CONSTRUCTION OF AN ICONIC SIGNATURE BRIDGE IN DELHI

Conference Paper · October 2021

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CONSTRUCTION OF AN ICONIC SIGNATURE BRIDGE IN DELHI

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Abstract

The presently under construction at Delhi over river Yamuna Signature Bridge is an iconic bridge of its kind which is languid in perpetual motion to the onlookers where nationals from ten countries were involved as such the project is truly an international structure.

The very complex geometry of the slanted steel pylon of 151 m height meant to be twice the height of Qutub minar is around 675 m having cable stayed span of 251 m, flanked with approach spans on either side of the main bridge. The bridge has a dual carriage way of 4 lanes each with 1.2 m, central verge for anchoring cables and accommodating maintenance walk way, crash barrier etc. The total width of the deck is 36 meters. The steel composite deck being integrated with pylon is supported on spherical bearings of the capacity of 17000 KN while eight numbers of backstays are anchored to a specially designed pendulum bearings which can take the uplift to the tune of 6000 KN which in turn is anchored to a hybrid foundation of caisson and piles.

The unprecedented nature of design of foundations, bearings and the pylon called for ingenious and first time construction engineering & methodology to be evolved whether for hybrid foundations, concrete technology, erection of large capacity & special type of bearings, fabrication, trial assemblies, welding including very long & critical in situ welding of pylon base & finally segmental erection of three dimensionally varying pylon.

While critical foundation, substructure including bearings & concrete technology are covered in separate papers in the same congress, the complex construction engineering has been captured in detail in this paper.

Keywords: Back stay anchorages, Cable stay, Slanted Pylon. Composite deck, Segmental Erection, Iconic structure.

i. Introduction

The conception of new 8-lane bridge across river Yamuna 600m downstream of the existing barrage cum bridge at Wazirabad, Delhi was a culminated decision of Delhi government for making a landmark structure in Delhi and to develop the surrounding area. This necessitated the development of approaches (Western as well as Eastern) on both sides of conceived Signature Bridge (Fig. 1). Western & Eastern approaches as shown in the Fig.1 was a separate contract (depicted as 1) from that of main Signature Bridge contract (depicted as 2).

On Western side, grade separators comprised of flyovers, loops and ramps was constructed to ensure signal free traffic movement at the proposed intersection of bridge with Road No.45 and existing intersection at Timarpur, Nehru Vihar and Wazirabad. Road widening, construction of footpath, storm water drains, cycle track and subways were also part of Western approach into a Tourist Destination. Eastern approach included construction of Embankment of about 2.0 Km length, river training work, river protection works, widening of existing roads, construction of roads, footpath, cycle track, storm water drain etc. In addition, 6 lane flyover was also constructed at Khajuri Khas intersection with rotary at ground level to ensure signal free movement,

