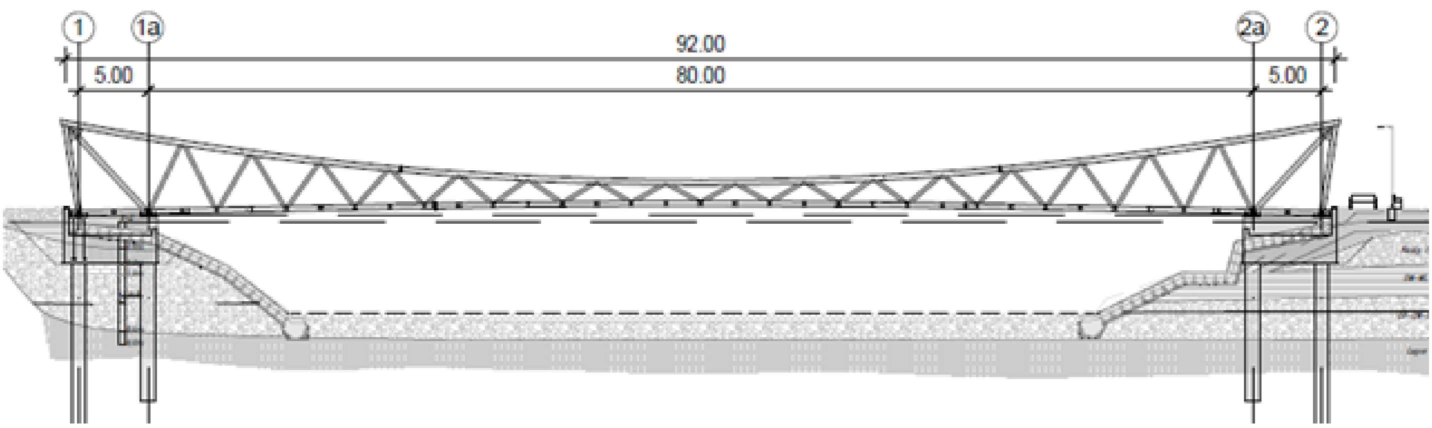


Figure 54: Arrangement scheme longitudinal section

Figure 55: Assembly and erection

Figure 56: River crossing

Welding details and the chamfer were designed according to ISO 9692, AWS D1.1/D1.1M and the CIDECT design guide.

The execution classes were EXC3 and EXC4.

The bridge consists of three segments, each weighing approx. 52 tons.

Assembly of the steel structure was performed with a mobile crane.

The cycling route gave the community a secure connection between the two cities, while the bridge over the Savinja River offers a safe crossing for pedestrians and cyclists.

Figure 57: Walking surface

Figure 58: Light and transparent footbridge above the river Savinja

IV. SOME CASE STUDIES IN TENDERING OR UNDER CONSTRUCTION

FOOTBRIDGE ŠPICA IN CELJE, SLOVENIA

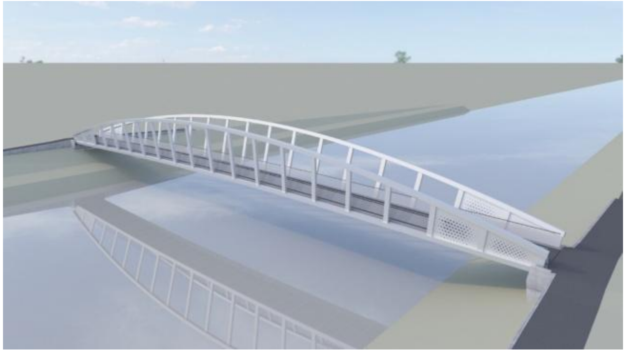
Footbridge Špica over the Savinja River in Celje is to be part of the G13 section on the long-distance cycling connection (DKP) in Savinjska Region in Slovenia.

The bridge is designed as a simply supported, arched-shaped Vierendeel truss, with a span of 76 m.

The static height of the twin girder varies from just 1.5 m, at the end supports, to 6 m, due to the arch-cambered upper chord, in the middle of the span.

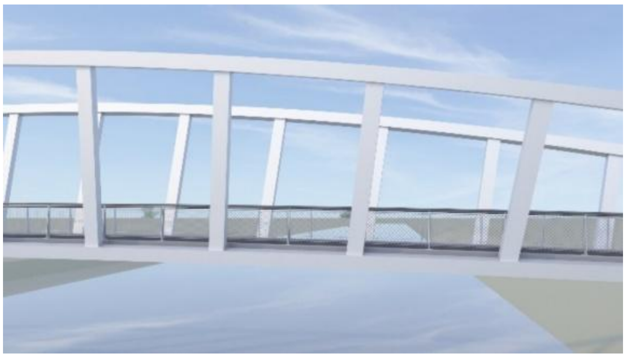
The verticals are placed at a distance of 4 m and oriented centrally (radially) with respect to the upper chord rounding.

Two parallel, outwardly inclined Vierendeel beams are connected in the lower chord plane with a composite 18.5 cm thin Hi-Bond deck slab, the upper chords have no connections.



↗ *Figure 59: Longitudinal layout*

→↗ *Figure 60: Pedestrian view*



→ *Figure 61: Mid span detail*

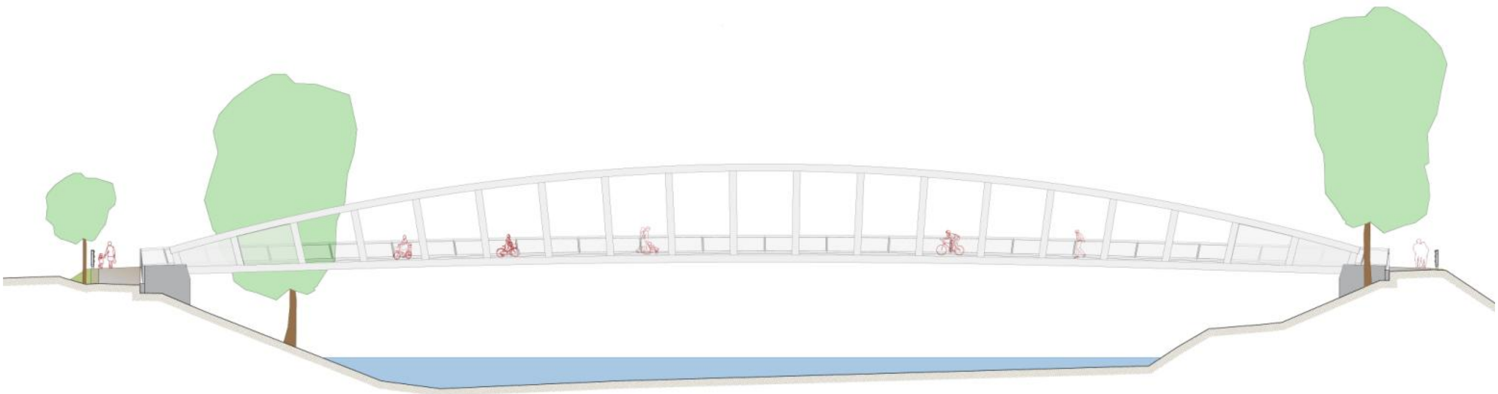


Figure 62: Visualization of the future Špica footbridge

Figure 63: Visualization of the Ceršak footbridge

FOOTBRIDGE CERŠAK IN CELJE, SLOVENIA

The Ceršak Bridge is intended to lead the international long-distance cycling connection Ceršak - Oberschwarza, between the municipalities of Šentilj (SLO) and Murfeld (AUT), over the Mura River, representing the border between Austria and Slovenia at the bridge location.

The bridge is designed as a suspended, single-span, wood-steel structure, without any supports in the river bed.

The span of the bridge amounts 86 m. The superstructure consists of two parallel glulam wooden beams B/H = 280/1,285 mm, set at 3.925 m apart and connected by steel frames (HEB 240) and stiffeners in the plane of the transverse beams.

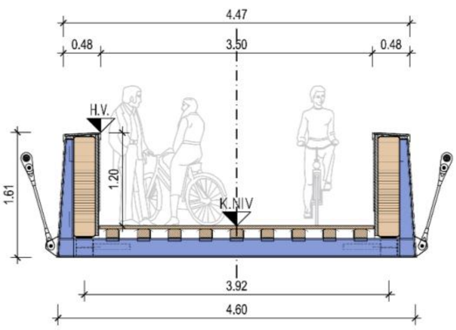
Longitudinally, the superstructure is supported by steel bearings at the abutments and, via steel hangers (spacers) placed at a distance of 8.60 m, suspended from high tensile steel ropes, which are anchored on top of the pylons on both end abutments.

The bearing cables are fully locked coil (sealed) ropes with filler and double anti-corrosion protection.

The diameter of the bearing cable is 63 mm, and the carrying capacity is min. 2,606 kN (260 t).

The hangers are classic steel tension rods (tension bars) with a diameter of 24 mm, lengths adapted to the geometry, and adjustable fork sockets at both ends.

The wooden bridge deck consists of 9 longitudinal beams B/H = 160/160 mm, 40 cm apart, and 40 mm thick transversely placed profiled planks.



Figures 64 and 65: Characteristic bridge cross section and raster bridge segment

Figure 66: Pedestrian view

Figure 67: Visualization of the Sava River footbridge

Figure 68: Pedestrian view

FOOTBRIDGE OVER THE SAVA RIVER IN KRŠKO, SLOVENIA

The footbridge over the Sava River in Krško is planned to connect the old town center of Krško on the right bank with the western part of Krško - Videm on the left bank of the Sava.

The footbridge is designed as an arch structure that crosses the Sava River in one span of 108 m.

Due to the asymmetry of the bridging conditions, the construction itself is also designed in this sense; on the right bank, the arch consists of two separate cross-sections, which merge at the top into a single cross-section that continues to the left bank.

The arch structure on the right bank of the Sava is represented by two box-shaped supports with external dimensions of 800/800 mm, which are joined at the top into a single cross-section of dimensions 800/1,600 mm, and continue to the left bank.

The height of the arch above the deck structure is 14.60 m.

The length of the arched structure is 101 m.

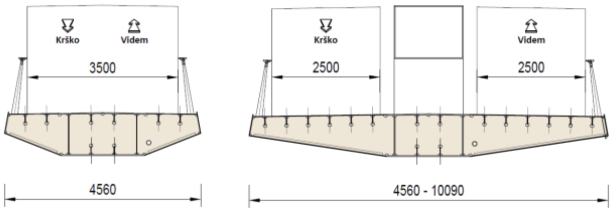


Figure 69: Cross section of the orthotropic deck

The geometry of the orthotropic deck is designed in such a way that on the right bank it passes between two split arches, while on the left bank the structure expands and recedes from the arch structure, at the same time indicating the direction of connection to the multi-purpose path that runs parallel to the Sava River.

