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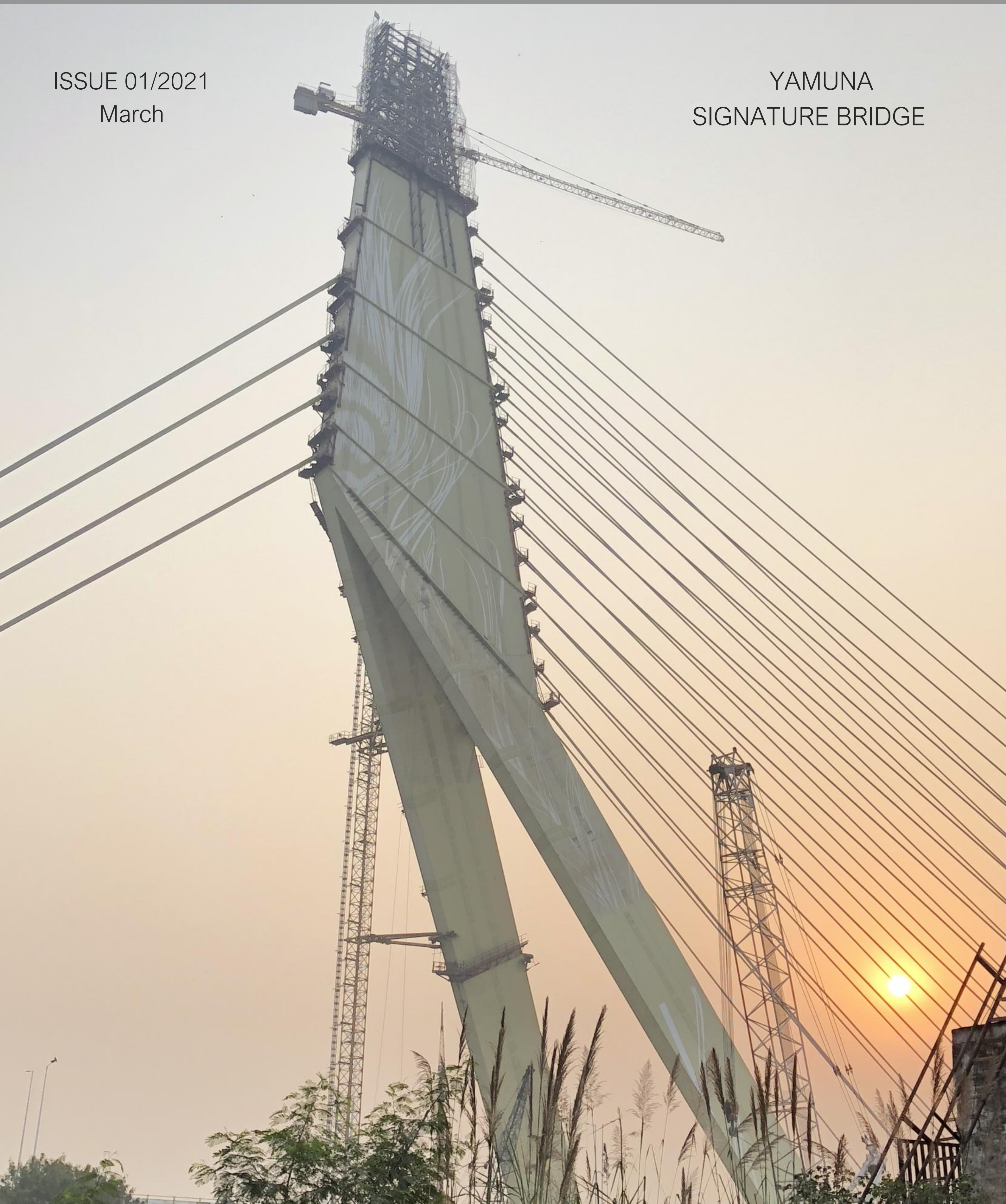

ISSUE 01/2021
March

YAMUNA
SIGNATURE BRIDGE

LIST OF CONTENTS

Photos on the Front and Back Covers: Yamuna Signature Bridge in India

Photo Credit: Swapnil Navalkar, GAMMON India

International, interactive magazine about bridges
e-mosty ("e-bridges").

It is published at www.e-mosty.cz. Open Access.

Released quarterly:

20 March, 20 June, 20 September and 20 December

Peer-reviewed.

Number: 01/2021, March

Year: VII.

Chief Editor: Magdaléna Sobotková

Contact: info@professional-english.cz

Editorial Board

The Publisher: PROF-ENG, s. r. o. (Ltd.)
Velká Hraštice 112, 262 03
Czech Republic

VAT Id. Number: CZ02577933

E-MOSTY ISSN 2336-8179

Dear Readers

This issue is dedicated to the first Signature Bridge in India. It is an asymmetric cable-stayed bridge with a main span of 251m and a total length of 675m. The crossing has a sharply bent, 151m high inclined steel pylon. It connects with National Highway 'Number One' near the existing point at Wazirabad on the Western bank and Marginal Bund Road at Khajuri Khas on the Eastern bank of the Yamuna River, thus, connecting North Delhi with East Delhi.

In the first article of this special issue, the conceptual and structural design of this bridge is described. The article was prepared by **Uwe Burkhardt, Mathias Widmayer and Mike Schlaich from sbp**.

The next article was prepared by **Swapnil A. Navalkar, Construction Manager – Engineering from Gammon Engineers and Contractors** *Pvt. Ltd. He focuses on the concept and planning of the project as well as on the construction details. The article is followed by photos from the construction of the bridge.*

The stay-cable system of the Yamuna Signature Bridge is described by **Andrea Castiglioni di Caronno and Tommaso Ciccone from Tensa**.

In the last article of this issue, **Peter Günther from Maurer** *describes spherical and pendulum bearings used on the bridge.*

I would like to **thank all authors and companies involved for their cooperation;** *and also* **David Collings** *and* **Richard Cooke** *for reviewing this issue, and* **Guillermo Muñoz-Cobo Cique** *(Arup) for his final check. I would also like to* **thank our partners for their continuous support.**

On behalf of the organizers, we would like to invite you to the Conference InfraMOST which will take place from 18 to 20 May 2021 in Gliwice. You can find more information on their websites www.inframost.info or on page 53.

We are happy to provide media support to IABSE Symposium which will be held in Prague from 25 to 27 May 2022. More information including deadlines for submission of abstracts can be found at https://iabse.org/prague2022 or on page 52. The invitation to the Symposium is here.

We have decided to dedicate part of future September Issues to BIM. We think it is an important part of bridge design and construction and we are happy we can bring articles on the latest developments in this area.

With our other magazine, e-maritime, we go on focussing on maritime construction projects, design and construction of ports and docks. We welcome cooperation with you and your company as well.

Magdaléna Sobotková

Chief Editor

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The magazine **e-mosty** (“e-bridges”)
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It is published at www.e-mosty.cz and can be read
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It is published quarterly: 20 March, 20 June,
20 September and 20 December.
The magazines stay **available online**
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The magazine **brings original articles about bridges and bridge engineers** from around the world.
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We are happy to provide media support for important
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The readers are mainly bridge engineers, designers,
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or people who just love bridges.

ISSN: E-MOSTY 2336-8179

INTERNATIONAL ONLINE PEER-REVIEWED MAGAZINE
ABOUT PORTS, DOCKS, VESSELS AND MARITIME EQUIPMENT

e-maritime

The magazine **e-maritime** is an international, interactive, peer-reviewed magazine about ports, docks, vessels, and maritime equipment.

It is published at **www.e-maritime.cz** three times a year:

30 March, 30 June and 30 November.

September Issue is shared with the magazine e-mosty ("e-bridges"): "Vessels and Equipment for Bridge Construction. BIM" which is published on 20 September at www.e-mosty.cz.

It can be read free of charge (open access) with possibility to subscribe.

The magazines stay **available online** on our website as pdf.

The magazine brings **original articles about design, construction, operation and maintenance of ports, docks, vessels, and maritime equipment** from around the world.

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The magazine e-mosty was established in April 2015 and its first issue was released on 20 June 2015 as a bilingual English – Czech magazine aimed mainly for Czech and Slovak bridge engineers.

Very quickly it reached an international readership.

In 2016 we extended the already existing Czech and Slovak Editorial Board by two bridge experts from the UK, and since then four more colleagues – from the USA, Australia and The Netherlands – have joined us.

Since December 2016 the magazine has been published solely in English.

Each issue now has thousands of readers worldwide.

Many of our readers share the magazine in their companies and among their colleagues so the final number of readers is much higher.

Most importantly the readership covers our target segment – managers in construction companies, bridge designers and engineers, universities and other bridge related experts.

The magazine e-maritime was established in 2018 and its first issue was released on 30 March 2019.

The magazine is published in English. It is going to cover a vast range of topics related to vessels, maritime equipment, ports, docks, piers and jetties - their design, construction, operation and maintenance, and various maritime and construction related projects.

The Editorial Board already has two members – from the UK and the Netherlands.

Both magazines are with Open Access with possibility to subscribe (free of charge).

In January 2019 we established their own pages on LinkedIn with constantly increasing number of their followers. Number of subscribers of both magazines is also increasing.

We also know that the readers usually go back to older issues of both magazines.

DESIGN OF THE YAMUNA BRIDGE

Uwe Burkhardt, Mathias Widmayer, Mike Schlaich, sbp

ABSTRACT

Rapid urbanization all around the world, especially in India, has put considerable pressure on the existing infrastructure. Bridges play a key role in infrastructure development and can become an important landmark for a city or a region at the same time.

One such bridge is the "Signature Bridge" in Wazirabad, Delhi, which is a new landmark while helping to channel traffic flows.

In this paper, the conceptual and structural design of this bridge will be described.

INTRODUCTION

Already in the 1970s the founders of the authors´ office had developed strong ties with India. Actually, the Second Hooghly River Bridge (nowadays called Vidyasagar Setu) in Kolkata was their first major overseas project.

The cable-stayed bridge with two H-shaped pylons from which parallel wire cable bundles fan downwards, is the result of an intensive 18-year design-and-construction process.

The Vidayasagar Setu, which was opened to traffic in 1992, was the first cable-stayed bridge designed with a composite deck and it has become the origin of many such long-span cable-stayed bridges all over the world.

Over the years detailing and building methods have evolved. Durable and safe cable systems which comply with international standards have replaced in-situ made solutions.

The same applies to large scale bearings, expansion joints as well as monitoring and maintenance equipment.

The new Signature Bridge in Delhi is a flagship project representing state-of-the-art construction possible nowadays in India.

The client had requested a landmark structure that would lend special significance to the location and its surroundings, a bridge that would by its size and design become an important and immediately recognizable icon for the megacity.

The resulting design is an appropriate balance between a well-thought, engineering structure and this specific wish of the client.

Globalization has it, that today also in India indigenous building has to be redefined and other issues such landmark designs have surfaced.

The Yamuna Bridge is envisaged to become an attraction that will serve as the starting point for a new recreation area in the Indian capital and which will improve quality of life in an area burdened by pollution.

The bridge is part of a major traffic route designed to relieve existing high-speed roads.

The cable-stayed bridge connects with National Highway 'Number One' near the existing point at Wazirabad on the Western bank and Marginal Bund Road at Khajuri Khas on the Eastern bank of the Yamuna River, thus, connecting North Delhi with East Delhi.

Considering the tremendous rise in population in the Trans Yamuna area, there is a pressing demand for an East-West corridor on the river.

For that purpose, the bridge carries four lanes of traffic in each direction.

The client, Delhi Tourism & Transportation Development Corporation (DTTDC), in the first instance asked only for a concept and feasibility study for the bridge, but in the end commissioned a joint venture of schlaich bergermann partner, Germany and Construma Consultancy Pvt. Ltd., India together with Ratan J. Batliboi Architects also with the detailed design.

CONCEPTUAL DESIGN

The Bridge is one of the many infrastructure projects that are being built in New Delhi.

The area around the bridge will later be developed based on the concept of the architect Ratan J. Batliboi into a park and the Yamuna River will be widened to lake-like dimensions.

Therefore, the client had asked for a rather long-span but light-weight bridge and a design which could become one of the area's attractions.

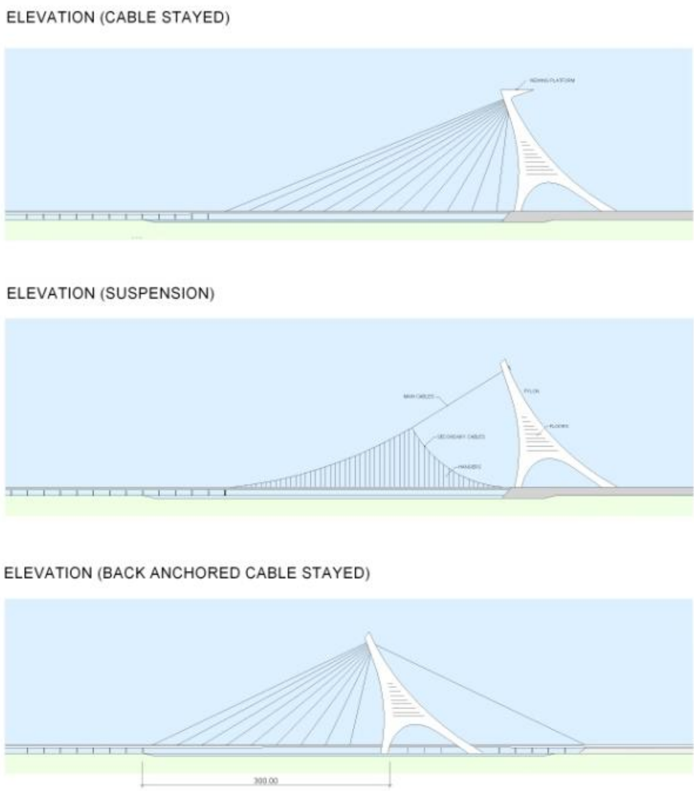


Figure 1: Early concept studies for the bridge © sbp

Based on this context, during various design sessions, numerous alternatives for the future bridge were drafted and evaluated.

At the same time, the design evolved from well proven structural solutions such as a slender composite deck which was used for the first time for the Vidayasagar Setu in Kolkata.

Once approved by the Delhi Government and the Delhi Urban Arts Commission, the design of the Yamuna Bridge was further developed.

The most striking feature of the bridge is the inclined pylon. The top of the pylon is formed by a steel-glass structure which houses an inspection platform.

This glass pylon head can be illuminated, maintaining the long-distance effect of the bridge even at night.

The layout of the upper part of the pylon allows for large scale artistic design, which is not possible with pylons of conventional cable-stayed bridges.

A typical Indian ornamental graphic was envisaged to further enhance the uniqueness of the pylon.

Due to its inclination, the pylon weight can compensate for a significant part of the dead load of the main span.

This cable-supported part of the deck spans 251m crossing the area of the future lake without supports to the ground.

Towards the approaches the same deck section continues with piers supporting it at 36mintervals.

The pylon is located towards the eastern shore, forming a symbolic gate connecting Wazirabad area with New Delhi.

The result of the conceptual design process for the Yamuna Bridge was a structure which tries to combine robustness and structural sanity with the expectations that come with a Signature Bridge.

STRUCTURAL DESIGN

The asymmetric cable-stayed bridge has a main span of 251m and a total length of 675m.

It is a single-masted cable-stayed crossing with a sharply bent, 151 m high, inclined steel pylon.

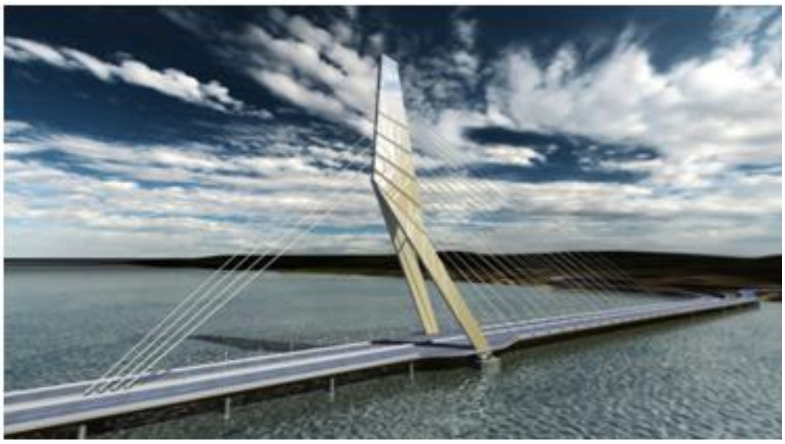


Figure 2: The rendering shows the ornamental graphic making reference to a peacock feather © sbp

Figure 3: The illuminated top of the pylon work as a beacon

The composite deck of the bridge carries 8 traffic lanes (4 in each direction). It is about 35m wide and is supported by lateral cables spaced at 13.5m intervals.