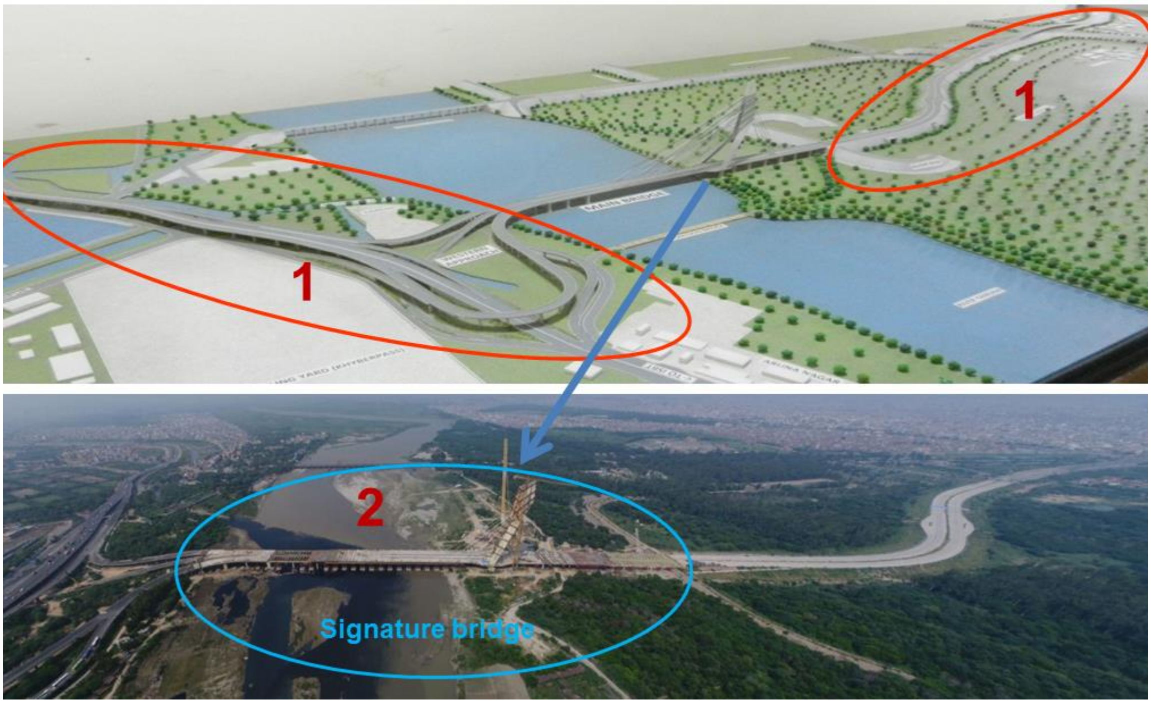

Fig.1 General arrangement of approaches and main bridge

Infrastructure plays a significant role in the economic growth for a rapidly developing country like India. In last 3 decades, longest, tallest, biggest many iconic bridges have been built in China. However, recent appetite for iconic status among the rulers clubbed with huge investments in infrastructure has given rise to an exciting time ahead for bridge builders and it looks like the next 3 decades belong to India. It is not necessary that a bridge has to be longest, tallest, etc. to be iconic, but when the identity of the surroundings are known by the bridge and development start taking place around, the bridge attains its iconic status. Signature Bridge at Delhi is envisioned to be one of such bridges.

ii. Conceptualisation of Iconic structure

The area under the bridge is envisioned to be developed later as a park and the Yamuna river is to be converted in to lake like dimensions with river channelization to enable boating facilities and other tourist attractions. So the conception and design of iconic structure that can enhance the character of tourist attraction was entrusted to the team of Architect Ratan J Batliboi, structural designers Slaich Bergermann Partners & Construma by the client DTTDC.

With the above context at hand, during innumerable brainstorming sessions numerous long span light weighted cable stay bridges were evolved. The challenge was not only to conceive a bridge that is iconic, but also having a form following the flow of forces thereby being in harmony with structural engineering concepts at the same time symbolising local culture or tradition or character.