Figure 70: Longitudinal view

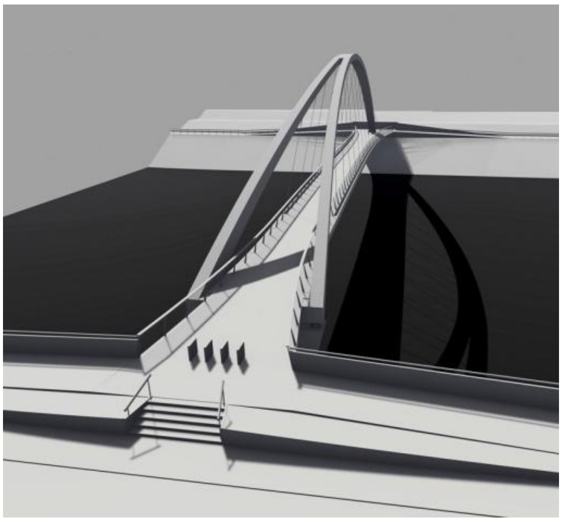


Figure 71: Rendering from the old town

SUSPENSION FOOTBRIDGE IN CELJE, SLOVENIA

The suspension footbridge is located on the footpath that connects the old town centre of Celje and the most important visual feature of Celje, the Old Castle.

The connection runs through the city park and climbs to a good half of the height of Miklavški Hrib and crosses over the suspension bridge to Grajski Hrib and ends at the old castle.

The rope structure between Miklavški and Grajski Hrib gives up to 500 people on the bridge the opportunity to cross the valley at a height of up to 100 m with an impressive perspective.

The total length of the bridge structure is 528 m while the footpath length is 505 m.

Four high-strength steel suspension cables with a diameter of 80 mm form the primary support of this suspended construction.

On each side of the structure, the bridge is anchored in massive abutments; the tensile force is anchored by 34 rock anchors in the compact rock to a depth of up to 35 m.

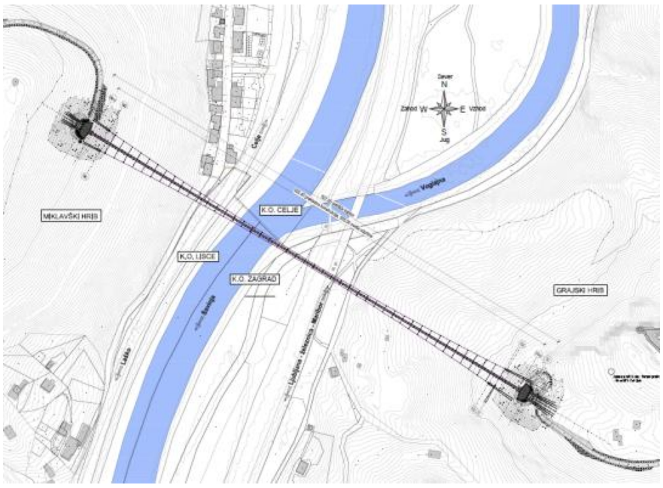


Figure 72: The location of the bridge

The arranged wind ropes run laterally like a harp and ensure the lateral stability of the bridge in wind.

The walking surface is a steel grid with a clear width of 1.20 m.

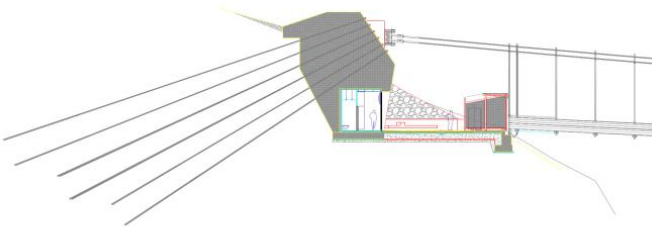


Figure 73: Massive abutment with rock anchors

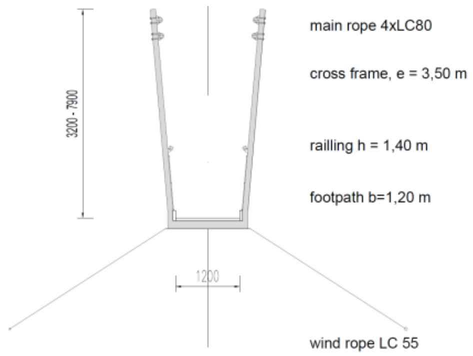


Figure 74: Cross section of the footbridge

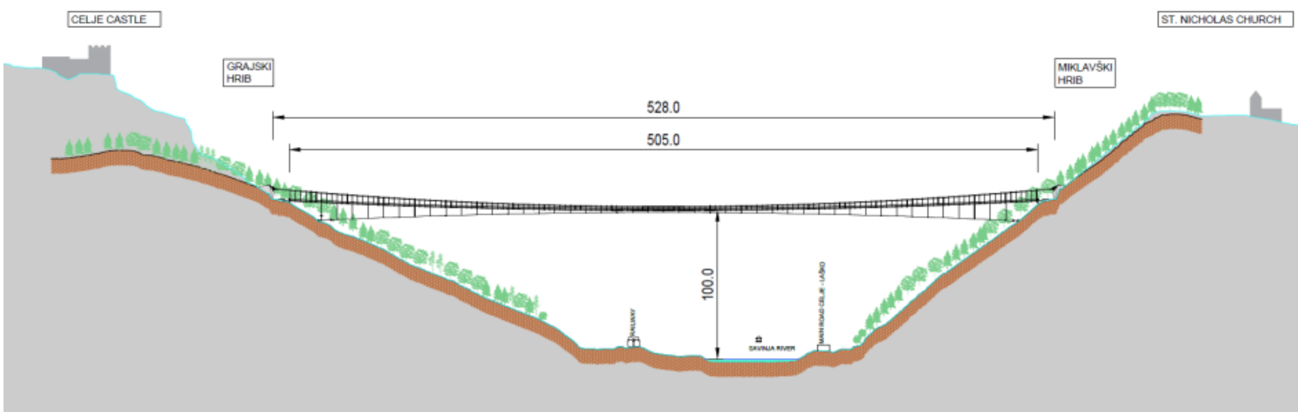


Figure 75: Longitudinal view

Figure 76: Rendering of the suspension footbridge in Celje

CONCLUSION

Pedestrian bridges do not have as many restrictions in terms of geometry and traffic requirements as road and railway bridges.

Mandatory details prescribed by the standards (safety fences and technical details necessary for traffic) are practically non-existent for footbridges or they are less restrictive.

Therefore, footbridges can, as is evident from the shown examples, vary widely in appearance and structural design.

As a result, footbridge prices can also vary considerably.

When compared per unit of surface, footbridges are often much more expensive than road bridges and even railway bridges.

The main reason for the higher cost per m^2 against the road and railway bridges lies not only in a smaller surface area but also in unique designs, special materials and equipment on pedestrian bridges.

Concrete, as the cheapest building material, is rarely used for pedestrian bridges.

Movable footbridges, with the additional sophisticated mechanic and electric gear and mechanisms, especially stand out as the most cost-consuming.

Due to the smaller weights and loads, footbridges are much more slender than other bridges.

As a result, in the analysis of the structure, the most important part is the service limit state, especially deformation and vibration.

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ST. ELMO BRIDGE, BREAKWATER AND LIGHTHOUSE, MALTA

Magdaléna Sobotková

Figure 1: View of St. Elmo Bridge, breakwater and lighthouse

GRAND HARBOUR (PORT OF VALLETTA)

The Grand Harbour has been used as a port for thousands of years thanks to its strategic position and its natural characteristics.

It is a natural deep-water harbour and it extends for about 3.6 kilometres inland.

Its two-arm breakwater renders it a safe, all-weather port throughout the year, open on a 24 hour basis, although entrance may be restricted during strong Easterly winds.

Megalithic remains which were found on its shores show that the area has been settled since prehistoric times.

Over the centuries various buildings have been built on its shores. Between 1530 and 1798 it served as a naval station for the Knights of Saint John who settled in Birgu (also called Vittoriosa).

They improved its fortifications which later proved very beneficial as they provided protection during various raids on Malta, mainly by Barbary corsairs and the Ottoman forces.

At these times, Fort Saint Elmo and Fort Saint Michael were built and Senglea was founded.

On the peninsula between Marsamxett and Grand Harbour the capital city of Valletta was built.

Over the years, more fortifications and settlement were founded around the inlets, including Fort Ricasoli and the city of Floriana which is bordering Valletta.

Figures 2 and 3:

Location of St. Elmo Bridge on the map, and its position in the Grand Harbour

Source: maps google

Cospicua was also founded which is the third of the "Three Cities" together with Senglea and Birgu which lie in the southern-east part of Grand Harbour.

During the 19th century Grand Harbour served as a British strategic naval base in the Mediterranean. Between 1903 and 1909 a breakwater consisting of two arms was constructed.

The aim was to improve the already excellent natural conditions and to protect the port from strong northern and north-eastern winds in winter.

Thanks to the construction of the St. Elmo breakwater the port and its facilities can be fully utilised in all weather conditions.

Today the Port of Valletta is a multi-purpose port equipped to offer a large spectrum of maritime services including:

- Various cruise/ferry and cargo berths
- Specialised grain and cement silos
- Petroleum installations, bunkering facilities
- Ship repair and building yards
- Ship chandelling
- Reception facilities
- Other ship related services

Warehousing and open storage facilities are available throughout the port area.

Figure 4: General View of St. Elmo Bridge, Breakwater and the Lighthouse

Click on the image to open it a higher resolution

Figure 5: Construction of the breakwater and original bridge

Figure 6: The original St. Elmo Bridge (1909)

CONSTRUCTION OF THE BREAKWATER, LIGHTHOUSE AND THE FIRST ST. ELMO BRIDGE

The first studies of the strength of the winds and their impact on the port and possible location and size of a breakwater were started in 19th century.

Between 1900 and 1903 all necessary studies required to enable commencement of the design and construction of the breakwater were undertaken.

On 20th April 1903, during King Edward VII´s visit to the Maltese islands, a foundation stone laying ceremony took place.

Underneath the first stone, a copper casket with copies of contemporary papers was embedded.

The breakwater has two arms constructed of limestone and concrete bricks.

The shorter arm, from the Fort Ricasoli side, is 122m in length and has a width of between 11.5 and 12.1m. It faces northwest.