DECK

Two carriageways separated by a concrete crash barrier as well as two lateral emergency pathways form the deck.

The deck is formed of outer I-shaped longitudinal main girders with a height of 2m and I-shaped cross girders at 4.5m intervals.

To provide sufficient space for eight lanes, the two outer main girders, supported by cables, are spaced 32m apart from each other. The emergency footpath has been placed on 1.5m long cantilevers outside of the cable planes.

All structural steel is grade S355 (or the Indian equivalent). The pre-cast deck slabs of concrete grade M50 span 4.5m. Their standard thickness of 25cm increases up to 70cm at the main tower and in the area of the backstay anchorage. All main and cross girders are welded.

To save material the cross girders have a variable depth with a maximum value of 2m in the centre and 1.4m at the connection to the outer main girders.

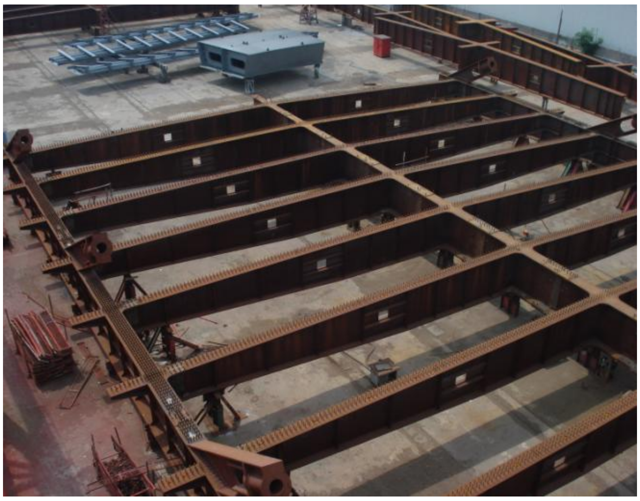
The steel components were not riveted together as in the Vidayasagar Setu times but instead are connected using high-strength, friction-grip bolts at splice plate and end plate joints.

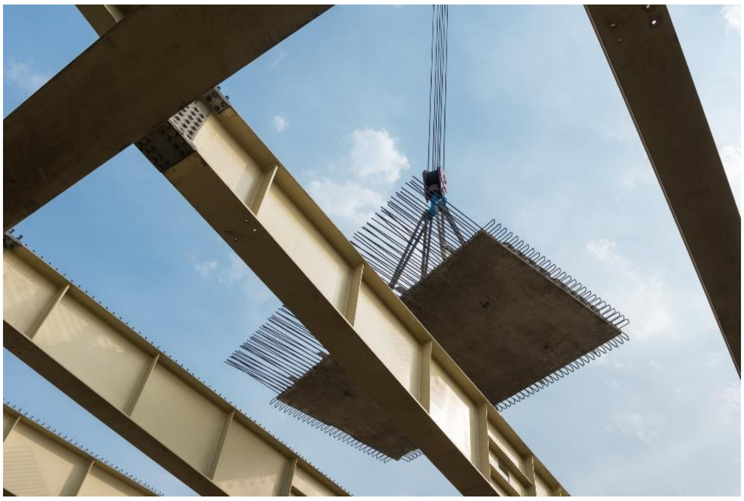
The result is a lightweight composite superstructure, which was temporarily supported during construction. The concrete carriageway slab acts like a strut to resist the horizontal force components from the cables.

The composite superstructure is therefore automatically prestressed or more accurately "precompressed." In this way the equilibrium of forces in the structural system is maintained and the usual complex arrangements for transferring the horizontal forces into the foundations are not necessary.

The deck is located relatively low above water which is shallow outside of the monsoon period. Therefore, it was possible to erect the entire deck on temporary trestles and to install the cables only afterwards.

Figure 4: View of the bridge deck





Figures 5 and 6: The steel cross girders for the deck during trail assembly and on site with a precast concrete deck slab © Left: sbp / Right: Andreas Deffner

Thus, full composite action also for dead load could be achieved, so that the concrete slab is transmitting even more compression force than in other construction methods. This is reflected in the distribution of the concrete slab thickness.

Outside of the cable stayed section, the precast reinforced concrete panels have a thickness of 250mm which gradually increases to 350mm thick panels towards the pylon and ends in a 700mm thick in-situ portion around the pylon legs.

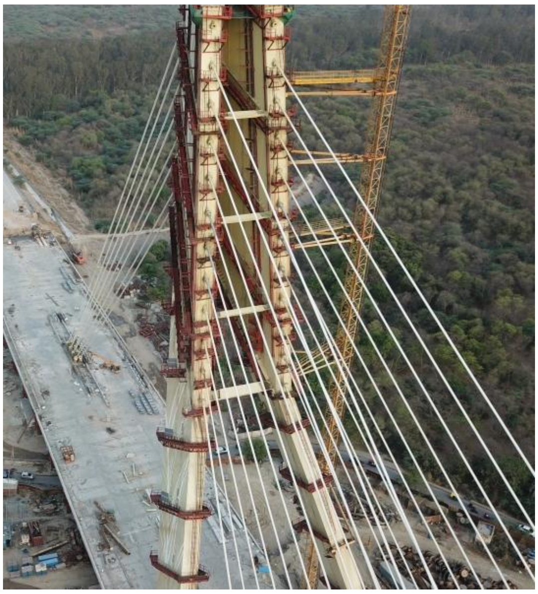
The precast deck panels are made of grade M50 concrete (similar to C40/50 in terms of Eurocode) with a size of 4.5m by 8m to minimize the number of transverse joints.

For the areas outside of the cable stayed section, with axial tension due to the composite action, the joint detail was further developed to allow for a central layer of reinforcement between the top and the bottom reinforcement.

The rigid connection between the concrete slab and the steel girders was achieved by shear studs with different diameters for main and cross girders.

To transmit out-of-plane shear forces, the end faces of the panels have been treated in such a way that the cementitious grout was removed, and the coarse aggregate became visible.

Furthermore, pockets have been foreseen in the end faces of the panels to transmit the significant



Figures 7 and 8: The main span is supported by two cable planes and the backstays are anchored in the centre of the deck in-plane forces safely. A state-of-the-art stay cable system with 15.7mm diameter strands made of steel grade 1860 has been used.

Since no fatigue tests for the largest anchor type were available with the supplier Tensa, such tests were performed especially for this project.

The larger active anchors are all incorporated in the interior of the pylon while the more compact passive anchors are located above the concrete, where they can easily be inspected and maintained.

The composite deck not only permitted a quick and simple erection, but also offers the economical advantage of having concrete balancing the horizontal cable thrust, a cost-free prestress.

The deck is transversally supported on both ends of the bridge and at the pylon. The only longitudinal deck support is at the pylon.

The longitudinal movement of the deck at its western end is approximately 250mm.

Figure 9: The pylon with the pattern of a peacock feather

CABLES

The deck is supported by two cable planes. The cables are directly anchored to the webs of the outer main girders at 13.5m centres with their dead ends, and are stressed within the stressing chambers at the top of the pylon.

The cables are made of bundles of parallel 15.7mm strands of grade 1860. Depending on the location, the number of strands per cable varies from 55 to 123 nos. at the main span and is 127 nos. for each of the backstays.

Corrosion protection was provided by hot-dip galvanized wires and individually coated strands encased in an outer PE pipe.

In the backstay area, the lower part of the cables is covered with steel tubes as a fire protection.

PYLON

The dynamically shaped pylon consists of two inclined legs, which are connected to the deck girders and bend mid-way.

The upper portion of the pylon anchors the backstay cables as well as the main-span cables, arranged in a harp like manner.

The tip of the pylon is created by a 30m high steel-glass structure, which can be illuminated to create a beacon visible from afar at night.

The two pylon legs, which are each supported on a spherical bearing, are fabricated out of rectangular box cross sections stiffened with ribs and merge halfway up the pylon.

Above this height, the pylon cross-section is V-shaped, with the V opening in the direction of the main span.

Also, the upper tower is designed as a hollow box section, made of a load bearing skin stiffened by internal stiffeners and bracings.

Here, for the first time, a graphic drawing is displayed on a bridge structure. The pattern of a delicate peacock feather chosen for the pylon reflects Indian culture and at the same time symbolizes elegance and lightness.

The four back-stay cables and twin 15-cable, harp-shaped fans are attached to the upper part of the pylon, which were fabricated in large segments.

The pylon is monolithically connected to the deck. It introduces horizontal forces in the longitudinal direction into the concrete of the deck. The horizontal forces in the transverse direction are taken by a strong steel cross girder that connects the two legs at the level of the cross girders.

Below the deck the pylon legs are supported on large pot bearings in order not to introduce bending into the substructure. Each bearing must transmit vertical forces of 170,000kN.

The inclined pylon relieves the load on the back-stay cables. Because the pylon's centre of gravity is on one side of the pylon foot, it counteracts some of the weight of the superstructure on the other side.

This three-dimensional consideration of the stabilizing moment of the pivot point at the pylon foot leads to an efficient structural system.

The pylon legs stand eccentrically on the bearings under the bridge deck so that the bending moment created by the bend in the pylon greatly reduces the moment in the opposite direction at the pylon foot.

A major part of the steel for the pylon is of grade S355. In very highly stressed zones, such as the area where the pylon is bent, grade S460 steel was used.

Above the top-most cable anchorage, the pylon rises further by about 30m forming the pylon head, a glass-covered steel structure that houses the illumination system and the platform mentioned earlier.

Figure 10: The glass-covered steel structure at the top of the pylon can be illuminated at night

FOUNDATIONS

The maximum scour level for the design flood is at about +178m and for normal flood, considered for the seismic case, about +182m. The rock levels vary in between +193m and +173m. Six foundations are made as open foundations with spread footings and 16 foundations are well foundations. Out of 16 well foundations, 8 are founded on alluvial soil and the rest on undulated rock, not only in the longitudinal but also in a lateral direction.

Figure 11: Raft foundation for one pylon leg

FINITE ELEMENT ANALYSIS

The pylon was also modelled with 3D shell elements. Second order effects were considered by geometrically non-linear algorithms applied to the pre-deformed system.

It should be noted, however, that even today it is not possible yet to realistically model all details of such a complex structure by computer.

The number of elements would become so large that not only computing time would become

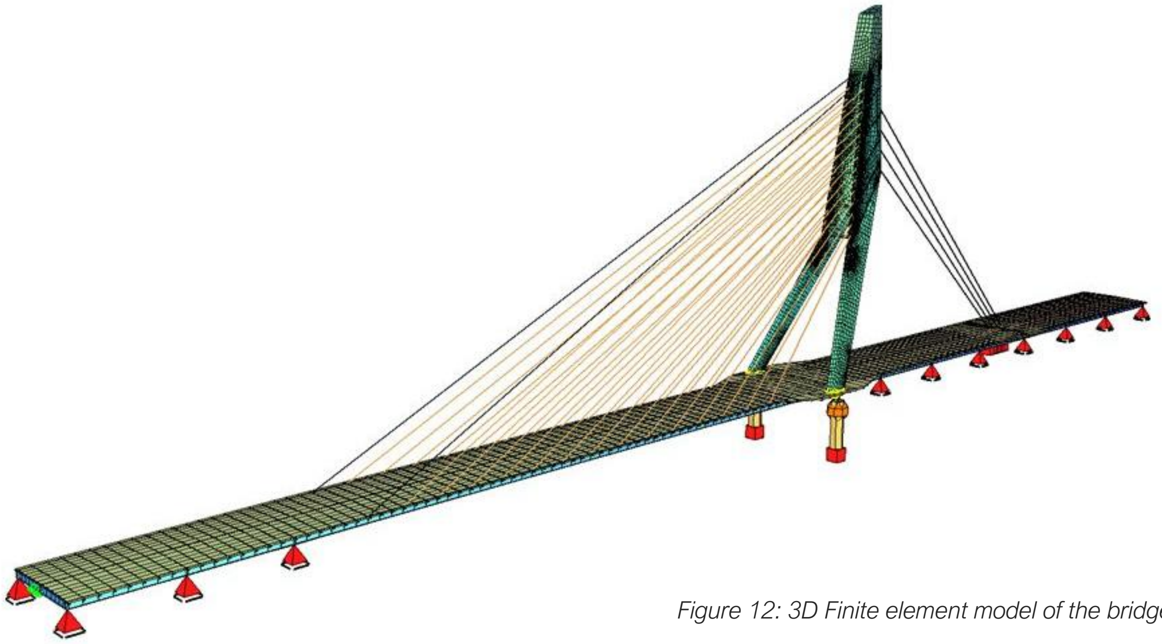


Figure 12: 3D Finite element model of the bridge © sbp

prohibitive, but also the output would be so voluminous that it would become hard to interpret the results. So, in this case the computer analysis was accompanied by conventional approximations for comparisons and checks.

The results of the extensive seismic analysis show that seismic forces from the equivalent static method with a uniform lateral load of 10 per cent of gravity are on the safe side. In the wind tunnel section model tests proved that flutter is no issue.

Of importance was the modelling of the pylon in order to get realistic assumptions for the wind loads to be applied. The average transverse wind load (based on a design wind speed with a 100 year return period) that was applied to the pylon, is in the order of 1.7kN/m^2. Local peak loads for the glass design at the pylon head are up to 4.2kN/m^2.

CONCLUSION

Only thanks to the persistence of the client DTTDC is the Signature Bridge New Delhi finally becoming a success.

The design was finished in 2007, just when steel prices dramatically increased due to the sudden surge of significant projects (such as the Olympic stadium in Beijing) that consumed worldwide steel production.

The project not only had to face steel price escalation but also survive the global financial crisis, land acquisition and soil problems. Now the bridge project is finally in use and frequently visited and photographed.

The Signature Bridge is a symbol of emerging India. It is a big leap forward compared to the riveted Second Hooghly Bridge thirty years ago. It can also be called a Signature Bridge because it is the signature under the promise to improve the areas around it, to clean the Yamuna River and to make the area a tourist destination with this landmark bridge leading the way towards a beautiful park and a lake.

Data block

Owner/Client: Delhi Tourism and Transportation Development Corporation (DTTDC)

Conceptual and structural design: schlaich bergermann partner, Germany

Cooperation: Construma Consultancy Pvt Ltd, Mumbai (foundations); Ratan J. Batliboi - Consultants Pvt Ltd, Mumbai (architectural advisor)

Wind Tunnel Studies: Wacker Engineers, Germany

Seismic Studies: IIT Roorkee

Checking Engineer: Systra and M.Virlogeux, France in association with Tandon Consultants, New Delhi

Construction: Joint Venture Gammon-Construtora Cidade-Tensacciai

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PLANNING & CONSTRUCTION OF INDIA'S FIRST "SIGNATURE BRIDGE"

Swapnil A. Navalkar, Construction Manager - Engineering
Gammon Engineers and Contractors Pvt. Ltd.

Figure 1: View of completed Signature Bridge

1. INTRODUCTION

Infrastructure plays a significant role in the economic growth for a rapidly developing country like India.

In the last decades many countries around the world have been in a race to build the longest, tallest, biggest and most iconic bridges.

However, with the ever-growing demand of infrastructure projects, and in order to compete with the rest of the world, there have been huge investments which have given rise to many ambitious and large scale projects in India.

"Signature Bridge" is one such project, which was conceived with an aim of constructing a cable stayed bridge, which should be unique and as it name implies "Signature".

Attempting such challenging project for first time, with no past references, we may foresee many unprecedented challenges.

Signature Bridge did have many such challenges. Nevertheless, overcoming all the geological, geographical, environmental and technical hurdles, and through meticulous planning, state-of-the-art engineering techniques and innovative construction methodologies, and with the help of expertise from over 15 countries, what was once a dream is today a reality.

The Signature Bridge is the tallest unsymmetrical cable-stayed bridge in India, with steel pylon 154m high. It is an elegant bridge, which has claimed to be the new landmark for the capital city of New Delhi, India.