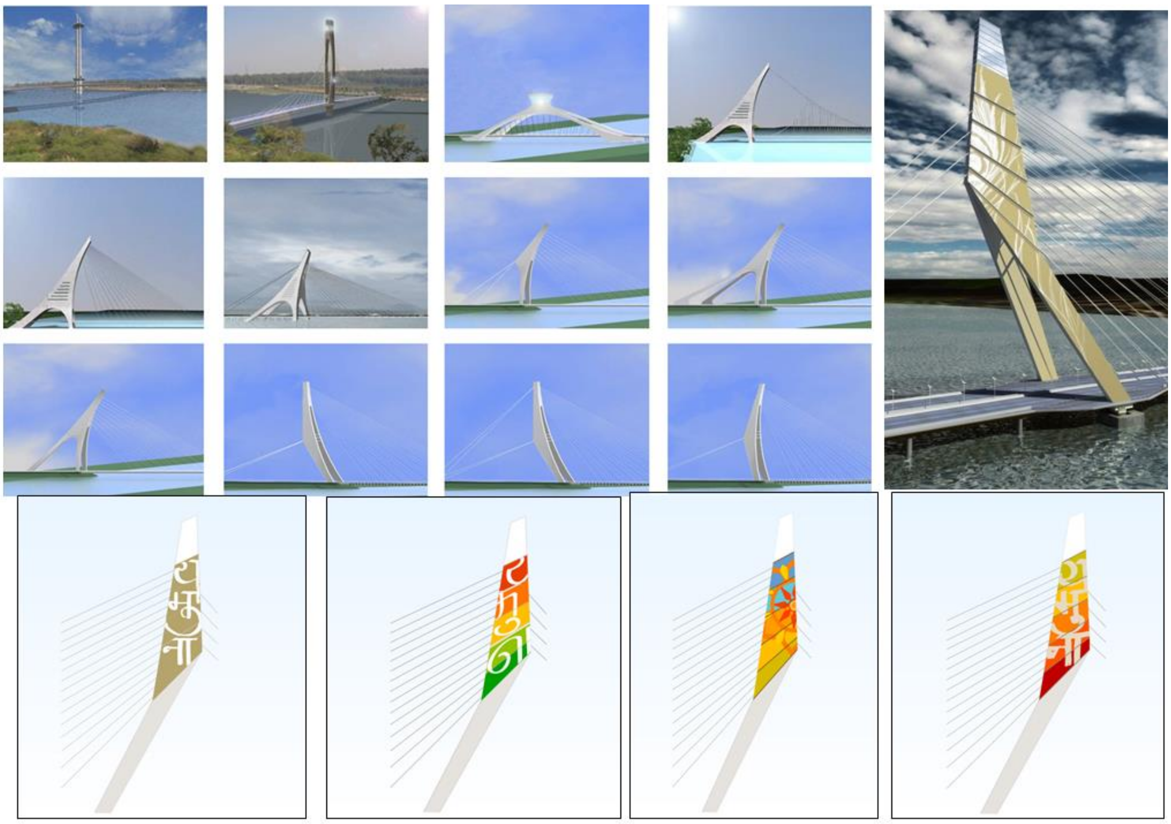

Fig .2 Concept evolution

During the phase of convergence (Fig.2) many options were tested with the fundamental principles enumerated above being in kept in mind before arriving at a solution which is almost twice the height of Delhi's another heritage structure Qutub Minar. There are two more bridges Alamillo and Erasmus of the magnitude of Signature Bridge at Delhi having closer resemblance with peculiar slanted Pylons.

Graphics on the bridge structure, particularly on the Pylon is perhaps featured first time in the world. Once again the pattern chosen was not only to symbolise Indian culture but also to reflect modern and progressive India. After having evaluated various options, peacock's feather was zeroed in as an appropriate emblem on the Pylon

iii. Description of the Iconic structure

Signature Bridge is an elaborated cantilever spar cable-stayed bridge (Fig.3), comprising of an asymmetrical inclined Namaste shaped Steel Pylon of 154 m height. Total length of the cable stayed bridge from expansion joint to expansion joint is 575 meters, with main cable-stayed span of 251 meters supported with 15 sets of cables on one side and counterbalanced by 4 sets back stay cables attached at a rocker bearing on axis 23. The bridge steel and concrete composite deck has dual carriageway of 4 lanes (14 m) each with about 1.2 m. central verge, space for anchoring cables, maintenance walkway and crash barrier on either side of central verge. The outer to outer width of the bridge is 35.20m, the approach spans are about 36 m long. Spherical bearings are provided on all the piers. Pendulum bearings are provided for back stays.