The longer arm northeast from the Fort St. Elmo is 378m long and has width of between 12.8 and 15.2m.

It was constructed with a 70m gap from the coast of Valletta in order to avoid water stagnation and to allow passage of small vessels especially from the neighbouring Marsamxett Harbour.

The foundations of the breakwater are formed by concrete blocks, each weighing more than 40 tons.

They lie on solid rock on the seabed.

The construction of the breakwater took over six years to complete and gave work to about 500 workers.

All underwater works were done by divers in standard suits.

The divers were working in large precast concrete caissons, which were filled with smaller blocks which were then concreted together as necessary.

The divers were supplied by air fed from the surface by a manually operated air pump. Concrete works rose from the seabed to about 60cm above mean sea level.

The St. Elmo arm of the breakwater was accessed by a steel footbridge consisting of two isostatic arched-truss beams each of 34.4m.

The trusses were constructed using rolled steel joist.

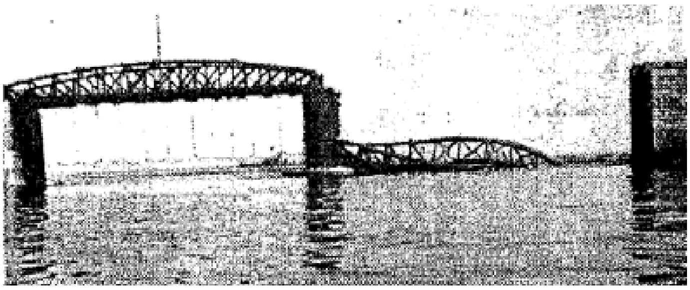


Figure 7: St. Elmo Bridge was partly destroyed during WWII (1941)

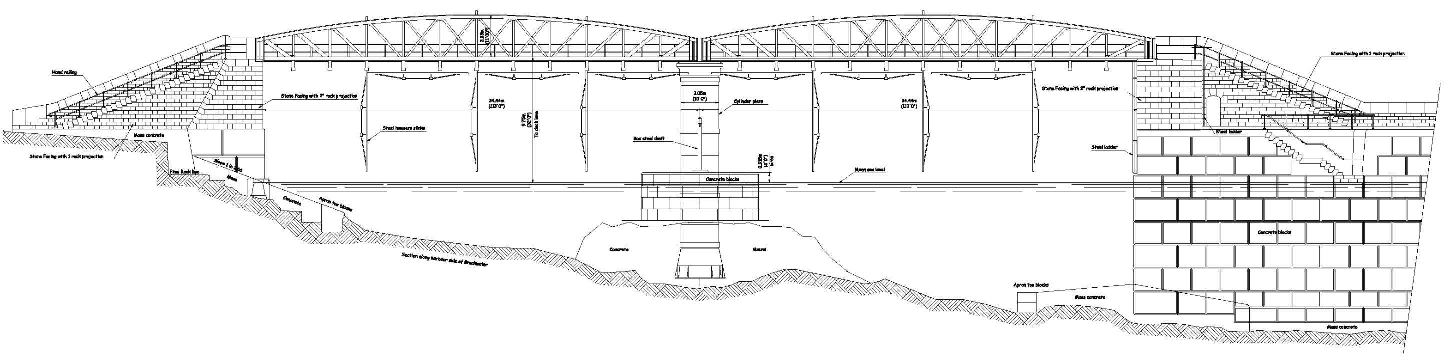


Figure 8: Elevation View of the original bridge

Click on the image to open it a higher resolution

Two steel cylindrical columns filled with concrete provided a central support to the footbridge.

The bridge was about 4.8m high and around 6.4m wide and the overall bridge length was 68.27m. The decking was constructed of timber, with steel grating at each support.

The construction was affected by inclement weather in 1904 which caused damage to the breakwater and also damaged the bridge.

However, the bridge was finished in 1906 and the whole project was declared as successfully completed in 1910.

The bridge was partly destroyed following an attack by an E-boat in 1941 and it was subsequently removed.

For more than 70 years the breakwater and its lighthouse were isolated, see Figure 9. They were only accessible by boat, until the opening of the new footbridge in 2012.

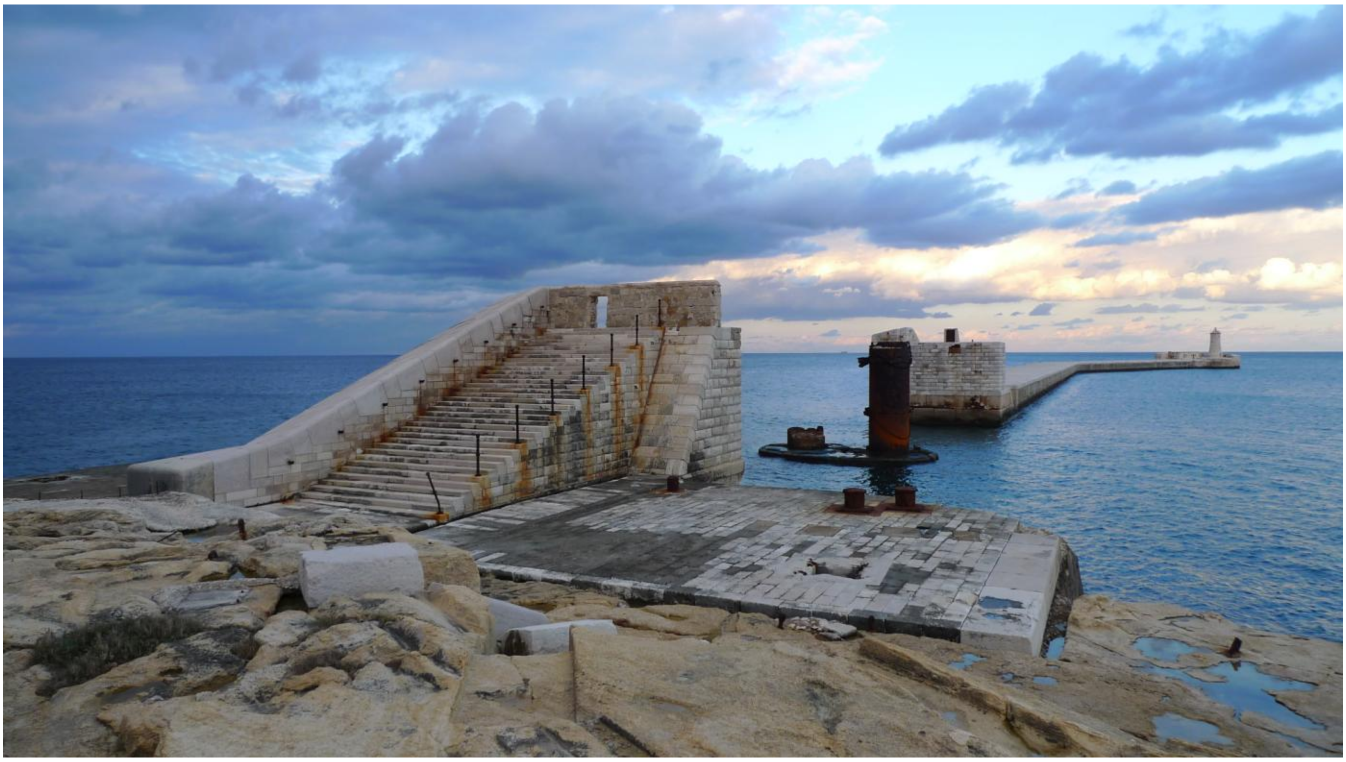


Figure 9: Breakwater and gap after the collapsed bridge was removed with the original central pier

THE LIGHTHOUSES

At the entry to Grand Harbour, there are two breakwaters, each with a lighthouse at its end: Ricasoli Lighthouse was built on the East breakwater and is characterised by a red lantern; St. Elmo Lighthouse is located on the West breakwater and has a green lantern.

In 2012 replica of the original lantern was installed. It has quick flashing green light with a range of seven nautical miles.

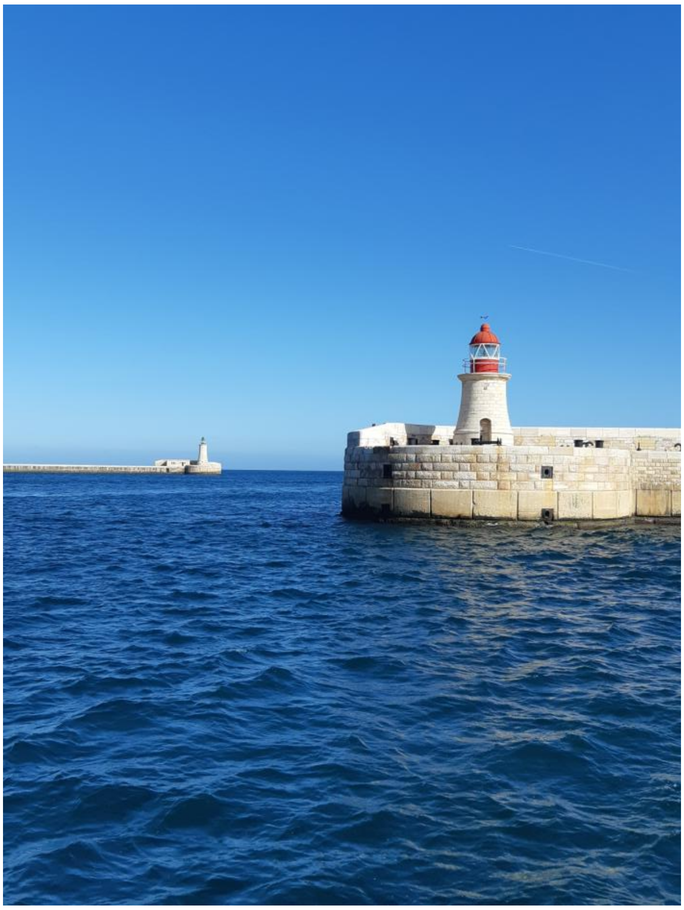
Ricasoli has 9m high tower, St Elmo has 14m high tapered tower with a lantern and a gallery. The towers are stone and unpainted.

Both lighthouses were completed in 1908.

→ Figure 10: Ricasoli Breakwater Lighthouse in the front with St. Elmo Lighthouse in the back

↓ Figure 11: St. Elmo Lighthouse

Both Images credit: e-mosty/e-maritime



CURRENT ST. ELMO BRIDGE

In 2009 an international design competition for the design, fabrication, transportation and erection of a new footbridge was organised by Transport Malta.

Several design constraints were included in the tender documentation relating to appearance, geometry, materials, durability and operation of the bridge.