It crosses the river Yamuna at Wazirabad improving signal free approach access from the NH-1 highway on the Western bank and Wazirabad Road (at Khajuri Khas intersection) on the Eastern bank, with entry and exit of traffic in two directions.

2. CONCEPT AS EVOLVED

With the conception of the new 8-lane bridge across river Yamuna, 600m downstream of the existing barrage cum bridge at Wazirabad, Delhi culminated in the decision of the Delhi Government for making a landmark Structure in Delhi and to develop the surrounding area.

This decision necessitated the development of the Eastern and Western Approaches on both sides of the conceived signature bridge. Western & Eastern approaches (depicted as 1) in the Figure below were a separate contract from that of main Signature Bridge contract (depicted as 2).

The area under the bridge is envisioned to be developed later as a park and the Yamuna River is to be converted into lake like dimensions, with river channelization to enable boating facilities and other tourist attractions.

So, the conception and design of this iconic structure had to enhance the character of tourist attraction.

During the phase of convergence, many options were tested before arriving at a solution which is almost twice the height of one of Delhi's other heritage structures, the Qutub Minar.

Graphics on the bridge structure - particularly peacock's feather on the Pylon - was to symbolise Indian culture as well as to reflect a modern and progressive India.

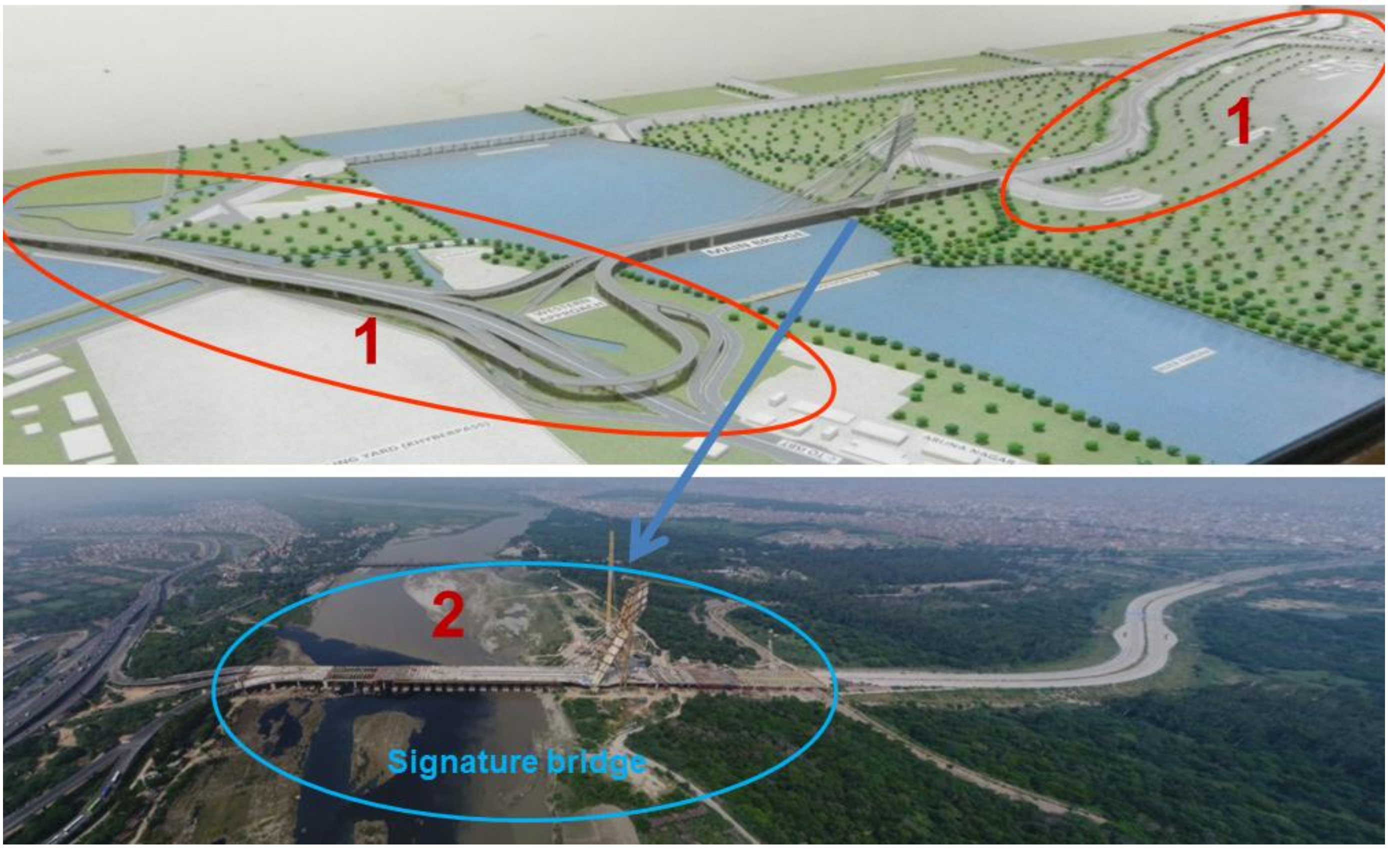


Figure 2: General arrangement of approaches (1) and main bridge (2)

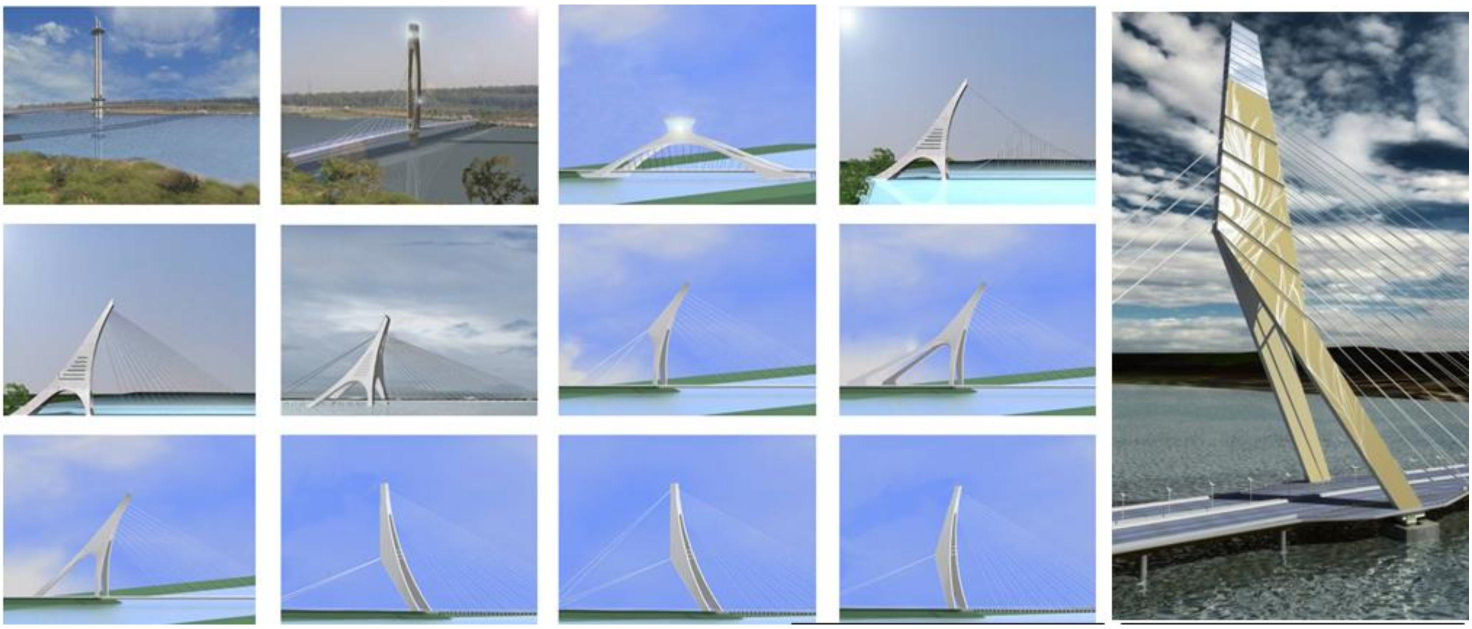


Figure 3: Concept of evolution

3. PROJECT DETAILS

Signature Bridge is an asymmetric steel cable-stayed bridge comprising of an asymmetrical inclined harp shaped Steel Pylon 154m high.

A total length of the cable-stayed bridge from the expansion joint to the expansion joint is 575m, with a main cable-stayed span of 251m supported with 15 pairs of cables on one side and counterbalanced by 4 pairs of back stay cables attached at a pendulum (rocker) bearing.

The bridge's steel and concrete composite deck has a dual carriageway of 4 lanes (14m) each with a 1.2m central verge, space for anchoring cables, a maintenance walkway and a crash barrier on either side of central verge.

The outer to outer width of the bridge is 35.20m. The approach spans are 36m long. Spherical bearings are provided on all the piers. Pendulum bearings are provided for back stays.

The deck spans 32m in the transverse direction. The composite deck consists of two main girders (I-shaped) in longitudinal direction and cross girders at 4.5m spacing along the deck.

Spans are 13.5m long on the cable supported part and 36m on the approach spans which are supported over concrete columns.

Most parts of the deck slab are made up of full depth prefabricated concrete elements of varying thickness from 250 to 350mm, stitched in-situ over steel girder flanges.

In highly stressed areas, near the pylon base and backstay anchorage, in-situ concrete up to 700mm thick was placed over scaffolding.

The Steel Pylon of 154m from top of the bearings consists of two legs made up of steel boxes which merge into one upper pylon body zone made up of a load bearing skin.

This is stiffened by internal stiffeners and bracings where the cable supporting the main span and the back stays are anchored.

The two independent pylon legs merge at a height of 50 – 80m. The upper end is called the kink diaphragm, which is the transition from pylon leg to the pylon body. Each leg consists of a hollow steel box.

The pylon body is a common structure above the legs, which takes the entire external load coming from the cables which support the deck.

At the height of 125m it has a 30m high, 3 level observation deck called the pylon head which is made up of beams and columns in a steel structure with a glass cladding which provides a 360 degree panoramic view of Delhi. Four inclined lifts are provided in the legs and the main body to reach up to the pylon head.

The major part of the pylon was made out of S355 high grade steel. In very highly stressed anchorage zones, S460 grade steel was used.

Each leg of the Pylon rests on two huge circular fixed bearings to transmit vertical loads of 17,000 tonnes each, making it one of the largest bearing of the world.

One of the pylon bearings was designed to allow transitional movement anticipated during construction, and this was locked once the erection was complete.

The cables are made up of bundles of parallel 15.7mm strands of strength 1,860 MPa and protected against corrosion.

Depending on the location the number of strands per cable varies from 55 to 123 at the main span and is 127 for each backstay.

Under the outer axis of the bridge independent foundations are provided up to a depth of 20m below ground level, as generally the rocky foundation stratum was determined at that level.

There are 6 numbers of open foundations (Figure 4) resting on rocky strata at a depth of about 20m.

The diameter of the main Pylon (P19) foundation (2 nos.) is 23m with a pier diameter of 5.5m. The foundations at a P20 & P3 (2 nos. each) is 7m with the pier diameter of 2m.

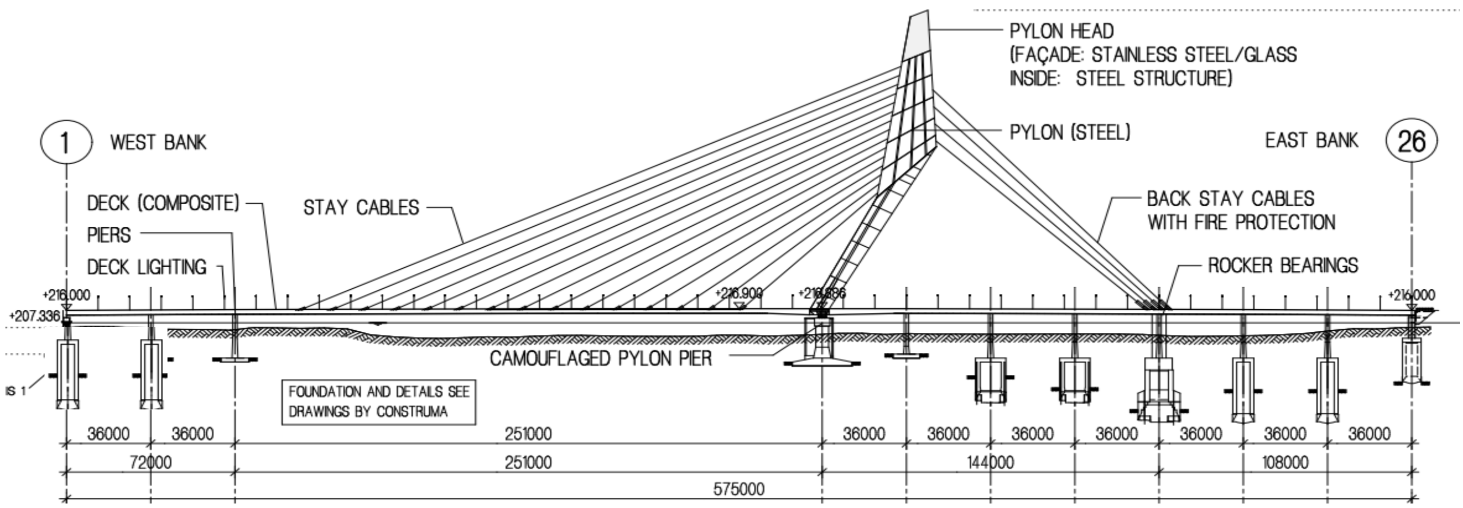


Figure 4: Elevation Showing General Arrangement of Signature Bridge

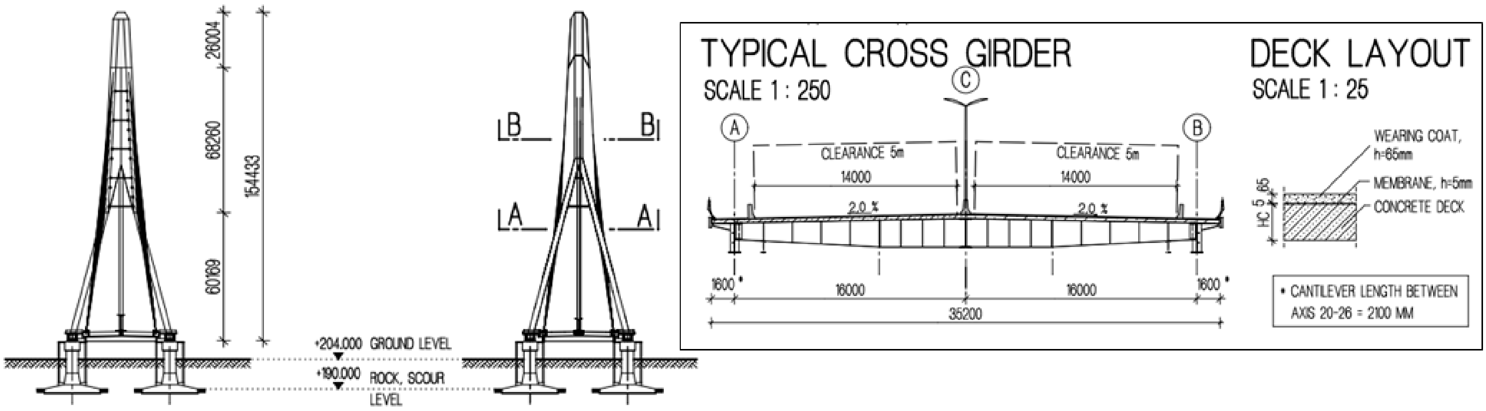


Figure 5: Typical Cross Section of Pylon and deck

The remaining 16 are well foundations with the varying diameters of 8 to 9m. Back stay foundation P23 has hybrid foundation which is a combination of piles through well steining with the tapering well diameter from 18m to 15.50m.

The design of the bridge was developed by Schlaich Bergermann und Partner, Germany in cooperation with Construma based in Mumbai and Ratan J Batliboi Architects, Mumbai.

Schlaich Bergermann und Partner were also engaged to carry out step by step construction stage analysis as per proposed erection methodology developed by Studio de Miranda Associati, Italy.

Studio de Miranda Associati, Italy was also involved in proof checking the final design and design of major temporary structures.