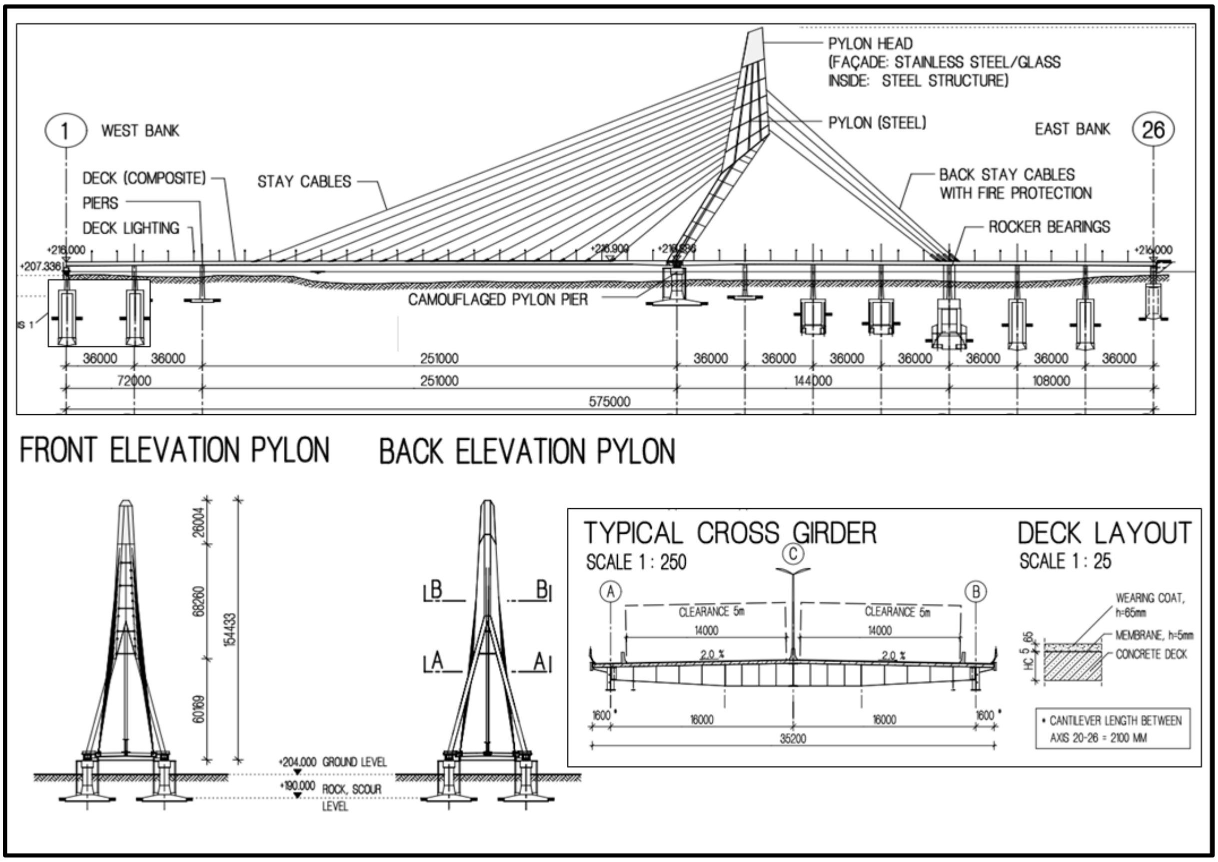

Fig. 3.General arrangement of Signature Bridge

The Steel Pylon of around 154 meters 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, stiffened by internal stiffeners and bracings, where the cables supporting the main span and the back stays are anchored to deck. Each of the pylon legs consists of hollow steel boxes which are roughly 50 – 80 meters high. The upper end is the kink diaphragm which is the transition from pylon leg to the pylon body.

It also has a pylon head, made up of beams and columns in steel structure with a glass cladding. Major part of the steel for pylon is of grade S355. In very highly stressed anchorage zones, S460 grade steel is used. Each leg of Pylon rests on spherical bearings to transmit vertical loads of more than 17,000t.

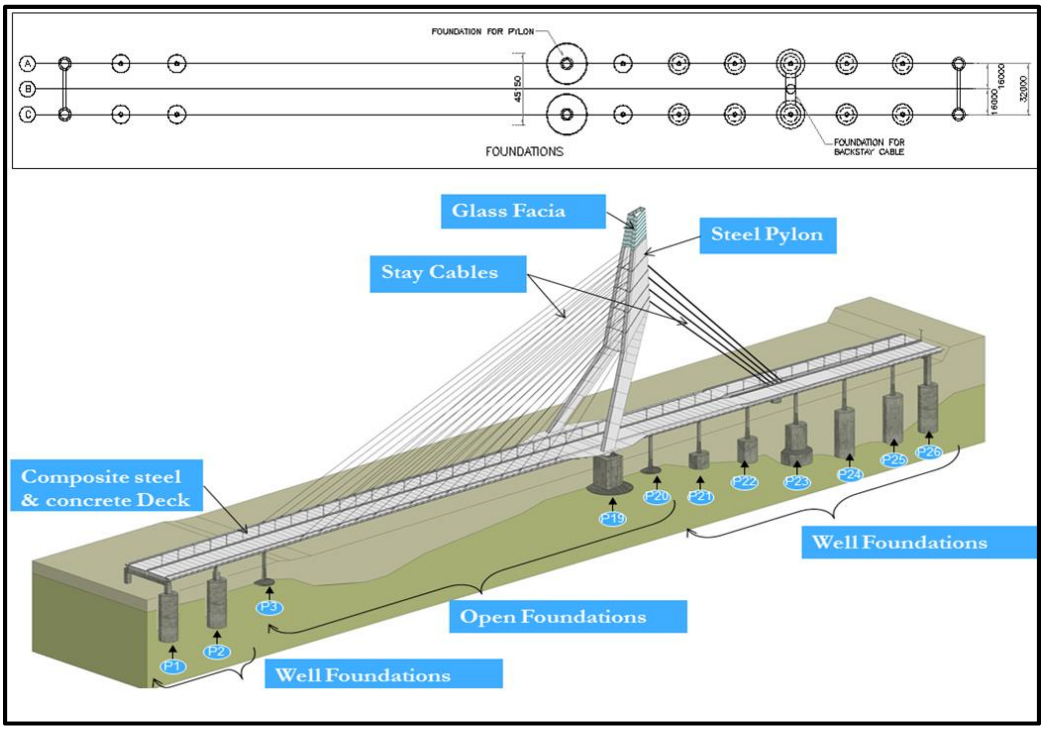

Fig. 4.Details of the foundations

The deck spans 32 m in transverse direction for 8 lanes of traffic, 4 lanes in each 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 of 13.5 m long on the cable supported part, 36 m on the approach spans which are supported over concrete columns. Most part of the deck slab is made up of full depth prefabricated concrete elements of varying thickness from 250 to 350 mm, stitched in-situ over steel girder flanges. In highly stressed areas, near pylon base and backstay anchorage, in-situ concrete up to 700mm thick is used.

The cables are made up of bundles of parallel 15.70mm strands of class 1770 Mpa, protected against corrosion with hot dip galvanization and outer PE-pipes. 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 backstay.

Under the axis A and C, the independent foundations are provided up to the depth of 20m below ground level as generally rocky stratum was geo technically determined at that level.