It was a requirement that the winning design should be suitable for the location with respect to the historical, social and cultural context and it was to be located in the same position as the original one.

From more than twenty tender submissions, the design of Arenas & Asociados in a Joint Venture with Maltese companies Vassallo Builders (contractor) and Bezzina & Cole (local engineering assistance) was selected.

Design

The footbridge is placed at the same location as the original one and has similar proportions. The main structural element is a single 70m span classic Pratt arched truss, placed on the open-sea side with a constant-width deck of 5.40m internal and 6.45m external width.

The main truss is aligned with the protection walls which were also the abutments and staircases. The depth of its bottom chord - which is an L-shaped box girder of high-stiffness - is set by the height of these walls.

The top chord with triangular cross-section coincides with the top face of the abutments wall at the bridge ends. The height of the truss varies from 1.83m to 7.20m.

Diagonal and vertical members have symmetrical triangular sections with bases located on the external plane of the truss.

Such triangular sections were designed because of their structural efficiency and to prevent rust effects, avoiding water to cumulate in the transition between diagonal and vertical members with the inferior chord.

The 0.95m deep secondary box-girder has a trapezoidal cross-section and it is filled with non-structural concrete to increase the weight of the structure.

It helps reduce accelerations induced by vertical vibrations without using dampers. The whole structure rests on elastomeric bearings.

One of the tender conditions was that the original bridge abutments should not be altered in fashion and should form part of the final design concept.

The central piers of the original bridge were not to be used in the design, however, they remain preserved.

The footbridge was designed as asymmetrical in section. The bridge asymmetry reflects many other asymmetries of the location:

- Separation of the breakwater from the shore;
- The existing abutments and staircases with thick wave-protection walls on their open-sea side only;
- The central pier of the original bridge that almost completely lost its sea-side column.

The bridge is vertically anchored to the abutments with four 25mm diameter stainless-steel prestressing bars at each end.

They are 4.25m long of which 1.25m is anchored and remaining 3.0m are free length to allow structure movements.

PROJECT OVERVIEW

Owner: Transport Malta

Architectural and Structural Design: Arenas & Asociados

Local engineering: Bezzina & Cole

Contractor: Vassallo Builders Limited

Steel:	185t
Timber:	10m^3
Concrete:	19.4m^3

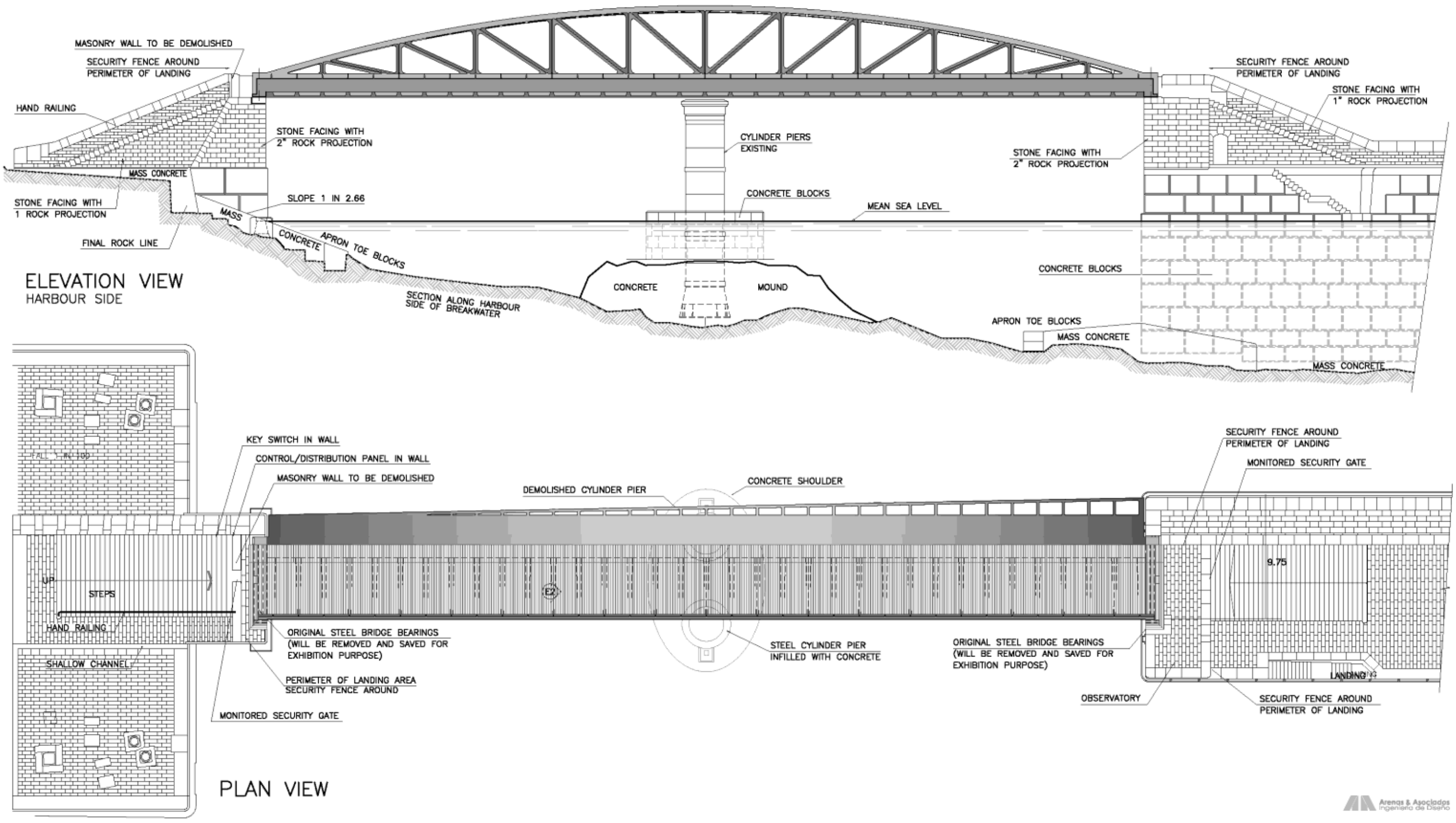


Figure 12: Elevation and Plan View

Click on the image to open it in a higher resolution

Longitudinal displacements are allowed by the free length of the anchoring bars.

For aesthetical reasons, the structure has a ladder- like structure on the outside.

Thanks to this, the top chord reaches the wider breakwater-side abutment with its same width, but not adding an additional weight to the structure.

The footbridge deck consists of timber boards, a lighting scheme and navigation lights.

Structural Behaviour

The structural behaviour of the footbridge is affected by its transverse asymmetry and the design of its cross-section which results in possible deformational loads of the two longitudinal structural elements of the bridge (truss and the secondary girder).

This is different in many aspects from other truss bridges. Also the use of a single truss, without its top chord transversally braced, makes it susceptible to second-order effects.

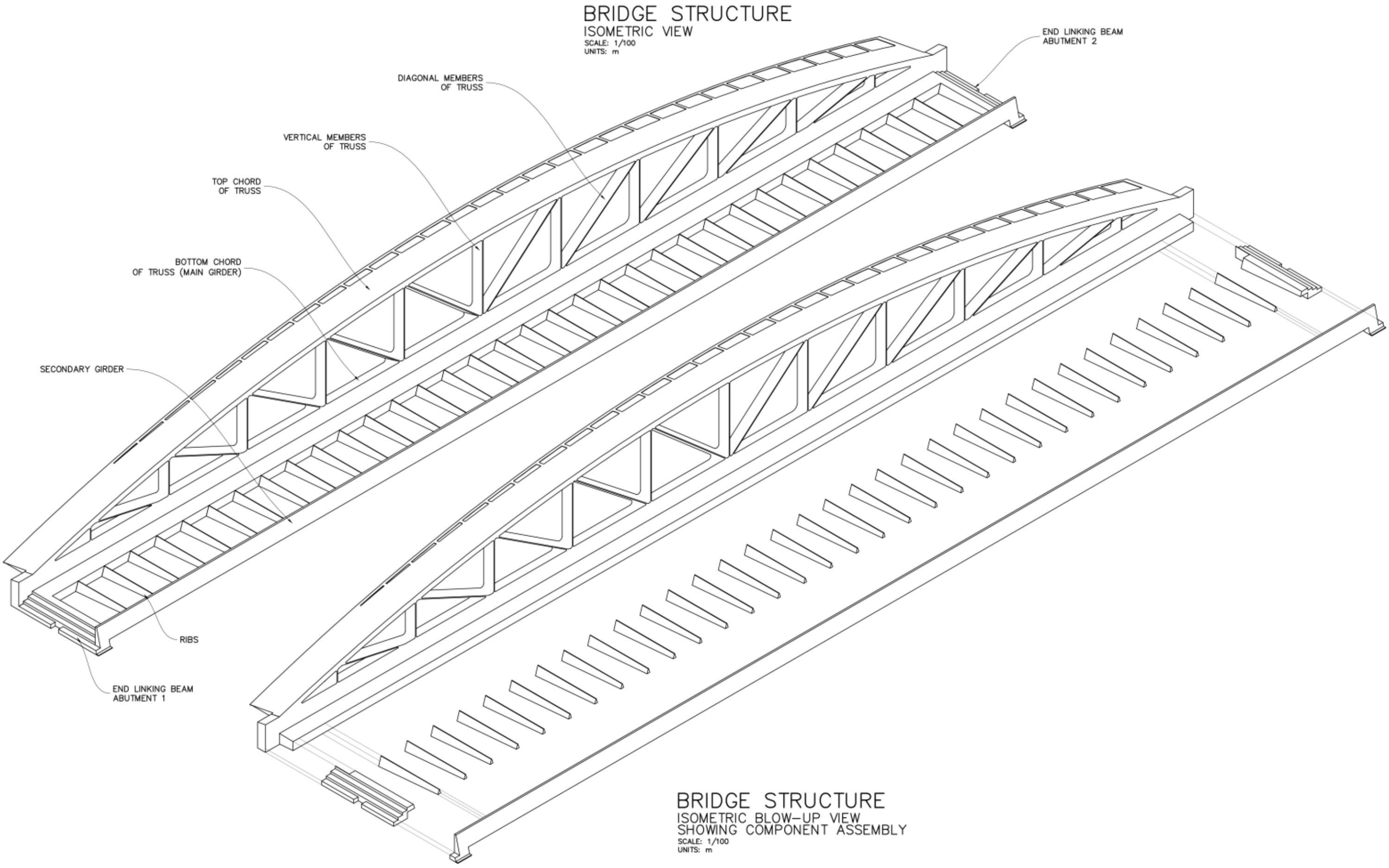
As a result, the out-of-plane buckling load of this to chord had to be allowed for in the design.