4. REALISATION OF SPECIAL FOUNDATIONS & SUBSTRUCTURE

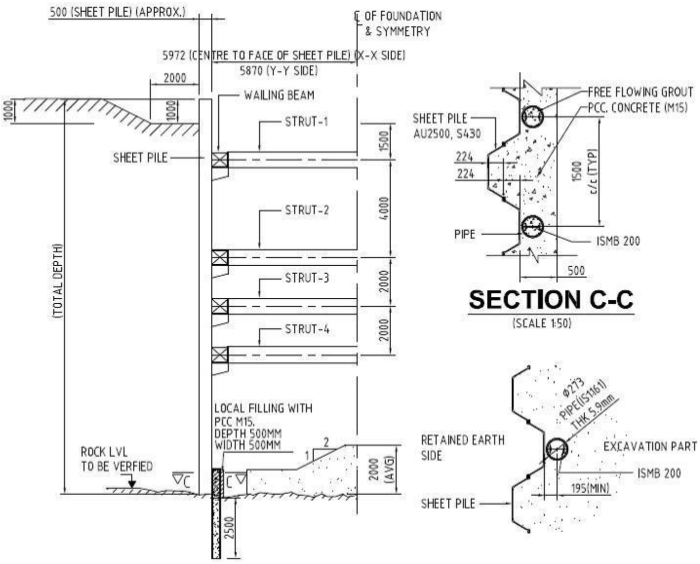
The subsoil strata at site was generally homogenous and comprises mainly of two types of layers, dark grey fine sand in 1st and in 2nd layer light brown sandy silt up to the rock layer around 20m below the ground level.

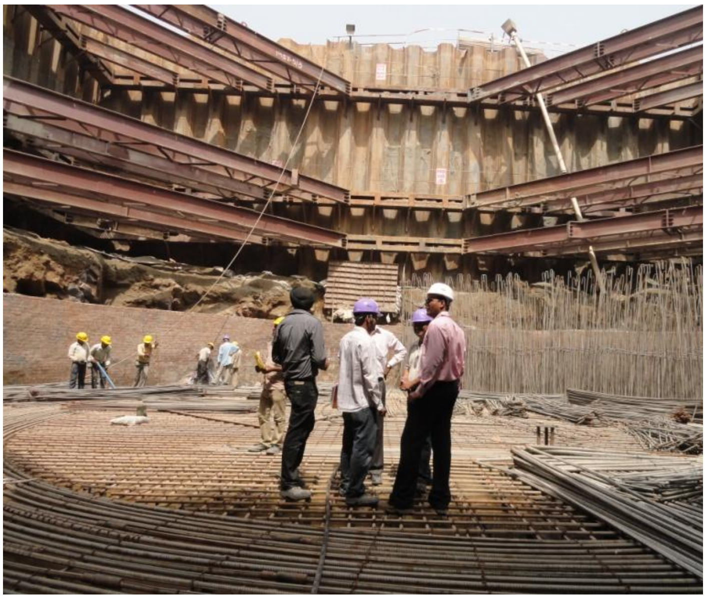
The rock met was generally weak to moderately strong quartzite.

Open and well types of foundations were proposed for this bridge, as there were large and sudden variations in the rock profile, along the alignment of the bridge.

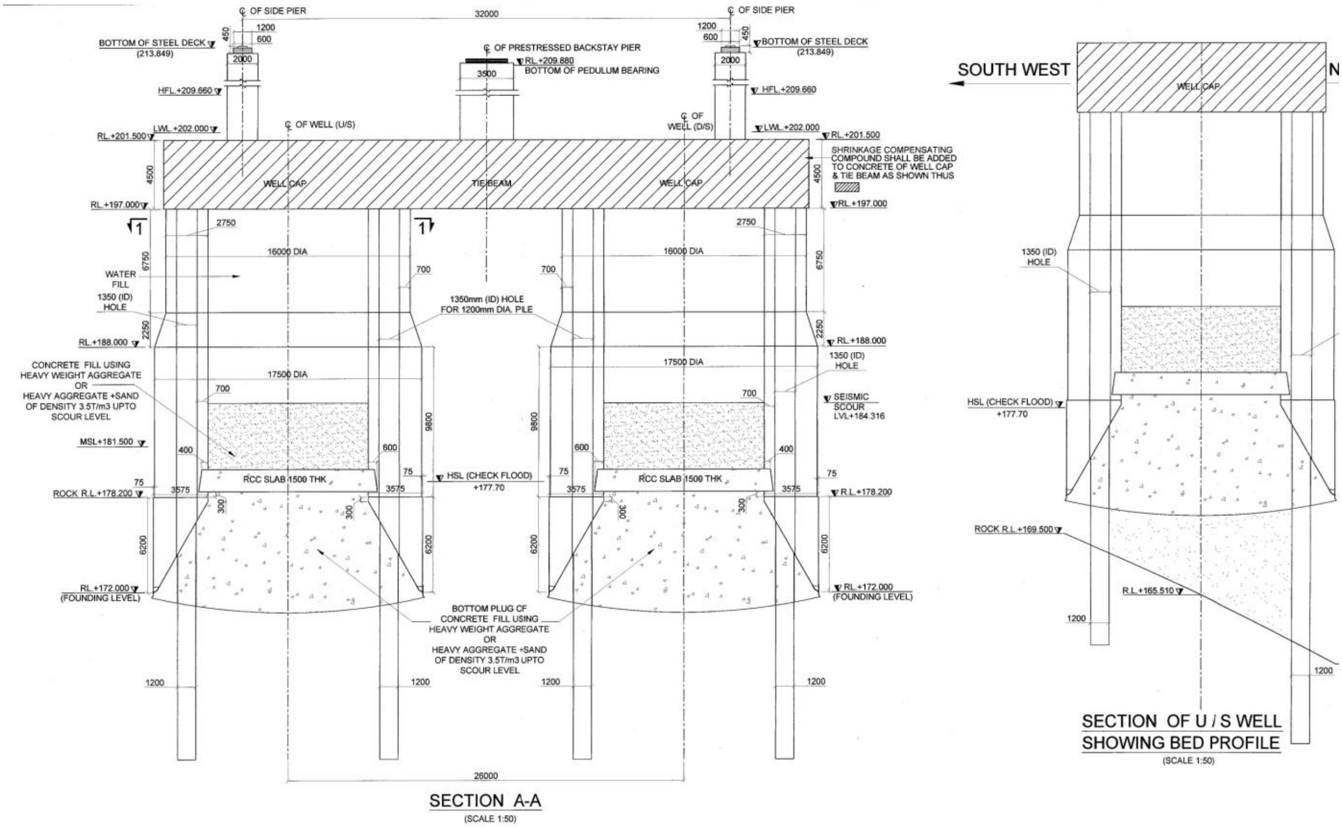
The bridge pylon was supported on two circular open foundations, each 23m in diameter.

Specially designed sheet pile cofferdams, resting on rock, supported with toe pinning and lateral supporting bracing arrangement, were used to excavate up to the founding level.





Figures 6 - 8: Sheet Pile cofferdam resting on rock with toe pinning arrangement



Figures 9 and 10: Well Sinking by Jack Down Method

Well foundations were proposed in most of the areas where the rock was at a very low level.

Anchor wells were constructed at P23 location, where the forces from the back-stay cables are transferred. The back-stay foundations consist of two wells 18m in diameter, connected with a common tie beam at well cap level, 12m below the ground level.

All well foundations were required to be constructed adopting jack down method of sinking for controlling the sinking operation without tilt and shift.

In the original design, wells were proposed to be supported on concrete block stools for enabling bottom plugging and 100mm dia. anchors to resist the sliding.

Placement of stool blocks beneath the sloping well kerb under water was not only impractical but also was high risk prone.

The cleaning of the base beneath the kerb by divers before placement of stools was posing the possibility of well sinking suddenly jeopardising the lives of divers working under water.

With the inclined rock level at the founding level, pile (230mm to 1,200mm) were driven to stabilise and support the well foundations on the sloping rock profile.

This principle of well construction was inspired by "Jogighopa Bridge, Kolkata India", where well foundations were constructed in similar geotechnical conditions.

Sinking of wells was done using a jack down method for precise and speedy sinking. Once the wells were sunk to their founding levels, RCD were used to drill piles through the wells.

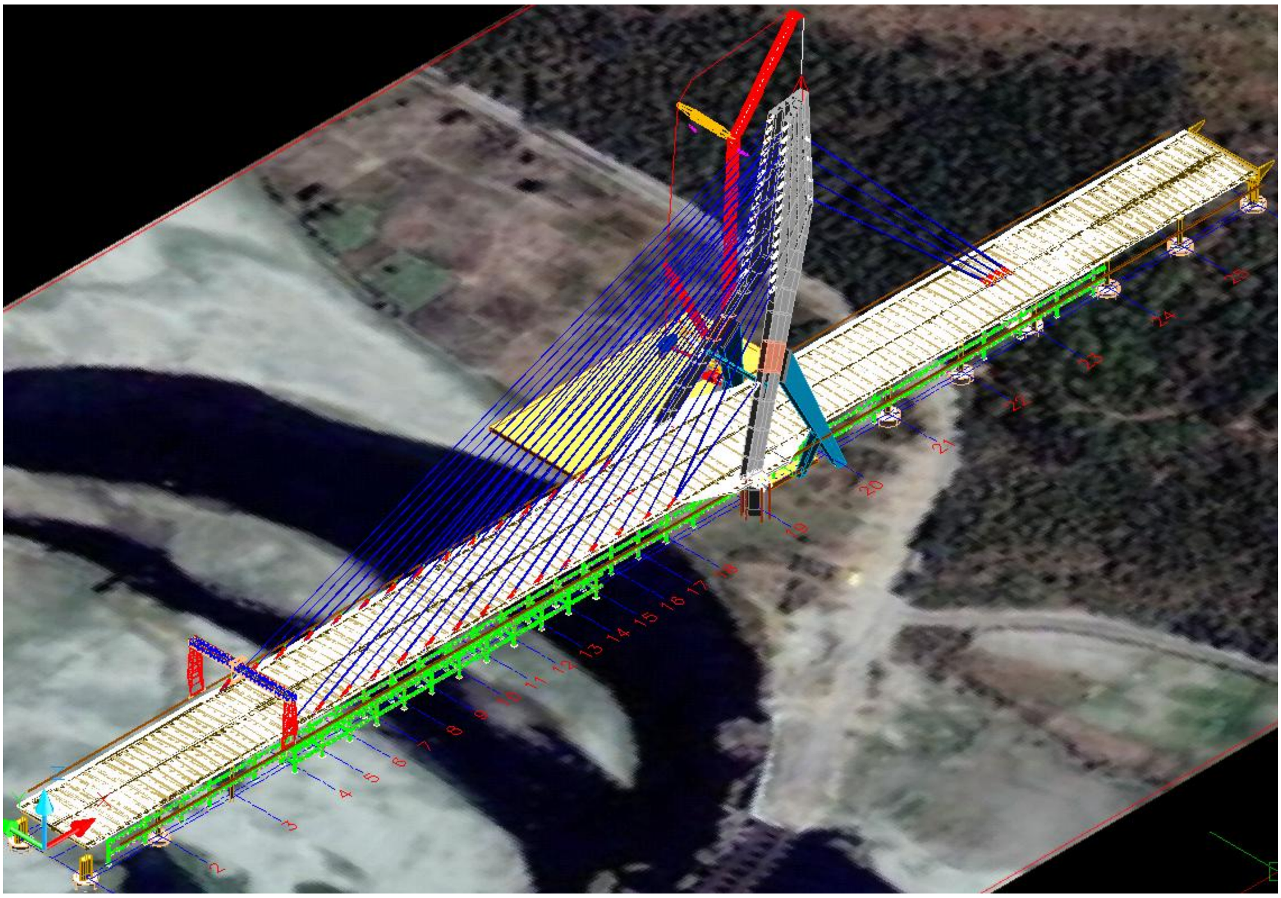


Figure 11: Proposed erection methodology

5. CONSTRUCTION OF SUPERSTRUCTURE

Cable-stayed bridges are usually symmetrical in nature and traditionally built by cantilever construction on either side of the pylon.

An unsymmetrical cable stayed bridge like Signature Bridge with an inclined pylon, supported on bearings, was a highly unstable structure during erection.

This demanded an innovative method of erection with a coordinated and calculated step by step erection procedure.

Extensive studies were conducted to develop project specific construction systems and methods which would be efficient and cost effective, while maintaining essential safety and quality control measures.

After working out several alternatives, it was finally proposed to erect the Pylon using a 1,250t crawler crane.

The pylon was supported with a specially designed temporary strut, until the system was stable after installation of the permanent cables.

Deck girders were supported over temporary trestles and erected using a Goliath gantry running over the same trestles and along the bridge.

Pre-cast deck panels were erected over the girders using the same Goliath gantry as for deck erection.

Based on the proposed erection methodology and erection stage analysis, temporary pylon supports were designed.

These props were not only designed to support the structure, but also to maintain and ensure correct geometry, with the help of suitable jacking arrangement.

Special tie down arrangements were installed at the base of the pylon to stabilize the initial phase of pylon erection cantilevering for about 40m.

A detailed stage-by-stage analysis was done to determine stress distributions and structural adequacy for all intermediate stages of erection. Sufficient strengthening of the permanent structure was done wherever required.

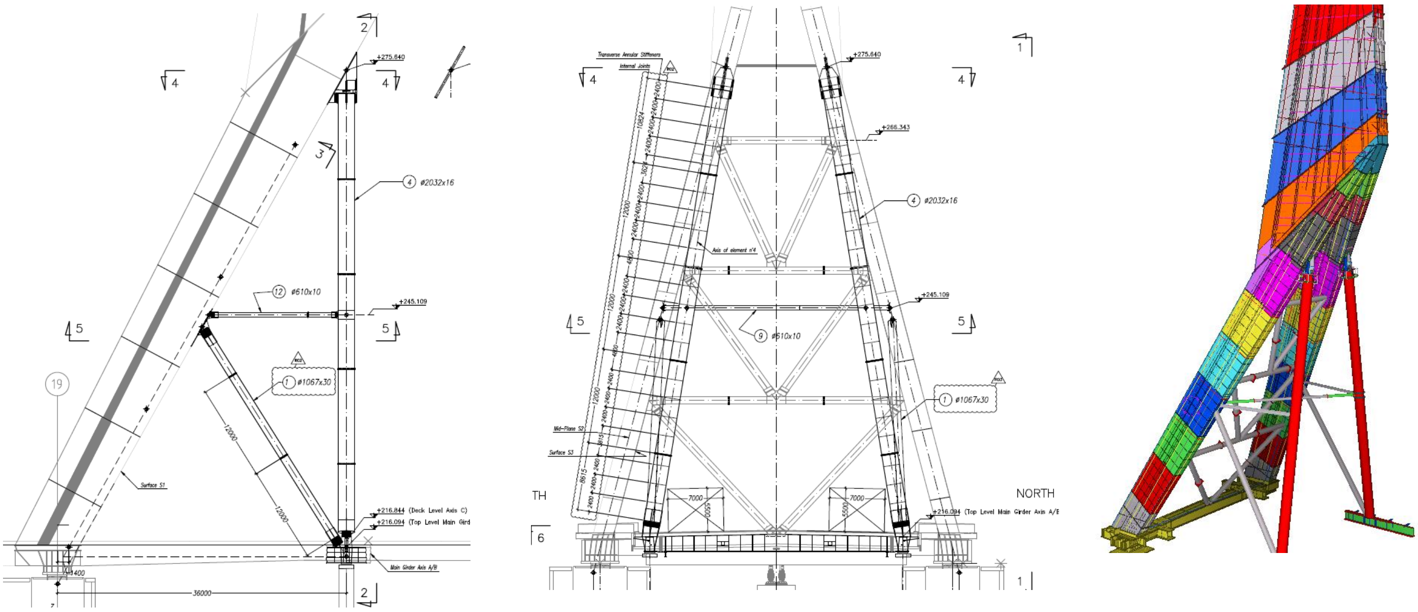


Figure 12: Pylon supporting structure

5.1 Understanding the structure and necessary design changes

Construction of the superstructure involved fabrication and erection of 14,700 tonnes of structural steel for deck and pylon.

The distinct characteristic of Signature Bridge was, that its pylon was an integral part of the composite deck and hinged at the pier top level over huge spherical bearings.