There are 6 numbers of open foundations (Fig.4) resting on rocky strata at a depth of about 20 m. The diameter of the main Pylon P19 foundation (2 nos.) is 23 m with Pier dia. of 5.5 m and that of lateral spans having foundations at P20 & P3 (2 nos. each) is 7 m with Pier diameter of 2 m. The remaining 16 numbers are well foundations with the varying diameters of 8 to 9m while back stay foundation P23 has hybrid foundation which is a combination of piles and wells with the tapering well dia. from 17m to 15.50m.

The design and construction aspects of special foundations including substructure and bearings are covered in detail in separate papers in the same congress.

iv. Construction Engineering

In an item rate contract like Signature bridge, starting from the final design, the bridge has to be constructed based on a system of detailed construction design called Construction Engineering (CE), which is the complex activity aimed to define and design the entire construction process as well as the construction of structures and equipment needed to build the bridge. The importance of Construction Engineering increases proportionally with the size and complexity of bridge. While the Final Design assumes that the bridge is a completed single structure, Construction Engineering must take into account the evolution of bridge construction and the numerous intermediate partial structures that arise grow and evolve during construction. The number of drawings required by CE is much larger than the number of drawings that define the final structure, and the designing work for large structures, is also greater. Signature Bridge, because of its large size and the unusual shape of its tower, required a challenging CE and many interesting problems as illustrated below.

a. Assessment of fabrication complexity

Construction of super structure involved fabrication and erection of about 14500t of structural steel for permanent deck and pylon and around 17000t for temporary and enabling structures. The distinct characteristic of Signature Bridge is its Pylon integrated with the composite deck and hinged at pier top level. The pylon with its harp shaped body, leaning backwards, would be the most unstable structure during construction stage. During construction engineering phase a detailed step by step erection methodology was developed to understand the behaviours of the structure at various stages of erection. Analysis of structure under various erection loads including temporary structure was performed to understand probable strengthening required to the structure during fabrication and erection stage.

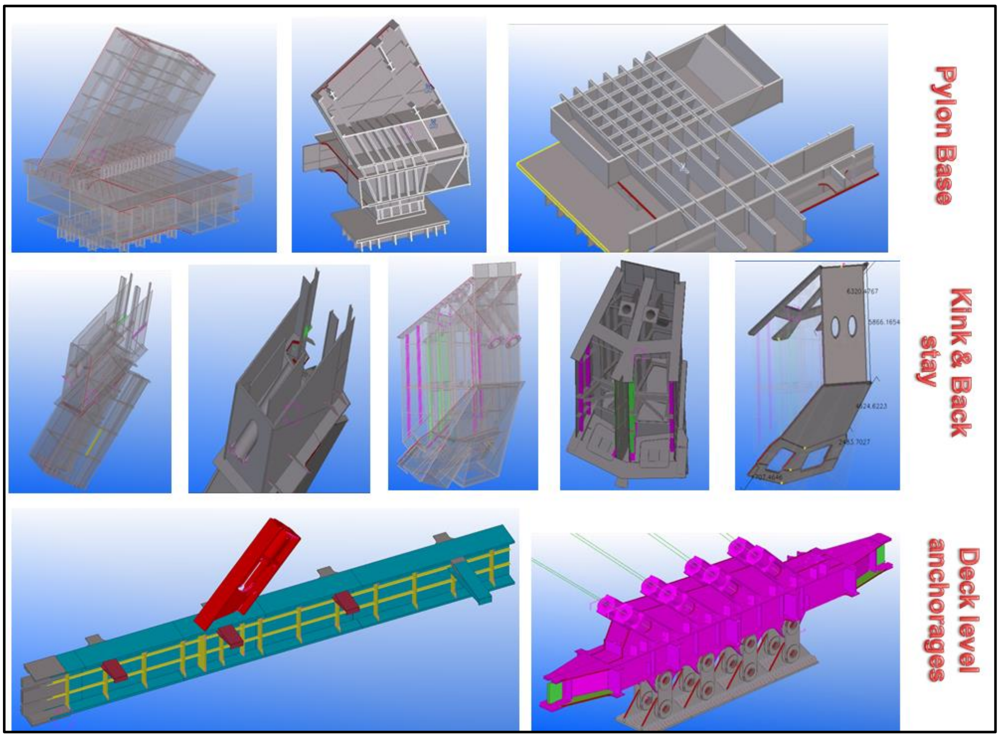

Fig.5.Fabrication complexities deciphered through digital model

Pylon is a 3 dimensional complex structure having inclination in all planes. It is made up of irregular panels welded out of varying steel plates of different grades. To thoroughly understand the complexities of the structure, dimensional weights of the elements to be fabricated, transported and erected, a true to scale digital model (Fig.5) of the bridge was prepared in Tekla (steel detailing software). It incorporates a Building Information Modeling (BIM), enhancing efficiency, accuracy and substantial reduction in wastage of material through proper detailing.