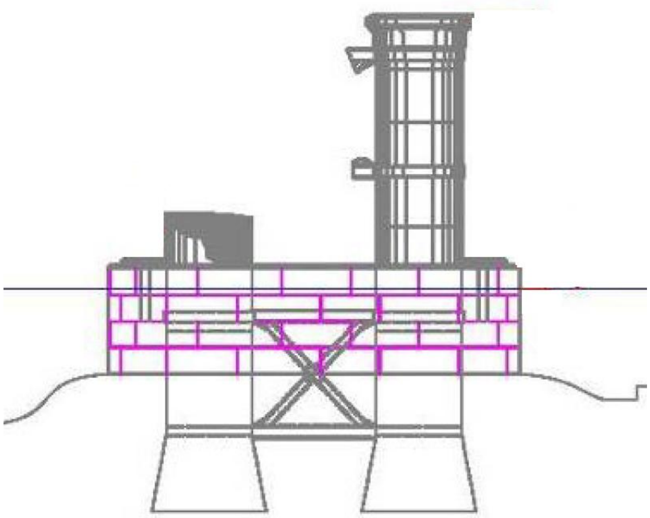
The footbridge was designed in accordance with Eurocodes 3 and 5. Comprehensive calculations were made including plate-thickness optimisation.

The design also had to allow for the steelwork being manufactured outside the country, transported and lifted at sea with the associated global weight limitations.

Several three-dimensional FEM models were run for checking the structures design details, and a second-order analysis was also carried out.

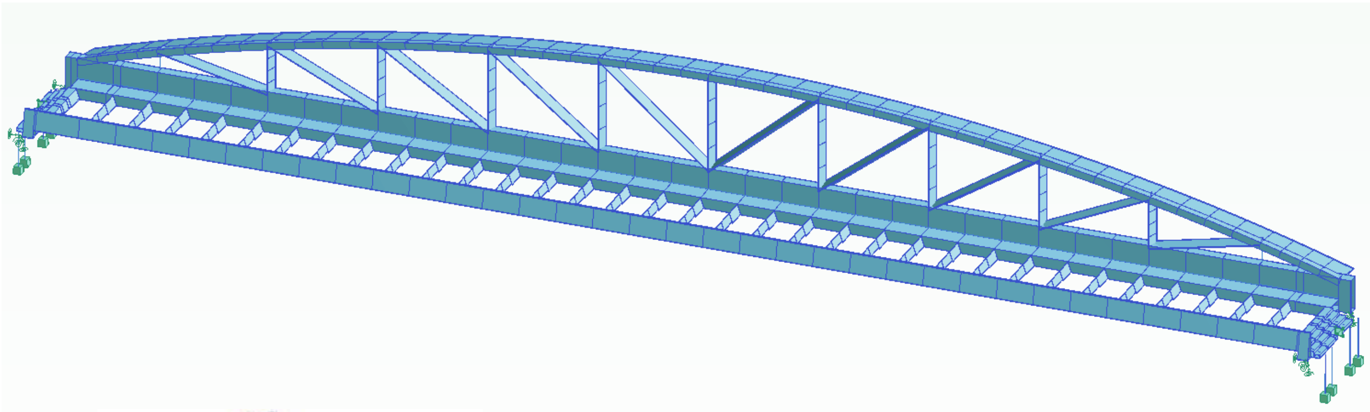
The induced vibrations from pedestrians walking across the bridge were studied with special care required due to the span, slenderness and asymmetry of the bridge.

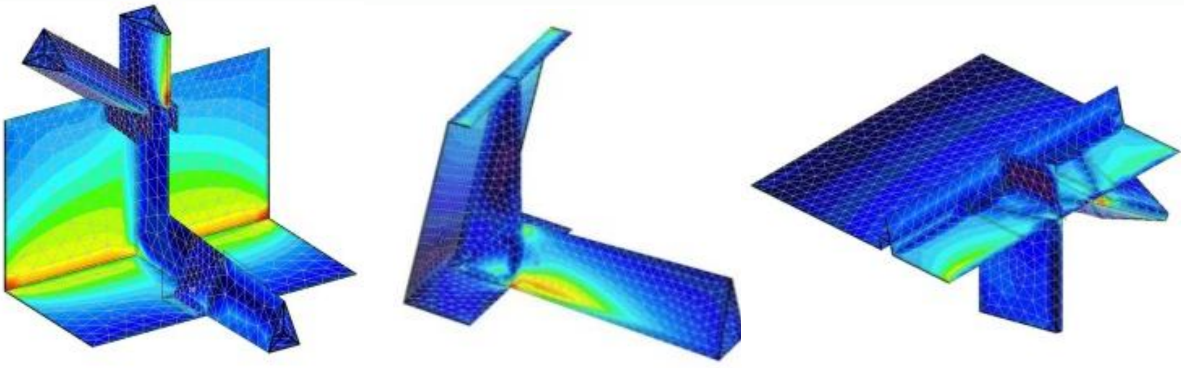


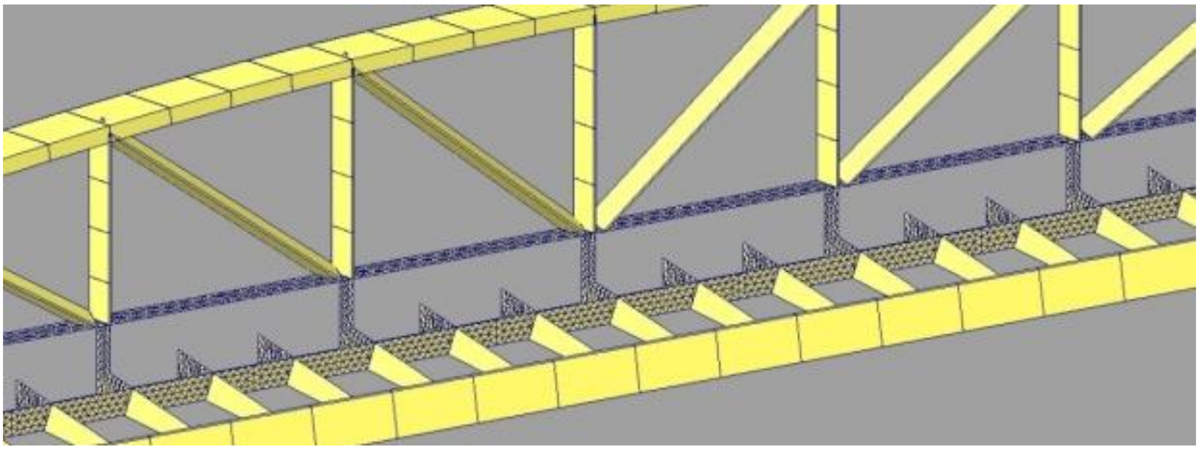


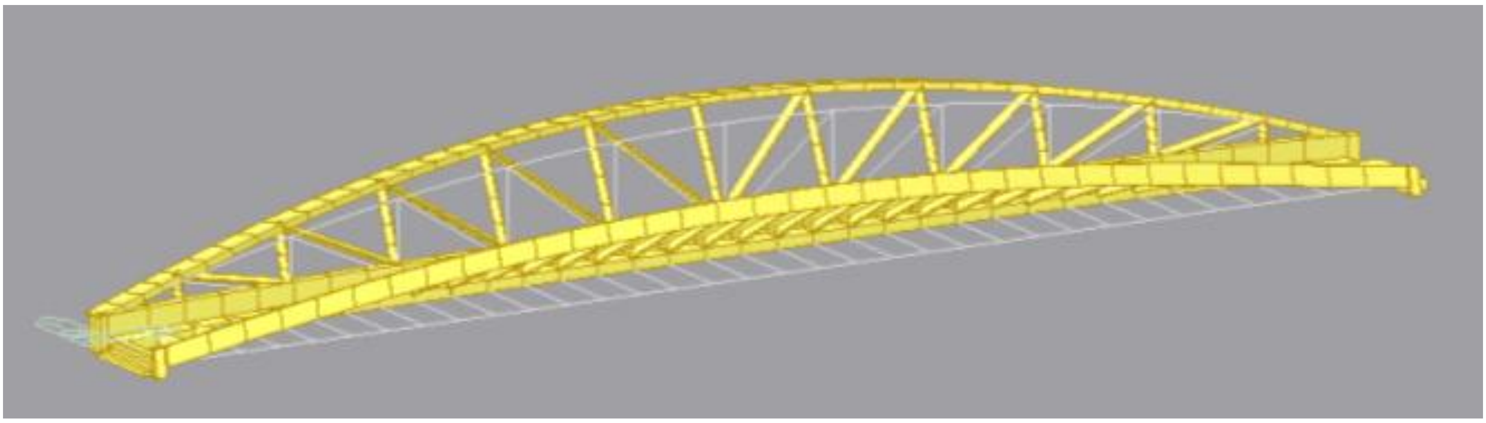
↑ *Figure 13: Isometric View*

← *Figure 14: The original bridge piers which remained preserved*









Figures 15 - 18: Structural analysis models. From top to bottom:

Main FEM model, specific FEM models of some of the joints (every joint has its own), specific FEM model for the analysis of the bottom girder of the truss and third vibration-mode shape

Fabrication, transport and erection

The steelwork was manufactured by Emesa in A Coruña in Spain. For economic reasons, it was transported nearly 1,000km overland to the port of Cartagena, also in Spain, in eight pieces using 35m long trailers.

The bridge was assembled in the port, loaded on board the heavy-lift vessel ´Storman Asia´ using the ship´s own 4,000kN derricks.

Specific trestle-type supports and a sling-system were designed and used for the transport. This was because the dimensions and asymmetry of the bridge almost reached the maximum capacity of the vessel. The lashing system was designed to resist the vertical and horizontal forces during transportation.

After reaching Valletta, a wait of two weeks for appropriate weather conditions was required. Weather forecast was carefully studied to do the placement in very good weather and calm sea conditions.