The pylon with its harp shaped body, leaning backwards, was the most unstable structure during construction stage.

The pylon is a 3-dimensional and complex structure having inclination in all planes, made up of irregular panels welded out of varying steel plates of different grades.

The maximum segment size to be fabricated and handled was about 6.5 x 6.5 x 15m and weighing from 60 to 560 tonnes.

For understanding the complexities of the structure, dimensional weights of the elements to be fabricated, transported and erected, a true to scale digital model of the bridge was prepared in Tekla Structures 16 (steel detailing software).

It was incorporated to a Building Information Modelling (BIM), enhancing efficiency, accuracy

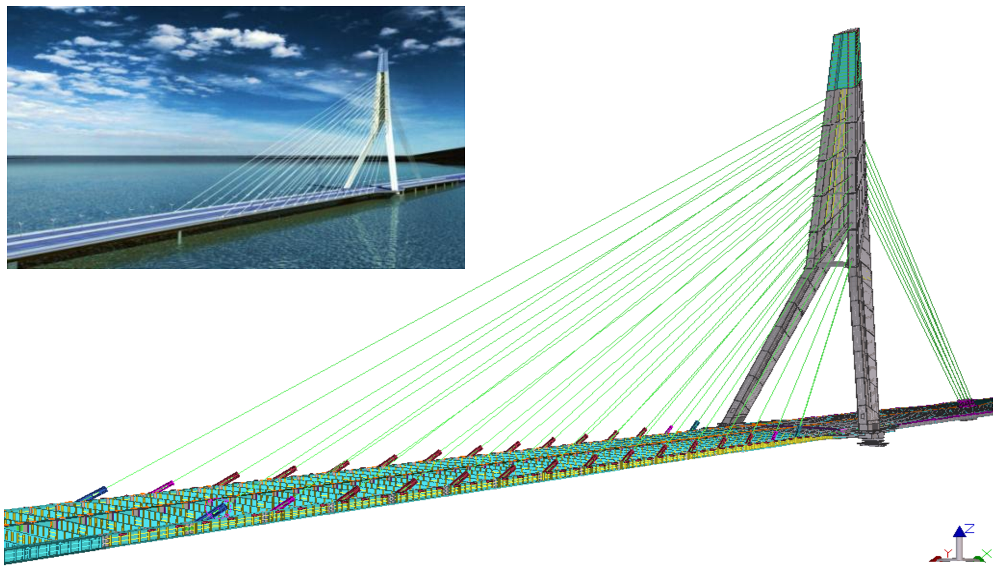
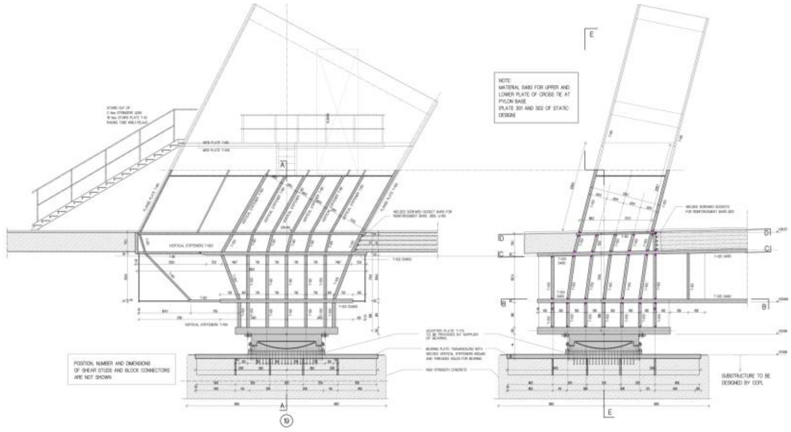
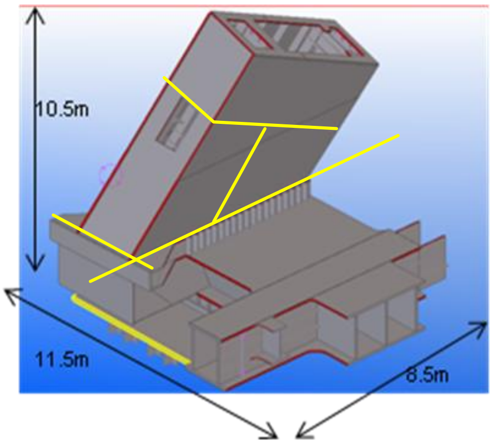


Figure 13: Full scale digital model in Tekla





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Figures14 and 15: Oversized Pylon Segments weighing about 560 Mt

and substantial reduction in wastage of material through proper detailing.

A feasibility study was done, by means of route survey to understand logistical challenges involved in the transportation of elements.

It was almost impossible to transport these heavy and oversized segments from the fabrication shop to site over Indian roads and especially on the existing bridges along the route.

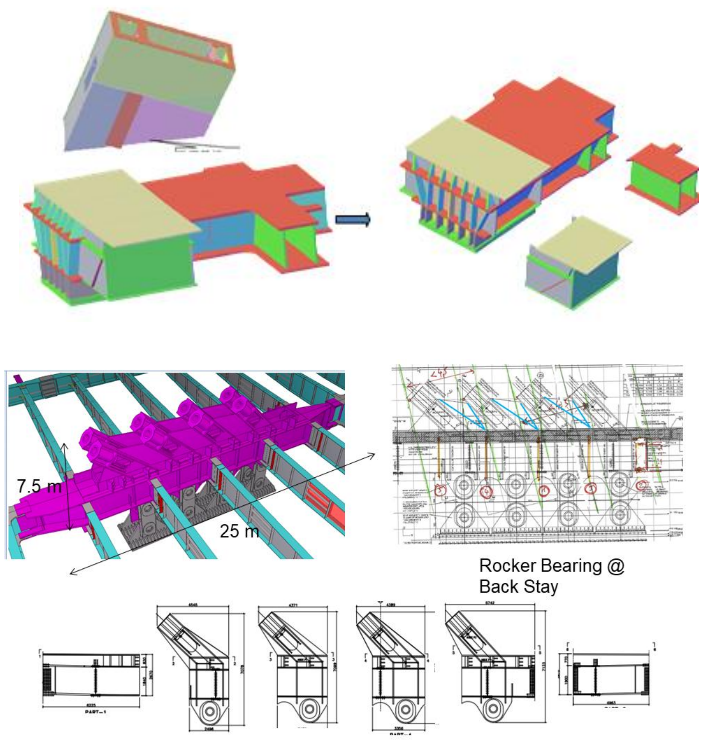
The setting up of a sophisticated fabrication workshop at the site, was not feasible due to time constraint and requirement of expertise.

To overcome the restrictions on transportation, the pylon was divided into sub-panels of transportable size by introducing additional splices.

The new splices were designed by Schlaich Bergermann und Partner and were introduced while detailing the fabrication drawings.

Segments of smaller size were fabricated in an established workshop, transported to site and reassembled before erection.

Deck girders were comparatively easier to fabricate and transport, with a maximum length of 30m and required no major design modifications.



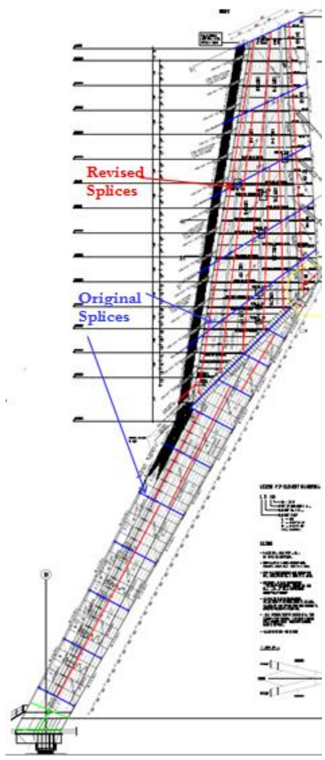
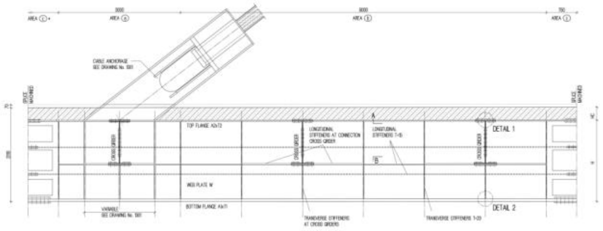
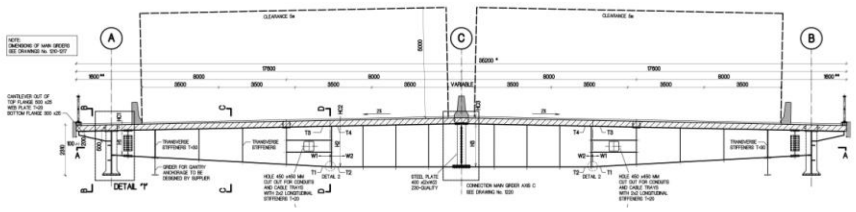


Figure 16: Additional splice introduced in pylon and rocker bearing





Figures 17 and 18: Typical Main and Cross girders

Click on the image to open it in full

5.2 Pylon and Deck Fabrication

Fabrication works involved almost 6,500 tonnes for the pylon & 7,500 tonnes for the deck.

Structural steel of grade S355J2 (+N) for thickness up to 80mm and grade S355NL for thickness above 80mm, confirming to EN10025, was used for the project. In the areas of highly stressed zones, like the kink zone of the pylon and pylon base, steel of grade S460 NL were used to improve deformation properties perpendicular to surface.

Plate thicknesses ranging from 12mm to 250mm were used for the fabrication work. With a huge variation in plate thickness, a precise method of detailing was required to ensure maximum utilisation with minimum wastage.

5.2.1 Scouting of appropriate Fabrication facility

With most of the on board and logistical issues resolved, fabrication works came with a new set of challenges. Pylon & Deck fabrications were the most technically challenging part of the job which required the highest level of accuracy with stringent specifications and code requirements.

Some of the major challenges involved in fabrication were:

- Use of plate with a thickness ranging from 12 to 250mm including Z quality steel, as plates above 80mm and special grades were not readily available in India.
- Adoption of an appropriate welding sequence to avoid deformation while welding thick plates of thickness 80 – 250mm.
- Preheating to temperatures in excess of 600 degree for thicker plates.
- Stress reliving arrangements due to heavy welding.
- High precession and tolerance requirement for drilling bolt holes & end milling/machining.
- Drilling almost 850,000 holes for HSFG bolts ranging from 12 to 36mm in plates up to 120mm thick.
- Non availability of Skilled Manpower.
- Requirement of special lifting equipment during fabrication & trial assembly to handle weight in excess of 500 tonnes.

Considering the above challenges and after scouting many fabrication agencies within India and abroad, the works was subcontracted to Jiangsu Zhongtai Bridge Steel Structure Co. Ltd, China that had experience in fabrication of steel bridge with capacity of fabricating over 50,000 tonne/month.

5.2.2. Fabrication of Pylon and Deck

Fabrication of pylon and deck segments required a high level of quality and accuracy, as they were key parts of the bridge.

Fabrication tolerance was very stringent, and it directly affected geometrical dimension of the whole segment after their trial assembly.

Following steps were followed during the fabrication process:

- Technical groundwork – preparing fabrication drawings, workout requirement of material, identifying appropriate welding procedure, welder prequalification, working out required equipment and support arrangements.
- Cutting of material and stamping of plates before panel welding.
- Panel welding and NDT testing.

- Fit up of entire segment and NDT testing.
- Initial survey and dimensional check, rectifications if required.
- Match drilling using predrilled splice plates.
- Machining end surface of the segment in contact with other surface at splice, which transfers load through bearings.
- Trial assembly and final survey.
- Blasting and painting.
- Packing & Dispatch.

5.2.3 Preparation of Fabrication drawings

Tekla structure was used to prepare all fabrication drawings.

A completely new model was recreated in Tekla introducing all the additional splice, details from various outsources components, connection of temporary structure and strengthening required for the same.

All drawings were digitally reviewed through a 5-level of checking. Only the final copy was stamped and submitted to the Client for record purposes.

More than 6,500 drawings including revision were prepared and successfully reviewed digitally.

Figure 19: Fabrication stage of Main body segments

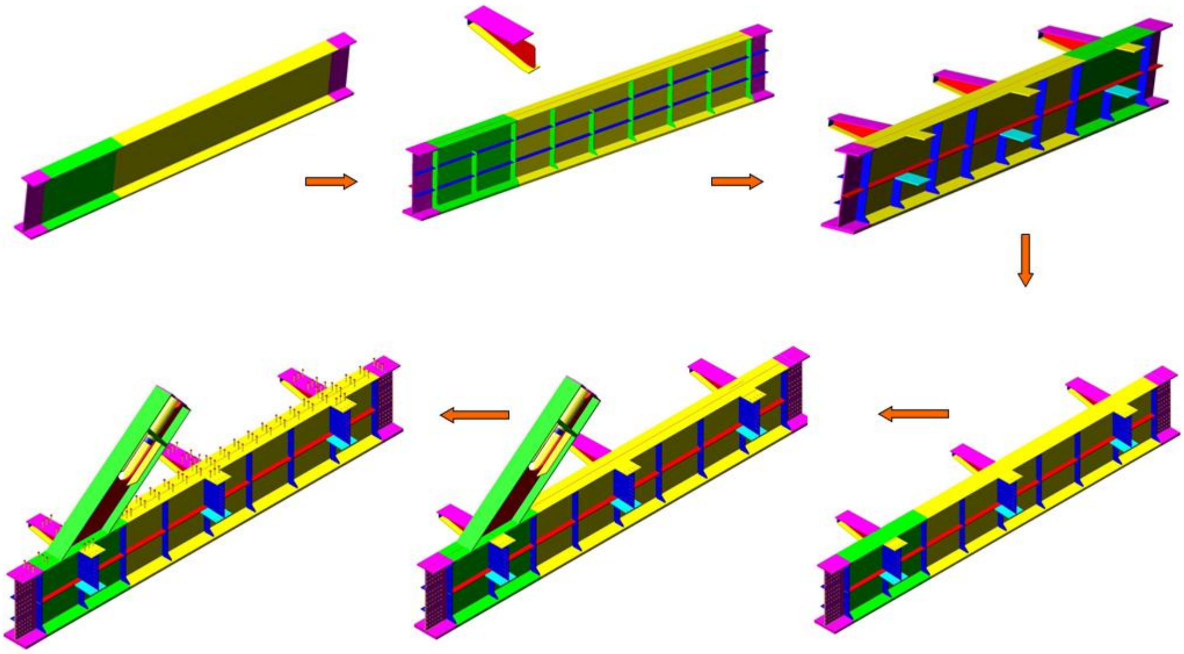


Figure 20: Fabrication stage of Main girder with anchorage

5.2.4 Stage of Fit-up and segment Fabrication

Various welding procedures were developed considering the size, angle and position of the plates to be welded.

Typically, SMAW, MIG and FCAW type of welding was adopted. Only qualified welders were allowed to ensure good quality of welds.

Typical stage of fabrication of deck girder and Pylon main body segment are explained graphically.

Various NDT testing like Dye penetration test, ultrasonic test, magnetic practical test, etc. were carried at every stage of fabrication.

All tests were witnessed by Lloyds, UK and were properly documented for further reference.

5.2.5 Drilling &Machining

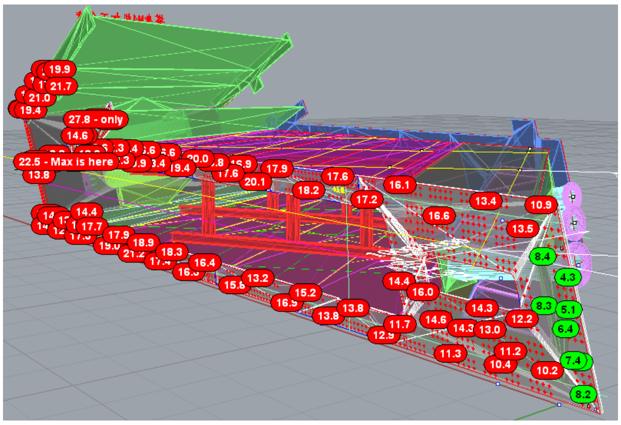
To ensure accurate geometry and for ease of erection, only bolted splice connection were allowed for all pylon and deck segments.