Deck was comparatively easier, but the same was also modelled to understand the integrated parts with pylon, such as tie beam, rocker bearing and anchorages.

As an outcome of the digital model it was understood that, pylon was a complex structure consisting of main panels made up of highly irregular stiffened and plated box sections of varying sizes. As per original design, maximum panel sizes were about 6.5 x 6.5 x 15 m and weighing from 60t to 560t.

A feasibility study (Fig.6) was done, by means of route survey to understand logistics challenges involved in transportation. It was realized that it was almost impossible to transport these oversized and heavyweight segments from fabrication shop to site over Indian road and bridges. To overcome the hurdle of restrictions on transportation, the pylon was divided into sub-panels of transportable size by introducing additional splices. Except for some welded joints at site, all additional splices were introduced as bolted connection.

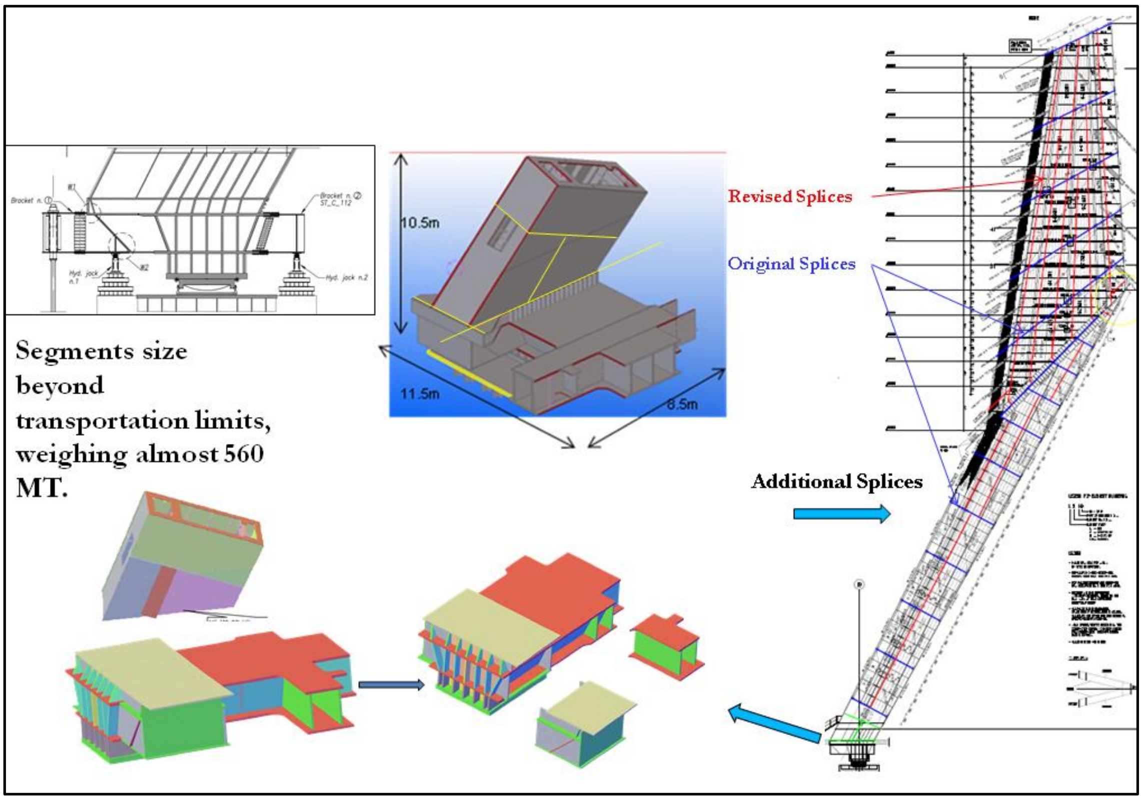

Fig.6.Resplicing to enable fabrication & transportation

It was proposed to fabricate these segments in an established fabrication workshop and then transported over road to site, where they would be reassembled before erection.

b. Panelling, preassembly, machining and trial assembly

With most of the logistical issues resolved on drawing board, fabrication works started with new set of challenges. Pylon and Deck fabrications were the most technically challenging part of the job with required high level of accuracy with stringent specifications due to the uniqueness of the structure.
Some of the major challenges involved in fabrication were,

- Use of plate having thickness ranging from 2.5 to 250mm including Z quality steel (plates above 80mm and special grades not readily available in India)
- Adoption of appropriate welding sequence to avoid deformation
- Preheating up to temperatures in access of 600 degree for thicker plates
- Stress relieving arrangements due to heavy welding
- High precession and tolerance requirement for bolt holes & end milling
- Drilling almost 8,50,000 holes for HSFG bolts ranging from 12 to 36 mm in plates up to 120mm thick.
- Availability of Skilled Manpower
- Requirement of special lifting equipment's during fabrication & trial assembly
- Availability of well-equipped fabrication facility, etc.
- Machining facility to carry out 36m long surface at one go.