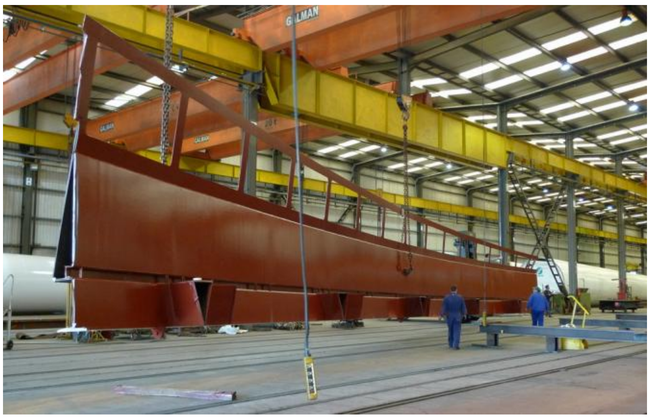
At site, the ship was moored in four different positions and the former pier foundation protected so the vessel could not damage it.

Quality controls were in place especially for the site work at the port; swell was established to be less than 20cm to undertake the final operation.

The bridge was lifted off the vessel and placed on the existing abutments and the new central steel pillar.

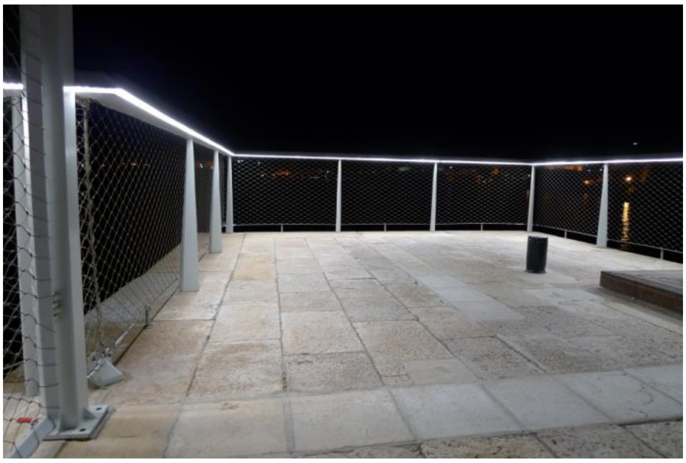
The abutments had a specifically designed RC slab on which the bridge sat which is not visible in the final arrangement. After that, timber decking, handrails and lighting were installed.

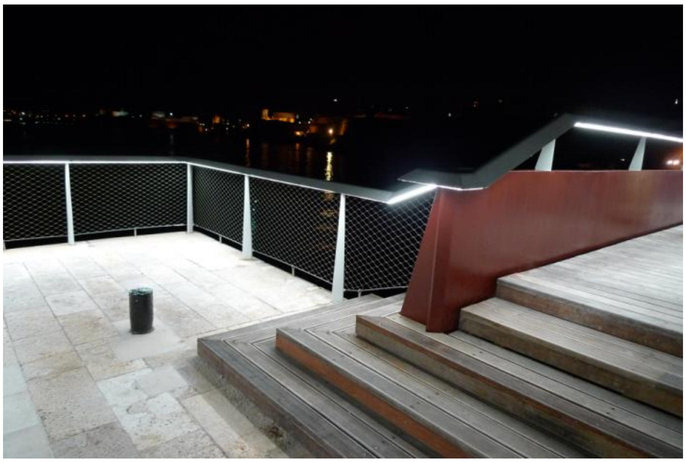
Video: Lifting and placement of the bridge.
Credit: Vassallo Builders.
(We apologize for the lower quality of the video)

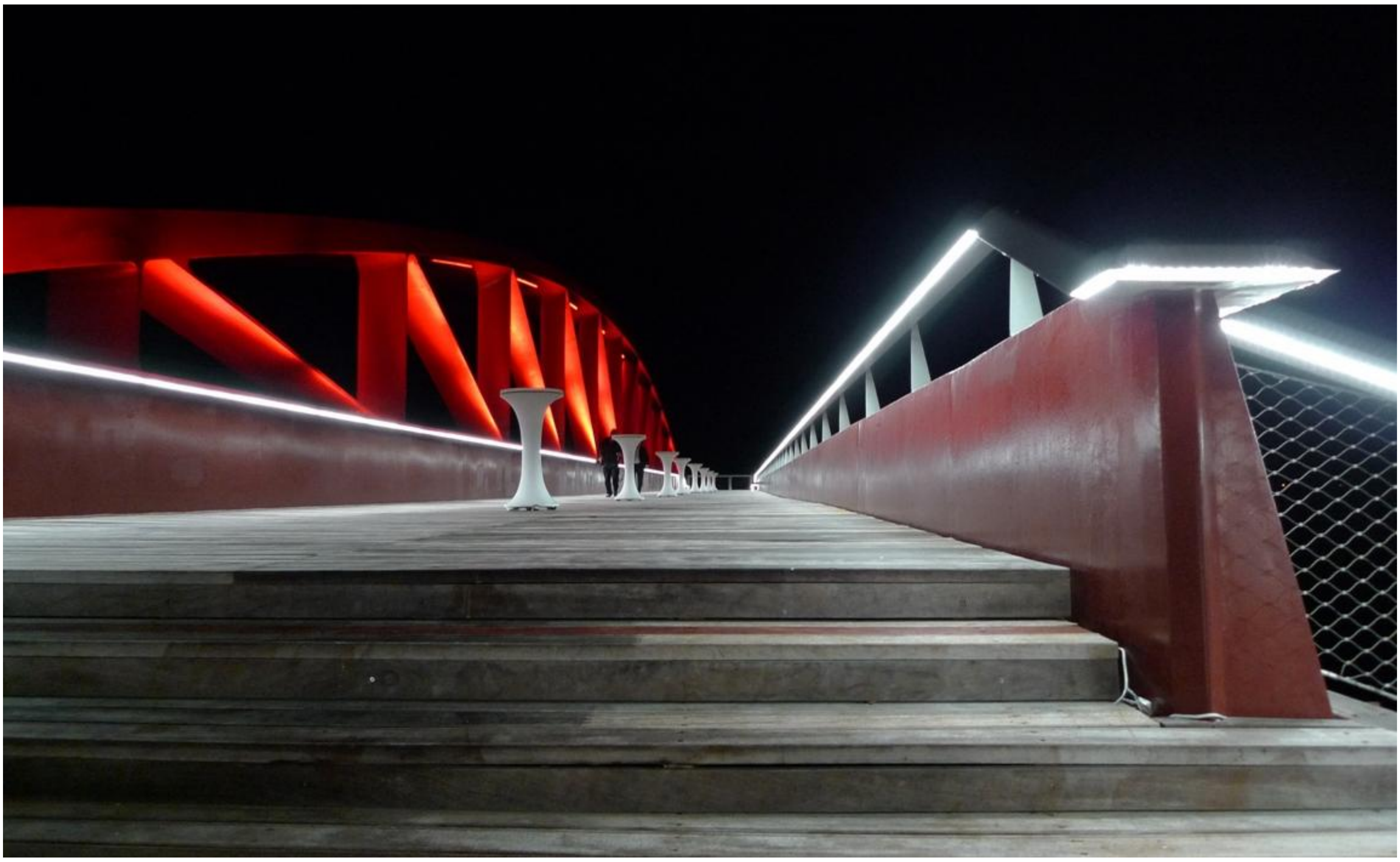


Figures 19 - 22: Bridge Fabrication
Photo Credit: Miguel Ángel González

Figures 23 – 28: Fabrication, loading, transport and lifting of the bridge







Figures 29 - 32: Completed Bridge

Maintenance of the bridge and the breakwater

The bridge was designed to withstand the harsh environmental conditions, especially direct wave impact together with strong winds.

As part of this design philosophy all elements and surfaces are accessible for maintenance.

Closed sections were used and their atypical (triangular) geometries enable water shedding so that it does not accumulate in the structure.

In the contact between webs and bottom flanges of the different structural members webs slightly exceed the edge to avoid water spills and salt accumulations, see Figure 33.

Thanks to the triangular cross-section of both diagonal and vertical members, the steep transversal slope directs water away from the joint.

With the same aim, the joints of the truss were smoothed with truncated cone transitions, see Figure 34.

Figure 33: Bottom and inferior view

Timber decking is divided in elements with reduced dimensions, movable by a couple of maintenance staff, to easily maintain the decking itself but also to guarantee easy accessibility to the steelwork under it.

Footbridge's timber decking is assigned to service Class 3 according to Eurocode 5; Tali Wood does not require any preservative treatment.

Since 2020 Infrastructure Malta, the owner of the asset, has commissioned some repair work on the breakwater and the bridge.

The bridge repeatedly suffered damage in heavy storms due to rough seas, which particularly impacted its wooden decking.

At one point, an exceptional storm left a gaping hole in the structure and the bridge had to be repeatedly closed.

As a result, Infrastructure Malta is now working to replace some parts of the bridge.

Current works also include the replacement of a large block of the breakwater´s deck (seaside overtopping protection wall) which has been dislodged by the impact of large waves over the years.

Figure 34: Detail of the truss joints

Figure 35: Repairs on the breakwater
Credit: Infrastructure Malta

Figure 36: Repair works on the bridge
Credit: e-mosty/e-maritime

Before the works started, some of the coping stones which had been dislodged into the sea by the severe storms and which were still in good condition were retrieved by divers.

These parts are reused and the missing parts replaced by limestone blocks from an Italian quarry at Trani.

The project also includes cleaning of the masonry of tar stains and other deposit which have accumulated over the years.

Maintenance works on the bridge also involve repairing and repainting the steel structure.

New handrails and electrical circuits with an improved lighting system are eventually installed. The central pier remains as it was originally.

The agency is also conducting studies to identify longer-lasting solutions to the wooden deck beams, the lighting system, handrails and other components.

Acknowledgement

I would like to thank especially

Arenas y Asociados,
Héctor Beade Pereda
and Bezzina & Cole

for their cooperation.