In order to optimise the number of bolts, the splices were designed to transfer the load partly through bolts and partly through machined contact surfaces.

This concept of splice designed reduced the requirement of bolts almost to half of its original

Figure 21: Machining end surface of girder

Figure 22: Machining pylon kink 32m long and 7m high



Figures 23 and 24: Pre-calculation of machining tolerance

requirements, but it calls for accurate and precise machined surfaces.

Tolerances of 0.1mm in 1m were to be obtained. The face of all main girders was machined to achieve 95% contact surface.

Pylon kink had the longest machine surface of 32m length and 7m height. The total area of machining was more than 3,500m^2.

Using a computerised controlled jacking system, every segment was positioned accurately in front of the milling machine.

Laser guided optical prism with a tolerance of 0.01mm was used to survey the raw face of segment.

Using this survey and with the reference of previous trial assembly survey, machining tolerance of every segment was computed using a 3D model.

Once the machining was completed, it was again surveyed to confirm its accuracy. Necessary rectifications were done on every machined face to ensure the correct global position of the segment within the tolerances.

More than 850,000 bolts holes were to be drilled within a tolerance of 1-3mm for varying size of bolts. A sequential method of drilling holes was adopted.

Figure 25: Drilling bolt hols using CNC machine

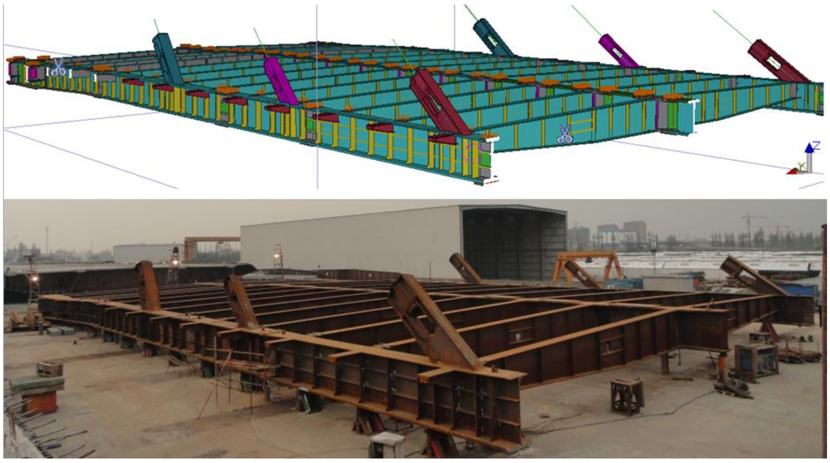


Figure 26: Part of trial assembly of Deck and comparison with digital model

Figure 27: Vertical and Horizontal trial assembly of Pylon leg Segment

Most of the splice plates were drilled using a CNC machine, which were used as a template for match drilling during the trial assembly, to ensure perfect contact of machined surfaces.

More than 12,000 splice plates were used and every splice plate was marked to ensure its correct position and orientation during erection.

5.2.6 Trials assembly & geometry control

To ensure stringent geometrical requirements and the correct orientation of segments during erection, both pylon and deck were assembled in units of 3 or more.

The last unit of the trial assembly was used as a match unit and reference for the next trial assembly. A total of 25 assemblies for deck and 30 for the pylon were conducted.

The results of all individual trial assemblies were digitally superimposed over each other using 3D modelling software, keeping pylon bases as the reference control points.

Anchorages of pylon and deck placed more than 250m apart were to be aligned precisely within a tolerance of +/-5mm. A precise geometry control during trial assembly was a key for the success of the project.

Figure 28: Fabrication and assembly of Pylon main body

Figure 29: Trial assembly of temporary Pylon supports

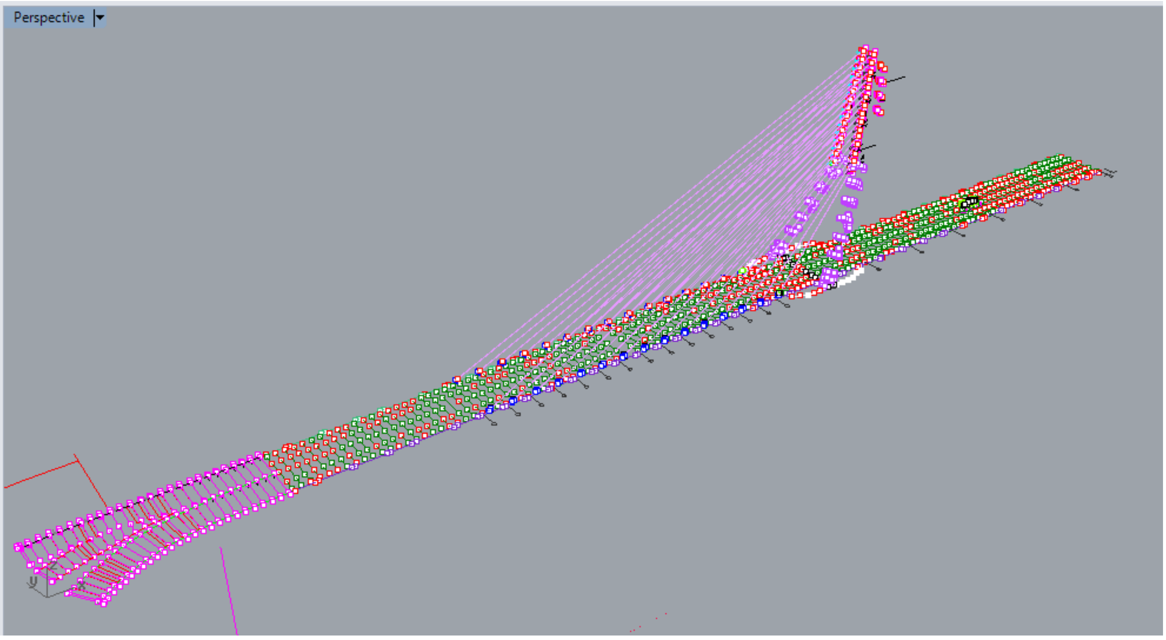


Figure 30: Survey tracking & Geometry control

5.2.7 Blasting and painting

To enhance durability of the structure and to minimise maintenance cost, all the segment of pylon and deck were grit blasted in a controlled environment and then painted with a 3 coat paint system.

Blasting was done in an environment-controlled facility using coppers slag to ensure Sa2.5 surface. The paint system consists of Zinc Epoxy Primer (75microns), High Build Epoxy MIO (100microns) as intermediate coat & Gloss Acrylic Polysiloxane (65 microns) as top coat.

5.2.8 Inspection & Shipping

All the phases of fabrication were inspected by Lloyds, UK, a 3rd party inspecting was conducted through all the segments in accordance with stringent code requirements.

After inspection at the fabrication yard, all segments were loaded on a 10,000t capacity barge.

These barges were transported through inland water ways to Shanghai international port, where the segments were loaded on open deck ship and shipped to Kandla port, Gujarat.

Figures 31 and 32: Blasting and painting

Figure 33: Loading of Segments on Barges at Workshop

Figure 34: Shifting of segments on a geared vessel

Figure 35: Transportation of Pylon base segments

Using geared vessels, the segments were offloaded on to trailers of sufficient capacities and transported on road, travelling a distance of 1,250km.

An advance route survey was conducted from port to erection site identifying all the hurdles in advance.

5.3 Deck erection

Erection of the deck consisted of erection of 13-20m long main girders and 30m long cross girders.

Deck girders were erected using a Goliath gantry with 60t capacity and 40m span, running on the specially designed trestles which were also used to support the girders until the cables were installed.

Pre-cast deck panels were erected over girders using same Goliath gantry for deck erection.

The majority of the deck concrete was in precast panels stitched by cast in situ concrete on top of the main girders and cross beams, except in the highly compressed P19 and P23 locations (Pylon & backstay anchor) where slab thickness was varying from 250mm up to 700mm with 7 layers of reinforcement.

5.4 Pylon Erection

Erection of the pylon was the most challenging part of the project considering its 3-dimensional geometry. Weights of individual pylon segments to be erected varied from 40t to 450t.

It was proposed to preassemble the segments on ground joining individual subunits of a segment through bolted splice joints. Specially designed alignment frames were used to recreate the same geometry achieved during the fabrication and trail assembly.

Figures 36 and 37: Erection of Deck girder using Goliath gantry

This was very important step of the process to ensure the basic design requirements, i.e. to achieve a perfect contact of the machined surfaces.

Once the segments were assembled they were placed on a specially designed turntable to rotate the segment in its predetermined final 3-dimensional erection geometry.

A careful monitoring of the geometry throughout construction was made to track structural behaviour, as predicted during the erection stage analysis.

5.5 Turntable

The final erection geometry for all segments of pylon legs, kink and main body was studied to understand the different 3-dimensional angles to be achieved during erection.

Based on the outcome, a turntable was developed and designed which would be used to rotate all the segments to its precise 3-dimensional erection geometry.

The turntable consisted of two beams placed one above the other. Once the segment was placed on the turntable, the first angle of rotation in longitudinal direction was achieved by lifting the beam at one end by crane and installing a predefined length of strut, while the other end hinged to the ground.

The second angle of rotation was achieved by lifting the upper beam and adding small struts between the two beams on one side and hinges with the beams on other side.

By changing the length of longitudinal and transverse struts, rotation for both mirror axes was achieved. A rigging plan was developed based on the rotated position of the segment, lifted with 3-4 slings of predefined length and capacity.

The segments were then erected using a 1,250t crawler crane. Specially designed alignment tools were used to ensure precise alignment of machined surfaces.

Sufficient strengthening of ground for movement of 1,250t crane was done.

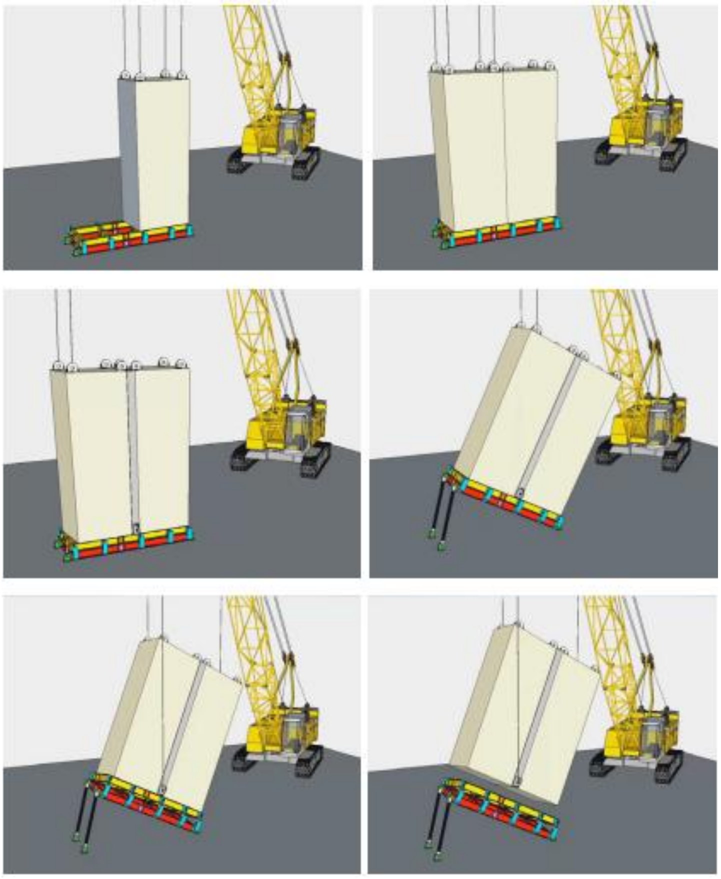


Figure 38: Sequence of assembly and rotation of a segment

Figure 39: Rigging of a typical leg Segment

Figure 40: Rigging of a typical Main Body Segment

Every stage of erection was studied, considering the progress at a given stage of erection. Using 3D software the exact location of crane, boom height, its angle, its movement, clashes with erected structures, etc. were checked and predefined to ensure uninterrupted erection.

As the height of the pylon increased, the crane configuration was also changed based on its technical specification and load chart.

5.6 Geometry Control

A careful monitoring of the geometry throughout construction was conducted to ensure that the structure behaved as predicted and the target geometry was met.

Since many of the quantities involved in the construction were only approximate values (exact elements dimensions and weight) or could be

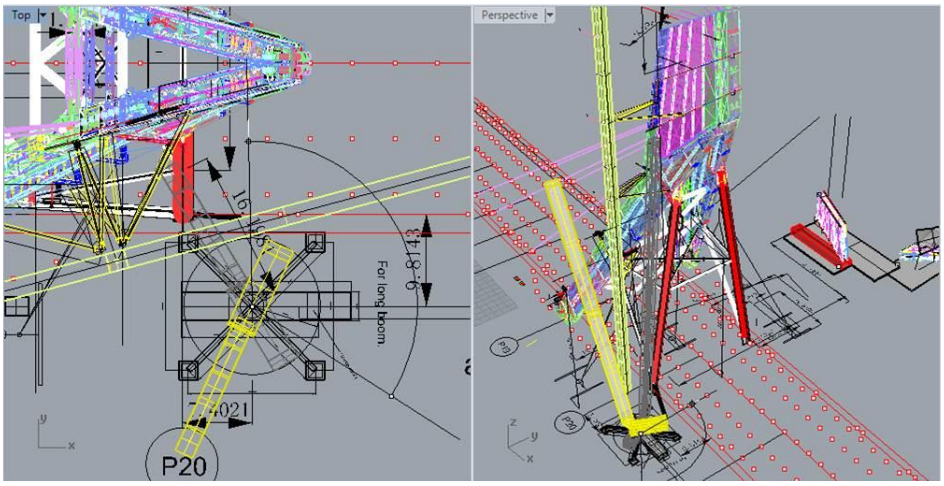


Fig.41: Checking of erection procedure at every stage

measured with a given tolerance (stay cable lengths and forces) and environmental conditions change during construction, and the calculation model itself was only an approximation of the real structure, a continuous monitoring of structural deformation during the construction was of fundamental importance.

For this reason, the structural geometry was checked after installation of every element and a daily survey procedure was started at the beginning of stay cable stressing.

5.7 Temperature effect

The pylon was very flexible, especially the legs which were leaning in a 3-dimensional plane for 90m height.

A supporting structure was detailed with a bolted connection to ensure correct geometry and perfect matching of segment at the pylon kink where two legs merge.

Deflections of the pylon were worked out based on its weight, but it was susceptible to differential temperature movement which made it difficult to align all bolt holes.

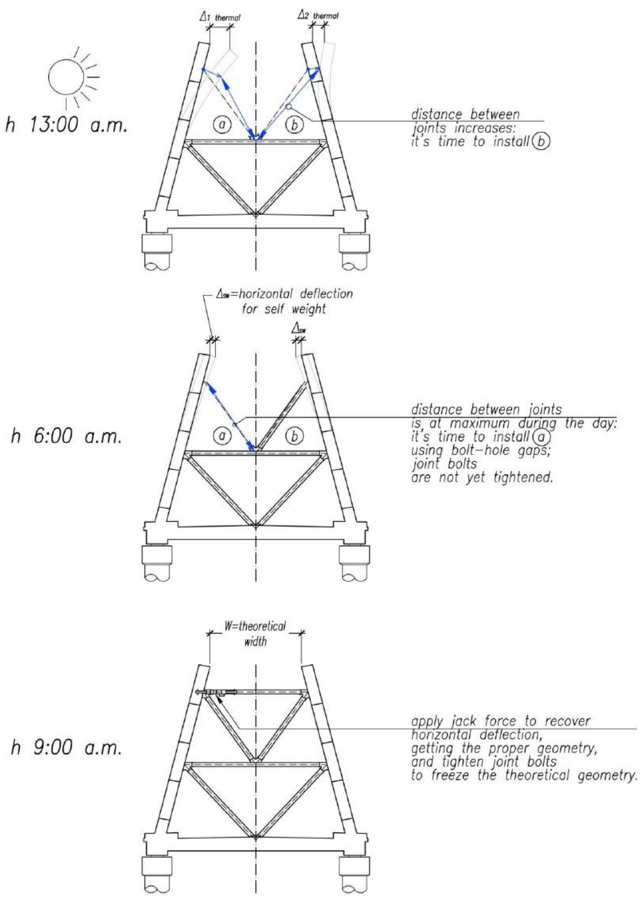
The Pylon position changed rapidly during the day, with movements around 20mm in longitudinal and vertical direction and up to 40mm in transverse direction.