Adopting the most appropriate welding procedure was very important to avoid distortions and deformations for welding of pylon segments and deck girders, and to ensure high level of accuracy and quality. Fabrication accuracy would directly affect geometrical dimension of the whole segment after their trial assembly, which were to be precisely matched within 1/10 of mm. Number of NDT testing like Dye penetration test, ultrasonic test, etc. were carried to ensure the desired quality of the product.
Two methods for drilling of holes were specially devised. Pre-drill holes on the web plate of the connection during panel fabrication and post-drilling method was applied for other holes which were marked and drilled with templates after fit-up, welding, rectification and milling of segments.

All the compression joints were designed to transfer load through bearing contact surfaces along with splice connection. To achieve appropriate bearing surfaces, all the contact surfaces in compression like main girder edges, pylon horizontal joints would be machined to have a surface planes not more than 0.3mm per meter. Longest machined surface was as long as 32m for pylon kink.

Following were some typical steps followed in the fabrication process,

- Technical groundwork – preparing fabrication drawings, workout requirement of material, equipment's and support arrangements.
- Procuring and testing of Raw material
- Cutting of material as per approved fabrication drawings.
- Panel welding and NDT testing
- Fit up of an segment and NDT testing
- Initial survey and dimensional check for fit-up segment. Conduct rectifications if required
- Machining end surface of the segment in contact with other surface at splice, which transfers load through bearings.
- Match drilling
- Trial assembly, match drilling and final survey
- Blasting and painting.

The deck structure (Fig.7) is made up of standard segments consisting main longitudinal external girders, anchor boxes and cross girders. The anchor boxes being a load bearing member are welded to main girders by full penetration thick weld. The splicing between the longitudinal girders are through splice plates and HSFG bolts and bearing contact that required high precision machined surfaces.

Trail assembly was performed in line with the sequence of erection at the bridge site. It was ensured that trial assembly jig had enough rigidity to avoid subsidence. Trial assembly for deck was carried out for minimum 5 segments.