References:

Héctor Beade Pereda (Bridge Designer and Project Leader), Guillermo Capellán Miguel (Technical Director), Alex Bezzina (Partner), Jonathan Buttigieg (Commercial Director), Pablo Alfonso Dominguez (Civil Eng.) & Marianela García Pérez (Civil Eng.) (2015): **A New Footbridge in Valletta Grand Harbour to Fill a Geometric and Historic Gap, Malta**, Structural Engineering International, 25:2, 213-217, DOI: 10.2749/101686615X14210663188493

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https://www.arenasing.com/projects/urban-bridges/st-elmo-breakwater-footbridge-malta

All photos and drawings

Credit Arenas y Asociados
and Héctor Beade Pereda
unless indicated otherwise

HOW BIM HELPED BUILD THE RIZE - ARTVIN AIRPORT BRIDGE IN TÜRKIYE

Zeljka Devedzic

Teamlead Sales Enablement & Consulting Infrastructure, ALLPLAN

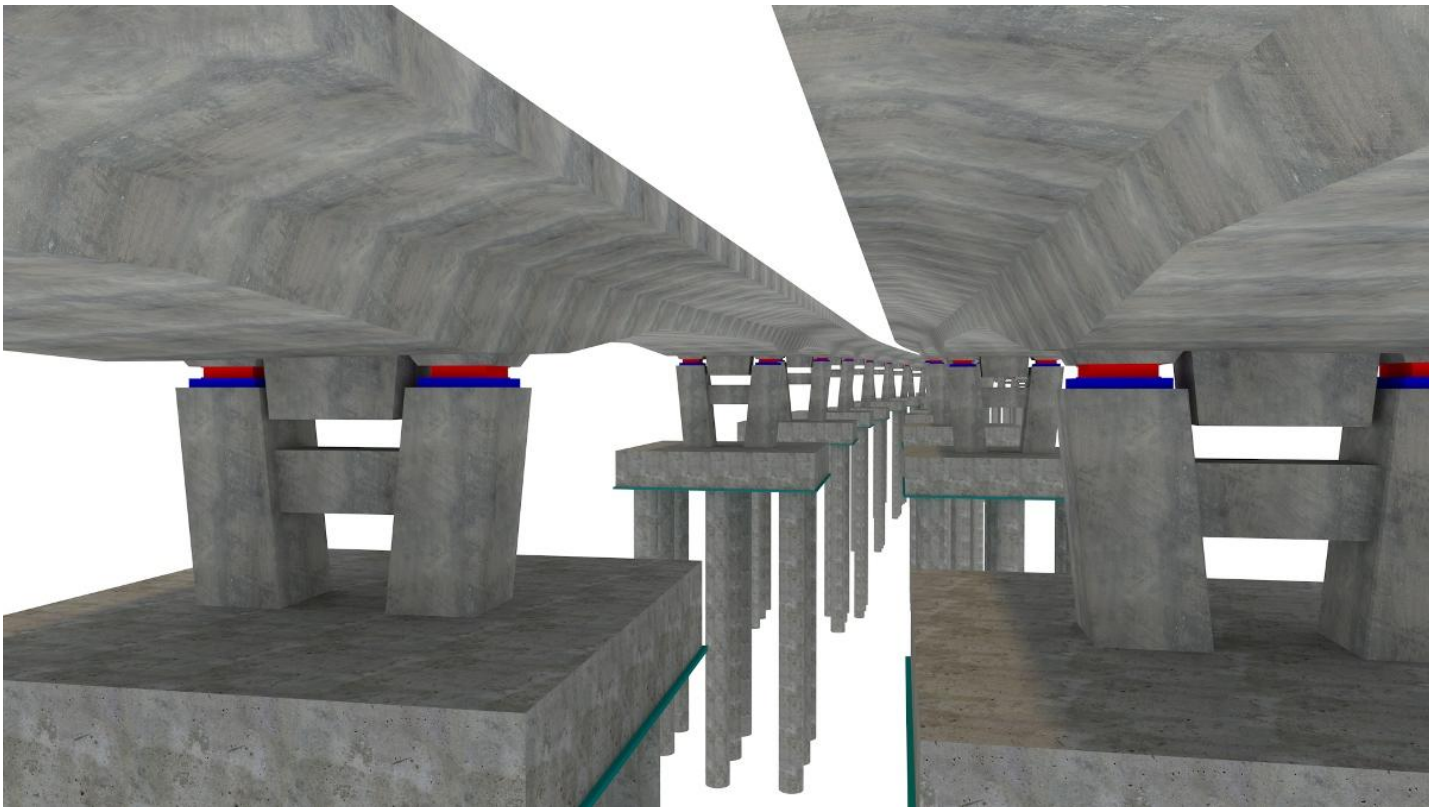

Figure 1: Allplan Bridge model

INTRODUCTION

The new Rize - Artvin Airport Located is located on reclaimed land off the northeastern coast of Türkiye.

The airport is a top priority for the Turkish government, with construction starting in spring 2020 and completed at the end of 2021.

As part of the works, the airport required a new cast in-situ, post-tensioned bridge to connect to the existing roads between the towns of Rize and Artvin.

Spanning 444 meters, the bridge deck reaches a variable thickness of 120 to 180 cm and has 13 spans along the length when construction is finished.

However, the bridge needed to be completed prior to the opening of the airport, leaving just a two-month design period for the engineering consultants, Yüksel Proje.

CHALLENGING SCHEDULE

The biggest challenge of this project was the design and construction schedule. While designing a bridge in just two months would be a tall order for any consultant, this was further complicated by the fact that the bridge was being built on reclaimed land.

As a result, there were additional geological surveys that needed to be carried out for the design and structural analysis.

Although the poor soil conditions and potential for earthquakes are common issues for bridge foundation designs in Türkiye, they nonetheless had to also be taken into account.

A further complication was the variable parameters of the bridge's geometry. For example, the deck depth varied across the bridge's cross-section; as the result, the tendon design was quite complex.

Another challenge was the eccentricity of the bridge piers, which used V-shaped beams to support the bridge deck.

As the deck rose, the distance between the piers increased, meaning that each pier was a unique shape and would have to be designed individually.

The number of piles and their spacing – as well as the axis of the post-tensioning tendons – also had varying geometry.

This made the design more complicated than a more straightforward bridge layout.

PARAMETRIC DESIGN AS KEY DRIVER

As one of the largest engineering consultants in Türkiye, Yüksel Proje is leading the way with regard to the use of Building Information Modelling (BIM) on their bridge design projects.

While the client had not specified the use of BIM on this project, Yüksel Proje realized that the only way to efficiently design the bridge in the time allotted was to use advanced BIM-enabled 3D Modelling software that would help remove or accelerate some of the manual design activities.

To achieve this, Yüksel Proje used Allplan and Allplan Bridge for a large proportion of their design work.

"*The main reason that we chose Allplan Bridge for this project was that the tendons and other geometry on this project were really complicated – so we needed a parametric bridge design program.*

Also, we had to make revisions in a very short time due to fast construction," explains Zeki Harputoglu, Design Coordinator and Civil Engineer at Yüksel Proje.

Allplan Bridge was used to prepare the BIM model of the bridge. It enabled teamwork with other disciplines and greatly assisted the design stage.

For example, the 3D terrain and road models could be imported into Allplan Bridge and then used as the basis for the bridge design, providing an accurate and coordinated base to work from.

Figures 2 and 3: Construction of the bridge

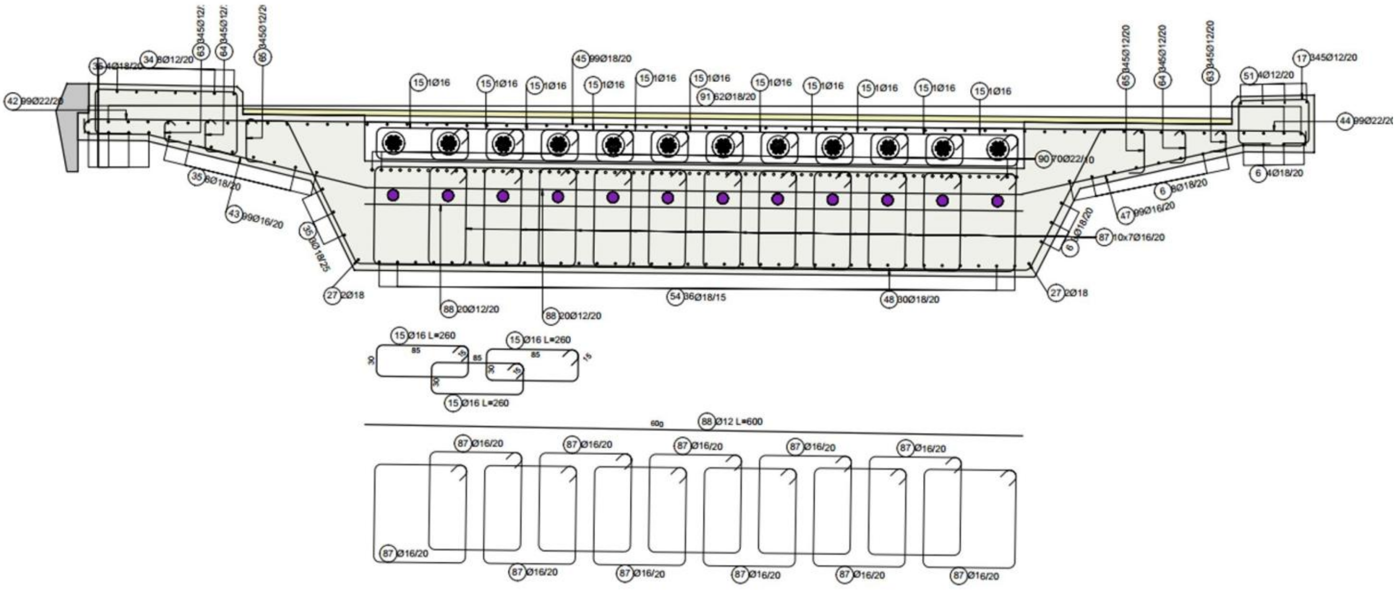

Figure 4: Cross-section of the deck

It allowed the bridge engineers to model different bridge alternatives and see the interaction between the geometry of the bridge with the existing site terrain, as well as any excavations and other site features quickly and easily.

The ability to import and export to other software programs without losing data through the IFC data exchange formats saved valuable time, made the design options easier to create and evaluate, and increased the quality of the design output.

The plan and profile coordinates of the start and end of the bridge (where it would join the existing roads) were provided by the Transportation department of Yüksel, which the Bridge department imported into Allplan Bridge.

From here, the bridge engineers used this information for the alignment of the bridge and designed the bridge to tie into these points.

Where needed, they were also able to manually input and adjust the coordinates.

Parametric Modelling helped when designing the bridge deck, as the geometry of the bridge deck varied along the length.