A periodic survey was conducted to monitor the movement of the pylon through the day. Based on the movements, the erection sequence was planned for a specific time of a day, taking full advantage of the movement, which once caused difficulties in Erection.

6. STRESSING OF STAY CABLES

The two independent legs of the pylon were supported on temporary supports until they met at a height of 90m at the pylon kink.

Above the kink, pylon main body and cable installation was followed in a well-defined and sequential process.



Figures 42 and 43: Temperature affecting the erection

Figures 44: Cable installation & tensioning

This was a key stage of erection, when the load of the pylon was transferred from temporary supports over the cables.

While monitoring the effects of construction loadings, element loadings and cable stressing on deformation of pylon & decks, correction factors for the environmental effects had to be applied.

The stay cable system consists of 15 pairs of front cables supporting the unsupported deck of 251m & 4 pairs of back stay cable balancing the weight of pylon and deck.

Stay cables are made up of parallel strands of numbers varying from minimum 55 to maximum of 127 of 15.70mm dia. with tensile strength of 1,860Mpa. Lengths of the cables varied from 85m to 285m.

The fixed anchors were located at deck level, while the stressing was done through anchors located in pylon main body.

Predefined lengths of cable were cut well in advance, based on the theoretical length worked out during the erection stage analysis. HDPE pipe were welded based on these lengths, then erected with tower crane and secured in position using a winch.

After the erection of every main body segment, a complete topographical survey was conducted to understand the anchor positions at that particular point of time.

Based on the survey results, final lengths of the strands were worked out before the strands were installed through the HEPD pipe. The strands were threaded through the dampers using a winch located in the pylon.

An iso – elongation method of stressing was adopted in a sequential process to ensure all the strands in a cable are stressed to uniform loads.

One load cell was installed in every cable to monitor the variation in loads after every erection stage. Final stressing of every cable was achieved in 2-3 stages depending its load and position.

Every stressing stage was further divided with first 80% of stress followed by a topographic survey to check stress in cable and movement of pylon and deck.

After comparing results with theoretical values, correction was made if required before the remaining 20% of stressing was done.

7. CONCLUSION

Signature Bridge was completed and inaugurated on 4th November 2018. On its completion, the new icon of Delhi stands tall above all structure of its kind and claims to be the tallest unsymmetrical steel cable stayed bridge in the India.

Such projects not only help in merging boundaries by bringing together experts from various corners of the globe, but also contribute in constantly raising the local construction standards through knowledge sharing.

India, being an emerging country with tremendous potential for growth in infrastructure sector, would benefit from such ventures, setting new standards for steel bridges in India.

8. ACKNOWLEDGEMENTS

- Owner: Delhi Tourism and Transportation Development Corporation (DTTDC)
- Designer for Owner: JV of Schlaich Bergermann und Partner, Germany for Superstructure and Construma – Delhi for foundations and substructure
- Architect: Ratan J Batliboi Architects, Mumbai
- Contractor: JV of Gammon - Construtora Cidade, Brazil - Tensacciai, Italy
- Consultant for Contractor and Construction Engineering: DMA - Studio de Miranda Associati - Milan – Italy

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[4] Swapnil A. Navalkar, *"Signature Bridge", setting a new trend for steel bridges in India,* International seminar on "Emerging Trends in Transportation Structures" organized by Indian Institution of Bridge Engineers, Mumbai, Nov 2012.

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[8] Swapnil A. Navalkar, *Construction Engineering for Signature Cable Stayed Bridge at Delhi,* India Institute of Bridge engineers and Bihar Rajya Pul Nigan Ltd., "Revolution in transportation infrastructure: Vision 2030", June 2019.

CONSTRUCTION PHOTOS

Construction of Open foundation under Pylon – P19

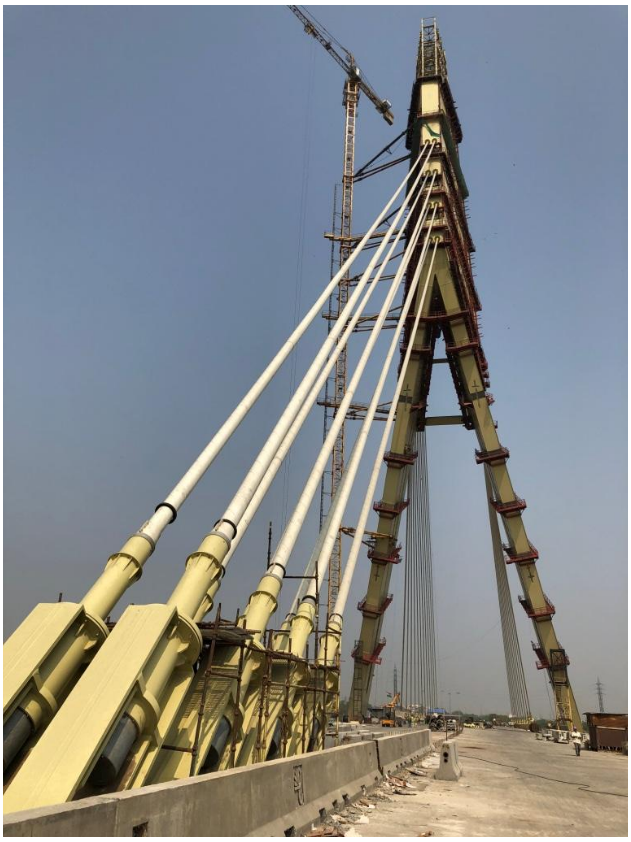
Construction of Open foundation under Pylon – P19

Construction of well foundation at back Stay – P23

Construction of well foundation at back Stay – P23

Temporary Structure supporting Pylon

Erection of Pylon at various stages



Pendulum Bearing & Back stay cable on completion

Erection of final pylon segment and Pylon Head

Pylon Graphics and View form Pylon head

STAY-CABLE SYSTEM
ON THE SIGNATURE BRIDGE

Andrea Castiglioni di Caronno, Tommaso Ciccone, Tensa

Figure 1: Side view of the Signature Bridge during construction

The Signature Bridge in Delhi is a cantilever spar cable-stayed bridge that connects Wazirabad to East Delhi, spanning over the Yamuna River.

From a structural point of view, this type of asymmetrical cable-stayed bridge exploits the inclination and the weight of the pylon to balance the deck permanent load and to decrease the overturning force on the pylon footing.

This peculiarity is usually absent in traditional cable-stayed bridges, in which the vertical pylon behaves as a cantilever subjected to the balanced force of stay cables.

The Signature Bridge is 675m long and 35.2m wide, with a dual four-lane carriageway. It has a 251m long main span and a 165m high pylon equipped with a lifting system to access the panoramic box located at 154m away from the ground.

The Y-shaped pylon has two legs rigidly connected to the deck. Front stay cables are combined into two planes with a semi-harp arrangement.

The two planes of the closely spaced back stays are combined into a radial arrangement running over the midplane of the deck superstructure.

The structural design of the bridge was assigned to Schlaich Bergermann Partner while construction was undertaken by a Joint Venture composed of Gammon India, Tensacciai and Construtora Cidade.

The stay cable system is one of the most iconic elements of the Signature Bridge. It is made of parallel strands with 15.7mm nominal diameter and a grade of 1860 MPa.

Strands were individually hot-dip galvanized, waxed and HDPE coated to ensure the highest standard in terms of corrosion protection.

In addition, the strand bundle is encased in a lightly coloured external HDPE duct, provided with double helical ribs on the outer surface to counteract rain-wind induced vibration phenomena.

Four types of stay cables systems – 127TSR, 91TSR, 73TSR, 55TSR – are used in the front stays that range from a length of 86m to 290m, with a spacing equal to 13.5m measured on the deck.

Figure 2: Front view of the spar with front stays

On the contrary, all the backstays are of the same type – 127TSR – and have lengths ranging from 130m to 150m.

The total amount of strands used for erecting the stay cables is approximately 700 tonnes.

All stay cables are equipped with a fixed anchorage at the deck side. An adjustable anchorage is used at the pylon side, where strands protrude from the anchor head with long tails that permit strand-by-strand restressing and replacement in the future.

The external stay pipe is provided with a special slider system at the bottom side that eases the connection of the duct to the lower anchorage structure.

This solution allows the duct to follow the actual cable catenary without the risk of mismatching on the fixing system, which might be caused by out-of-axis and installation tolerances unavoidable on long stay cables.

The bridge deck was built on temporary supports regularly spaced beneath its whole extension. At the same time, the two legs of the spar were erected and provisionally linked through a transverse member. Then, the pylon was built by gradually installing a few segments until reaching the top.

The segmental erection of the spar was accompanied by the gradual installation of stay cables to stabilize the tower and progressively lift the deck from its temporary supports.

The stay cable system suitability for the project was assessed through a full-scale fatigue and tensile test over a 52-strand cable at the EMPA laboratory in Zurich (Switzerland), this being the largest stay cable size that the rig allowed to test.

During the fatigue test, 2-million load cycles with a maximum force equal to 45% GUTS, a stress range of 200 MPa, and a static deviation at anchorage of 10 mrad were carried out, and no wire failure occurred.

In the subsequent tensile test, a maximum force of approximately 98% GUTS and an ultimate elongation of 2.2% were reached.

The stay cable system fully met the acceptance criteria stated by International Recommendations on testing of stay cables.

← Figure 3: Adjustable anchorage

↑ Figure 4: Bottom connection with special slider system

Figure 5: Full-scale testing set-up

Figure 6: Deck temporary support

Stay cables preparation was entirely carried out over the bridge deck. Cutting benches were laid on the ground to produce a cutting line for the longest stay cable to be installed.

Based on the actual plate-to-plate length, measured by a topographic survey on site after each new segment of the pylon was erected, the relevant stay cables were prepared to their final length.

At the same, the HDPE stay pipes were welded and equipped for lifting. The installation of each pair of front stay cables, i.e. upstream and downstream cable, respectively, took place consecutively to load both the deck and the pylon as uniformly as possible.

In general terms, the stressing operation was undertaken in a number of stressing phases: two for the front stay cables, and three phases for the backstays.

Then, each phase was furtherly split up into two stressing steps.

Figure 7: Strand cutting line

Figure 8: Front stay pipe hoisting

Figure 9: Backstay pipe hoisting

A load equal to 80% of the targeted load was applied in the first step of the phase, while the final load envisaged for the stressing phase, i.e. 100%, was reached at the end of the second step.

The subdivision of each phase into successive steps was aimed to verify the bridge construction model and, subsequently, to have better control of the bridge behaviour during loading.

Four main stages may be outlined for installing each stay cable: hoisting of the HDPE pipe, strand threading, strand stressing, and stay cable finishing.

Due to the length of stay cables, the hoisting of the duct was carried out through the main tower crane to reach the top anchorage with the upper end of the stay pipe.

Then, the bottom end was moved towards the bottom connection through a forklift. In this way, the stay pipe sag was recovered, and the duct aligned with the anchorages to start threading.

Threading was performed by using a winch fixed inside the bridge pylon and, more precisely, just above the top anchorage of the stay cable to be installed.

The winch rope was then passed throughout the adjustable anchorage by means of a system of pulleys and then released throughout the HDPE stay duct until reaching the bottom anchorage.

Here, the rope tip was connected to the strand by means of a special coupling device and, subsequently, lifted.

Once the strand reached the top anchorage it was locked off by installing the wedge, and as soon as the same operation was completed at the bottom side, it was stressed to the force required by means of a monostrand hydraulic jack.

Figure 10: Signature Bridge deck and stay cables during erection

Once threading of the stay cable was completed, all the strand bundle was tuned to the same final force required at the end of the first stressing phase (strand tuning).

The second stressing phase took place after the completion of the installation of all the bridge stay cables. Again, two stressing steps were carried out for detaching the deck from its temporary supports.

All the stay cables were equipped with a mono-strand load cell to monitor the load during construction and, subsequently, to adjust the stressing load of the successive phases based on the actual response of the bridge during loading.

Additionally, the stay cable tensions were cross-checked indirectly, by measuring the cables catenary, and directly, by carrying out periodic lift-off tests on some strands of each stay cable.

The measurement of the force was very rough, due to the difficulty of targeting the ideal axis of the stay cable through a topographic measurement, however, the values of forces showed a good agreement to the ones measured by lift-off and load cells, with maximum errors in the order of 10%.

After the stressing operations were completed, the finishing phase took place. Fire-resistant blankets were installed on all the backstays, up to a vertical height of about 12m, and then covered by means of an anti-vandalism pipe made of several steel shells.

A protective wax was injected under a small pressure to fill up all the protection caps and anchorage wax boxes, where the strand coating is removed to allow the wedge to grip.

The wax represents a continuous and leak-tight barrier that avoids the ingress of water and protects the surface of strands from corroding.

The Signature Bridge, with its elegant stay cable fan layout, represents an iconic result of bridge engineering.

It involves some of the most advanced technologies available in this field as well as the know-how of an international team of specialized and experienced companies.

Figure 11: Fire protection over backstays

Figure 12: Front view of the Signature Bridge

BEARINGS FOR YAMUNA SIGNATURE BRIDGE

Dipl.-Ing. (FH) Peter Günther, Technical Sales Director, Maurer

Figure 1: Fabrication of the MAURER MSM® Spherical Bearing

MAURER supplied MAURER MSM® Spherical Bearings, MSM® Shear Keys and Pendulum Bearings for the Signature Bridge in Delhi, India.

MAURER MSM® Spherical Bearing at the pylon base

The pylon in axis 19 rests on two, at this time the largest CE-marked spherical bearings worldwide.

On the load side, not only the magnitude of the vertical load N_{sd} = 230,850kN challenged the bearing design and production; in addition, it is the relatively high ratio of permanent and horizontal loads.

These loads caused by the pylon weight defined the huge outer dimensions of the fixed MAURER MSM® Spherical Bearings up to 3.1m x 3.0m and its weight of 26 tons.

Load transfer

The pylon of the Signature Bridge is unique. The inclination and the self-weight of the pylon require the hinges at the monolithic pylon base to handle the loads and get the horizontal forces balanced at the bridge deck.

The chart below provides specification of the ULS Loads, Figure 2.

The bearings were specified according to DIN EN 1337. Only the MAURER MSM® Spherical Bearing has got an ETA-06/0131 approval allowing for the usage of the MSM® special sliding material up to a diameter of 2.5m.

This permission was necessary to get the specified CE mark on the finished products.

ULS Loads

$maxN_{Sd}$=	230850	kN	$V_{x,Sd}$=	6000	kN	$V_{y,Sd}$=	23250	kN
$minN_{Sd}$=	97150	kN	$V_{x,Sd}$=	6000	kN	$V_{y,Sd}$=	23250	kN
Earthquake			$V_{x,Sd}$=	1800	kN	$V_{y,Sd}$=	36600	kN

Figure 2: ULS Loads specification for the spherical bearing

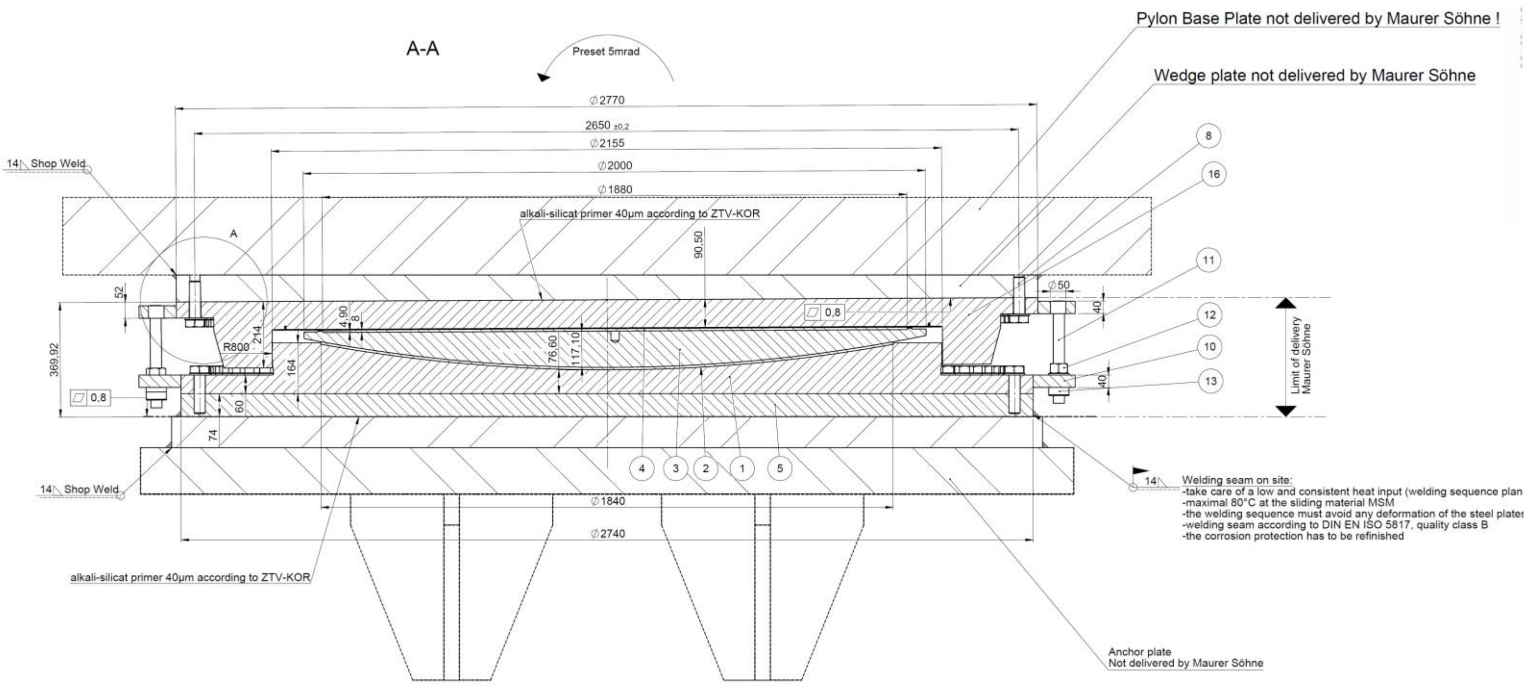


Figure 3: Elevation View of the spherical bearing

Figures 4 and 5: Fabrication and transport of the bearings

Temporary sliding area

The pylon was erected on the MAURER MSM® Spherical Bearings. Segment on segment was placed until the pylon had reached its final height of 154m.

If both bearings worked as fully fixed bearings, the incremental increase of the weight would apply extreme lateral forces to the bearings by pressure.

It was necessary to find sufficient space for the special sliding material under the pylon base.

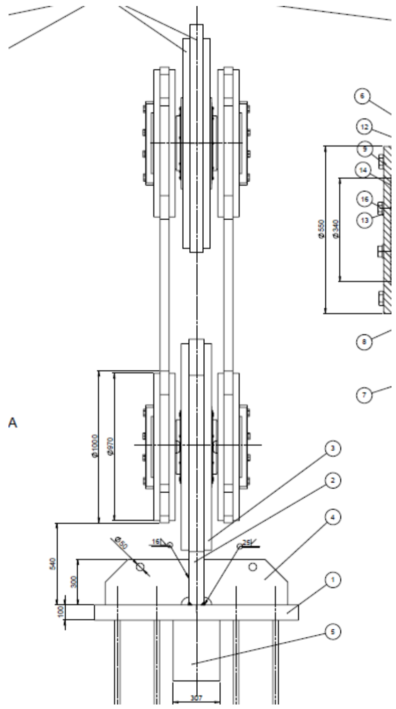
To avoid the extreme transversal pressure, one of the bearings was equipped with a temporary sliding area to allow for lateral deformation of the base during erection.

After the erection, the temporary sliding area was blocked by a fixation absorbing certain tolerances of the lateral deformation.

PENDULUM (ROCKER) BEARINGS FOR BACKSTAY CABLES

Four pairs of rocker bearings at axis 23 transfer the tension loads of the backstay cables to the foundation. N_{sd} = 2 x -27,500kN = -35,000kN tension forces apply to each pair of rocker bearings.

The movement and rotation are accommodated by large INA spherical plain bearings installed inside the eye plate of the deck and the anchorage, from the anchorage by DSI anchors Ø 36mm to the foundation.



Figures 6 and 7: Pendulum Bearings

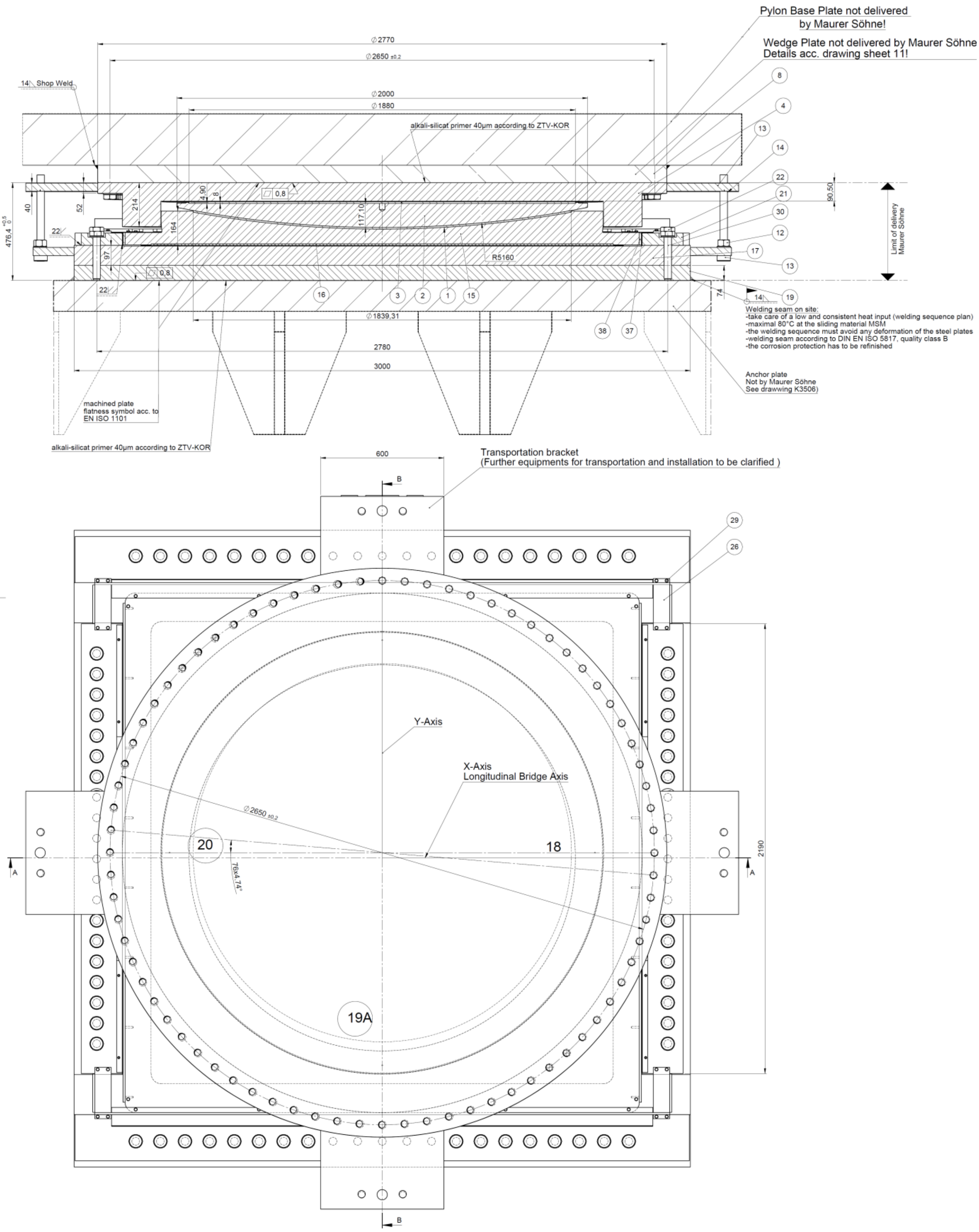
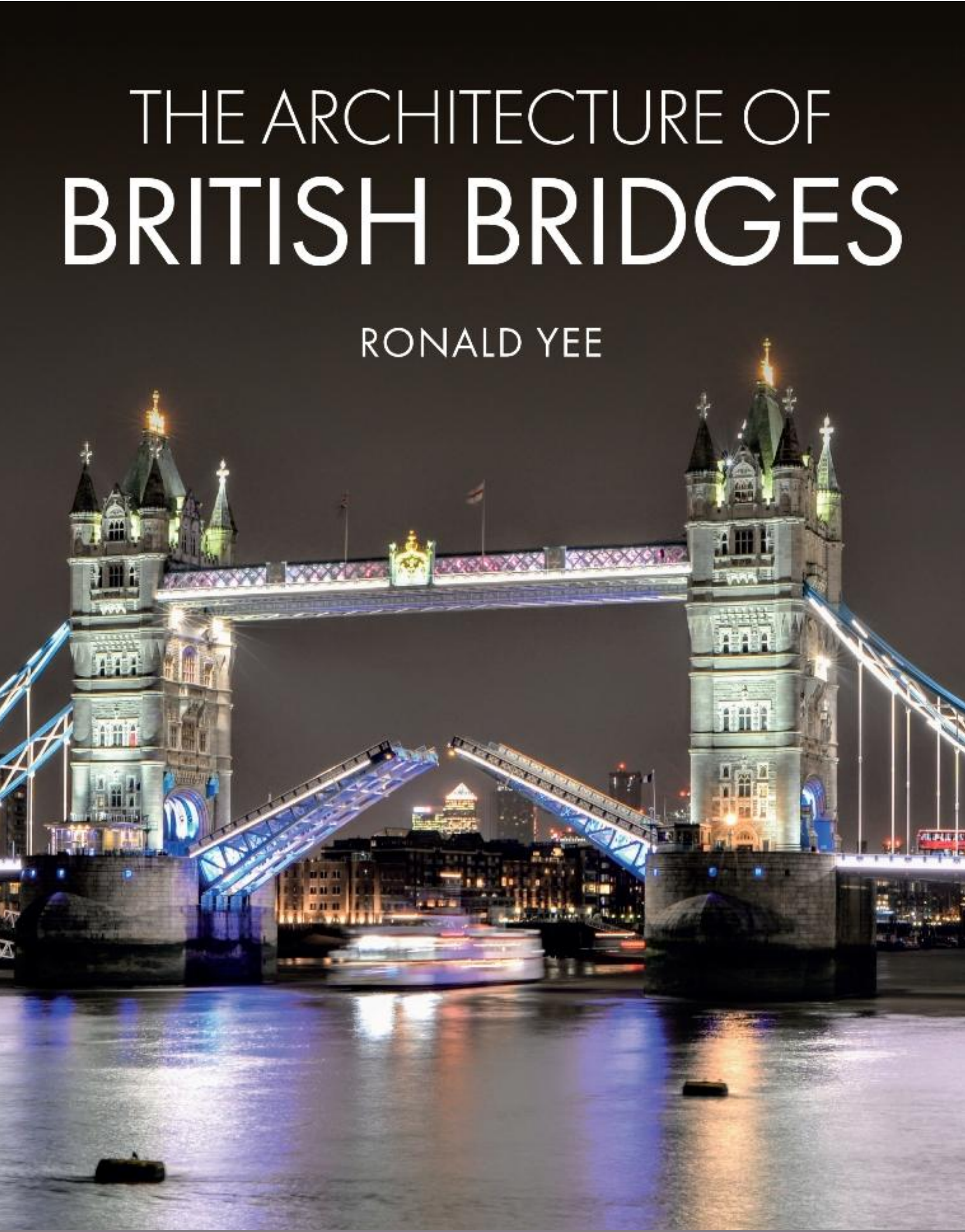


Figure 8: Elevation and Plan of the Bearing with specifications for transport



In 2021 Crowood Press published a book by Ronald Yee "The Architecture of British Bridges". This book starts with the notion of bridge architecture being more than just engineering design. It then traces the development of British bridges by construction material: stone, timber, brick, iron and steel, finishing with the contemporary use of concrete and advanced composite construction. The remaining chapters cover moving bridges, bridge parapets and bridge lighting as separate subjects.

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Assoc. Prof. Pavel Ryjáček

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Pavel Ryjáček, Organising Committee Chair, Czech Republic

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The Scientific Committee also invites for proposals for 'Special Sessions'.
The theme of a Special Session should be in alignment with the themes and topics of the Symposium. However, Special Session Proposals with significant contribution to the objectives of IABSE will be considered. If approved, the session objective text will be made available in the Prague IABSE Symposium website.

- Deadline for Special Session Proposal: **April 12, 2021**
- Notifications of Special Session Acceptance: **April 16, 2021**
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After approval of the Special Session Proposal, the session organiser(s) must send a list with a minimum of 5 papers with its corresponding titles and author(s), to iabse2022prague@c-in.eu ➔ until the **May 15, 2021**. The abstracts for the papers must be submitted before the deadline for abstract submission.

Session organiser(s) will be provided with a certificate attesting the organisation of the Special Session.
Read the rules for Special Session Proposals here ➔

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- New and innovative materials, technologies and structural solutions
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In case of any questions, please feel free to contact us at any time ➔

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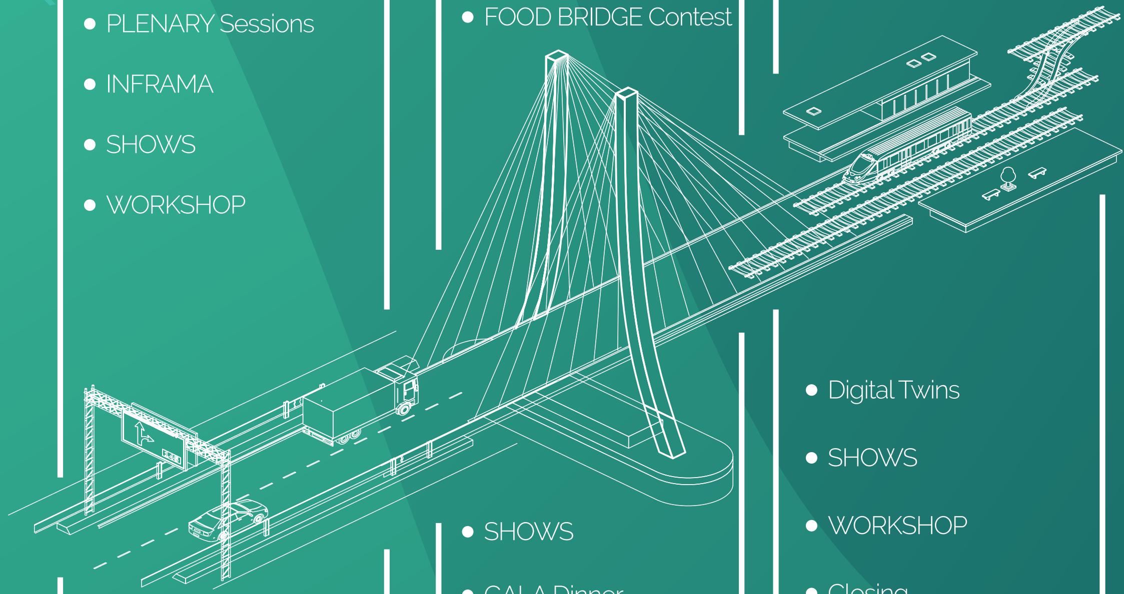

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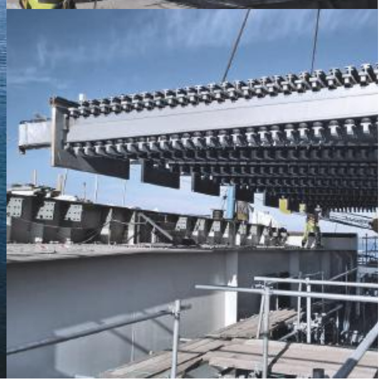

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References:

- 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
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Naeem Hussain
naeem.hussain@arup.com

Global

Richard Hornby
richard.hornby@arup.com

UK, Middle East & Africa

Steve Kite
steve.kite@arup.com

East Asia

Deepak Jayaram
deepak.jayaram@arup.com

UK, Middle East, India and Africa

Peter Burnton
peter.burnton@arup.com

Australasia

Marcos Sanchez
marcos.sanchez@arup.com

Europe

Matt Carter
matt.carter@arup.com

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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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