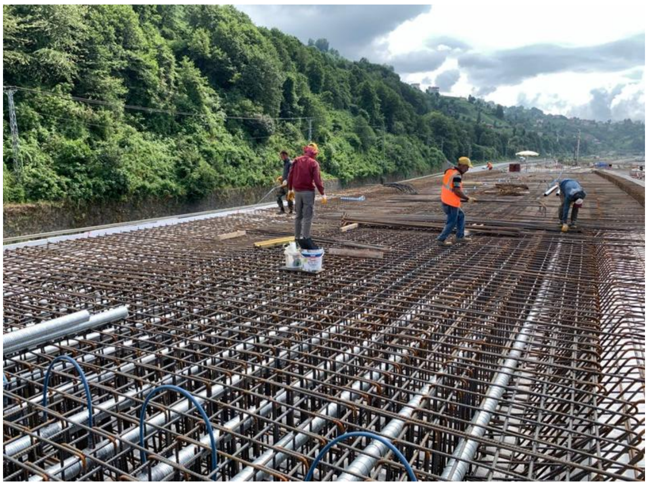

Figure 5: Deck Reinforcement

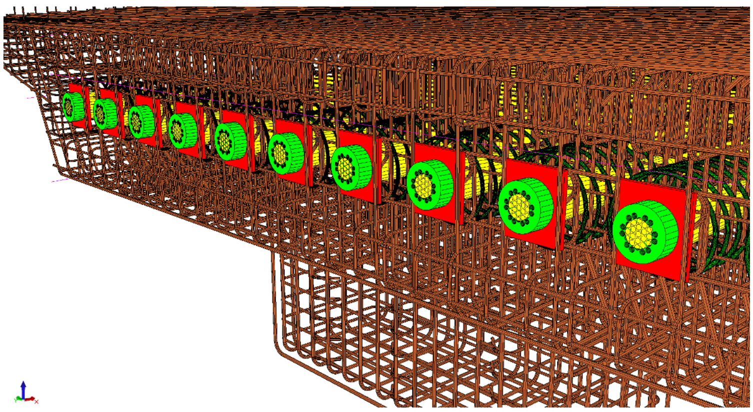

Figure 6: Deck reinforcement model in Allplan Bridge

The bridge cross-section could be created parametrically and then extruded along the bridge alignment to quickly create the 3D bridge model.

Allplan Bridge was also particularly helpful for modelling the complicated tendon geometry in the bridge.

Where the tendons crossed, it was particularly difficult to model accurately.

Here, parametric modelling was required to ensure the tendon design was done precisely and efficiently.

The ability to input the variations of the tendon profile and adjust the model easily by modifying these parameters made the design much easier than continually re-modelling the tendons with every design iteration.

Similarly, parametric 3D Modelling proved especially helpful for modelling the unique bridge piers.

Without parametric input, each pier would have had to be modelled individually, and manually adjusted the bridge geometry changes.

It could be avoided, and the piers were designed much more quickly by using parametric modelling to specify how the piers should react to the elements around them.

For example, if the bridge's vertical alignment is raised or lowered, the piers could adjust automatically to the right height.

"*If we did not have Allplan Bridge, we would have had to draw each pier manually in the software.*

But with this, we generate all the piers with one click – it is very helpful and saves us time," explains Murat Erdogdu, Bridge Engineer at Yüksel Proje.

With the 3D model, it was also much easier to visualize and check the seismic stoppers – which restrained the lateral movement of the bridge – and how they interacted with the piers to ensure the correct placement.

Once the bridge was modelled, it was imported into Allplan where the section details and reinforcement design and detailing were carried out.

The ability to take a section from the 3D bridge model and use it to create the reinforcement details and formwork plans also saved time while increasing the quality.

"*As the sections have originated from one 3D model, there is consistency between all these sections.*

As long as the bridge model is correct, the sections will also be correct," noted Burak Kurtman, Bridge Department Manager.

This saves additional drawing time and also makes the checking process much faster.

Other benefits of having a 3D bridge model included automatic clash detection tools and accurate quantity calculations.

Any collisions between different bridge elements were easier to identify with the automated clash detection feature, rather than relying solely on a visual check.

Similarly, the quantities could be quickly generated from the model with the in-built reports.

This improved the design quality and ensured that the design phase was as efficient as possible. With such a short design window, accelerating design activities was essential in order to deliver on time.

The bridge team is also supporting the contractor with the bridge construction process using BIM as needed.

Occasionally, during construction, the contractor has required different sections or data that were not submitted to the client with the final construction drawings.

However, with Allplan, creating this extra information has not been an issue.

"*With Allplan, we can very simply and easily generate these cross-sections or information and deliver these to the construction site quickly.*

So, the program is very beneficial for us and also for the contractors," says Burak.

BENEFITS OF BIM-ENABLED 3D SOFTWARE

While Yüksel Proje have been using Allplan since 2017, the Rize - Artvin Airport bridge was their first project using Allplan Bridge.

The benefits of using a specialist, parametric 3D bridge solution were clear for Yüksel Proje – without it, they would not have been able to complete the bridge design in the allocated timeframe.

The engineers estimated that without Allplan Bridge, they would have required at least four months to complete the design instead of just two – a significant increase.

This leap in productivity is why Yüksel Proje are now using Allplan Bridge to model nearly all their new bridge projects.

The project team have also begun to lead the way in terms of BIM and 3D Modelling, now using BIM on all their projects irrespective of whether it is a client requirement or not.

They are also requiring other disciplines to supply 3D models of their sections, to help ensure a coordinated approach between disciplines.

"*It is very helpful to use the 3D model for alternatives during the conceptual phase to see the interaction with the geometry, the terrain, excavations, and so on*," explains Burak.

For Yüksel Proje, 3D bridge design using BIM is no longer an optional extra, it is an essential part of delivering a quality project on time and to budget.

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Helgeland Bridge, Norway

Photo : Jules van den Doel

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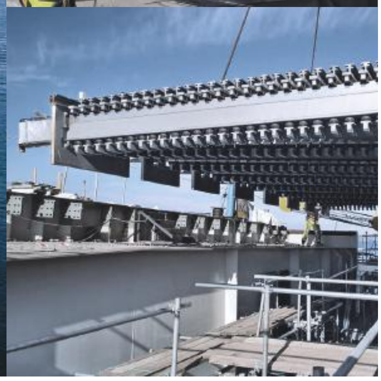

Scope of application:
The installation of the MAURER Swivel Joist Expansion Joint shall allow access to and protect the bridge deck from horizontal over load during a seismic event.

Features:

- Unrestrained absorption of specified movements and simultaneous transmission of traffic loads
- Serviceability of the structure after the earthquake
- Protection of the bridge deck from horizontal overload caused by extreme closing movements during the earthquake
- High life time expectation through use of high performance components
- Longitudinal seismic displacement of ca. 4 m
- Service velocity up to 20 mm/sec (10 times higher than for a regular bridge)
- Watertight across the bridge width
- Maintenance free

References:

- Bahia de Cadiz, Spain
- Hochmoselübergang, Germany
- Osman Gazi Bridge, Izmit, Turkey
- Mainbrücke Randersacker, Germany
- Millau Viaduct, France
- Rheinbrücke Schierstein, Germany
- Rion Antirion, Greece
- Russky Island Brigde, Vladivostok, Russia
- Tsing Ma, China

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*Wyatt Brooks and Kevin Donovan - "Eliminating Uncertainty in Market Access: The Impact of New Bridges in Rural Nicaragua," 2017.

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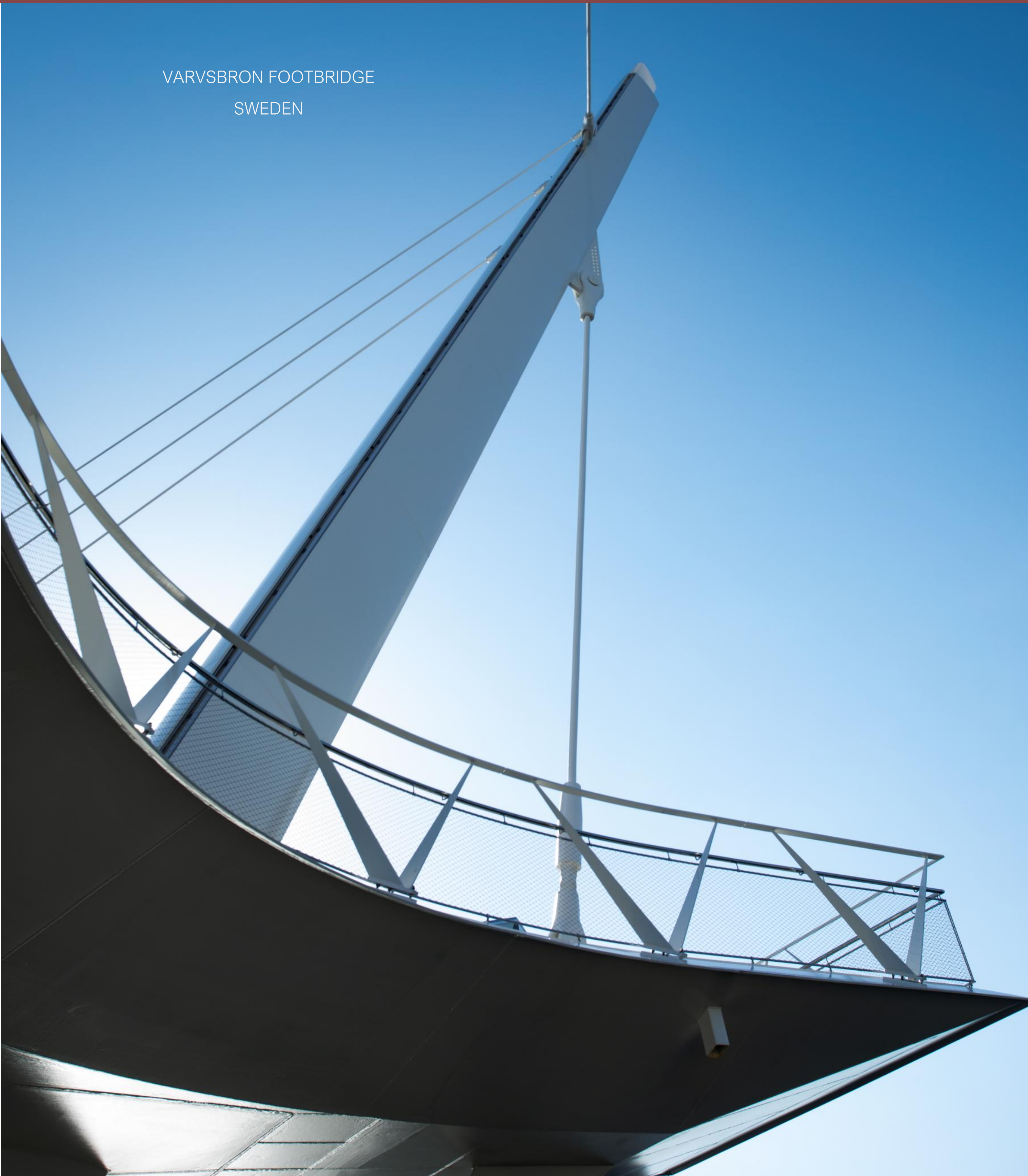

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