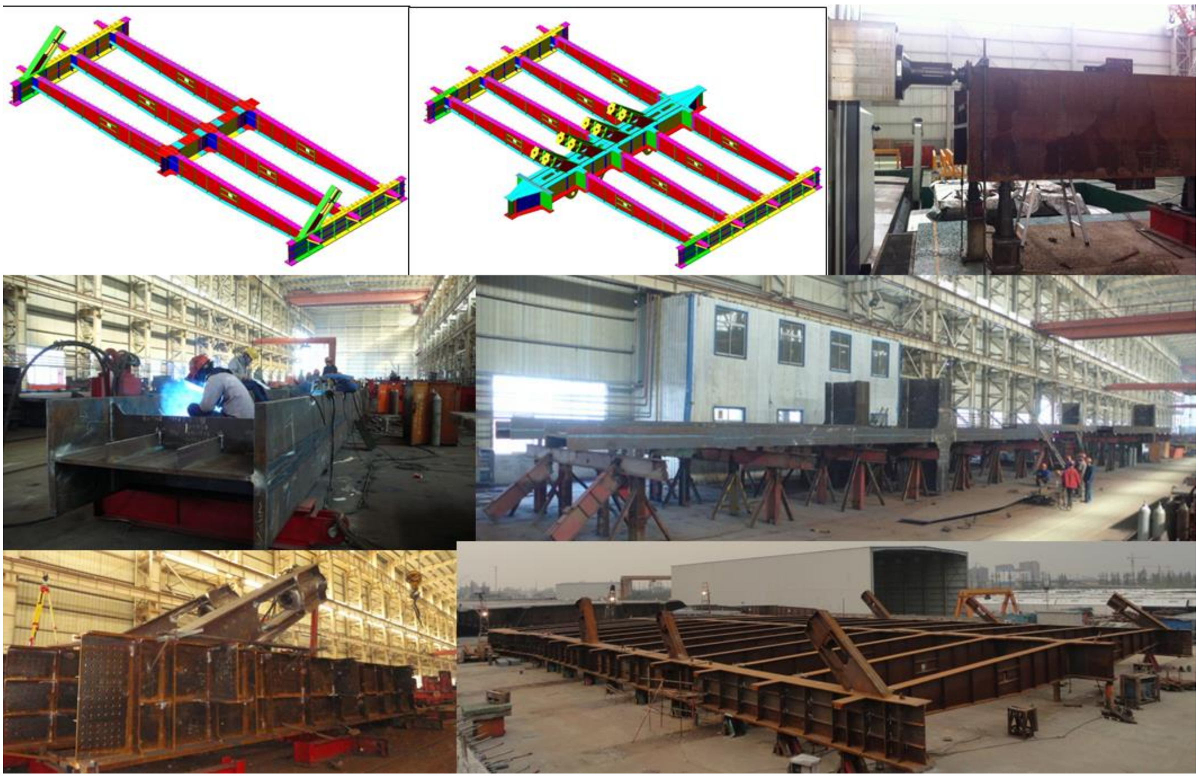

Fig.7 .Deck fabrication, trial assembly and machining

The pylon included four parts (Fig.8): steel leg segments, main body, pylon head segments. Steel leg was divided into 11 large segments L0 to L10, among which L1 to L6 were made up of two small blocks each. Main pylon body was divided into 5 large segments MB1 to MB5, each of which was made up of two small blocks. Front cable pylon was divided into 5 large segments F0-1B to F4-1B while rear cable pylon was divided into 5 large segments B0-1B toB4-1B.

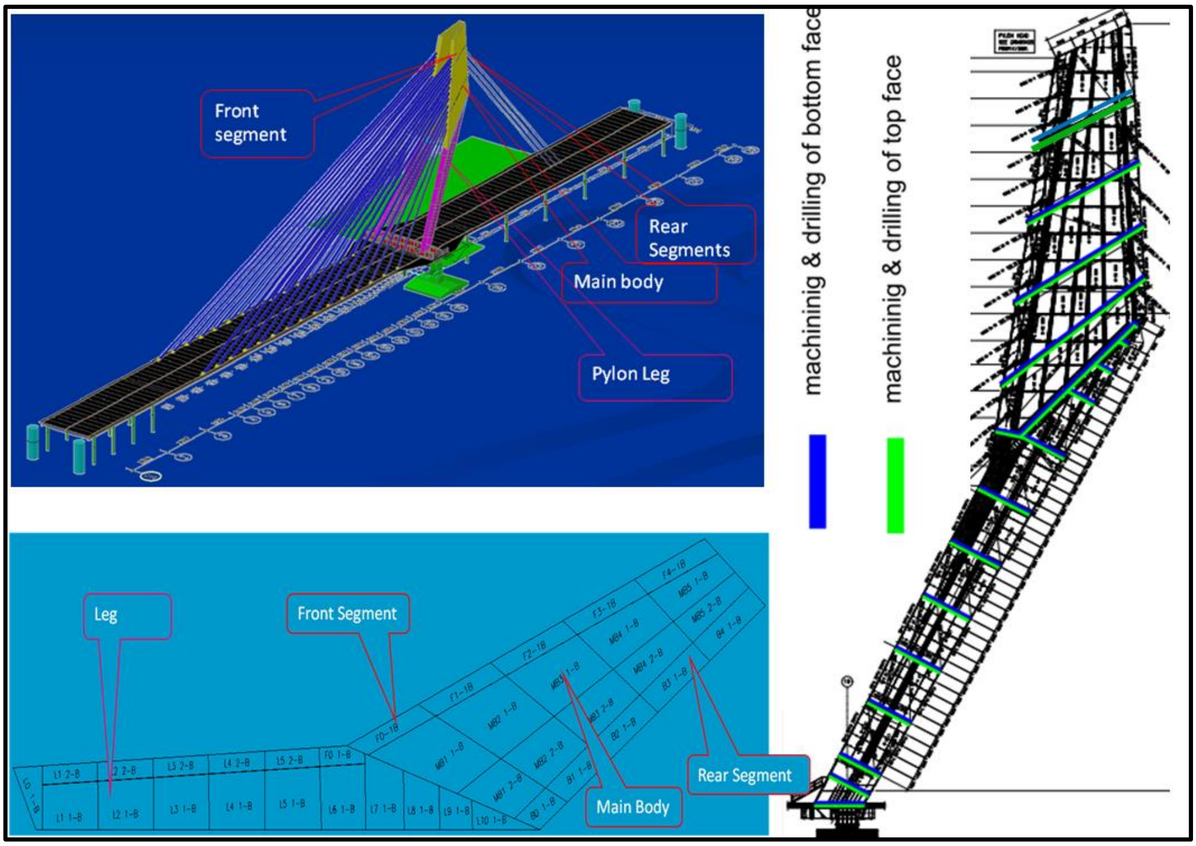

Fig.8 .Components of pylon and machining surfaces

The special attention regarding the following key points were warranted to decide the fabrication, trial assembly and geometric control procedures :

- The accurate geometric dimension of pylon structure with edge considering their complex configuration with heavy welding in volume and the control in welding shrinkage and in the structure deformation during and after welding.
- The quality of thick-plate welding.
- The requirement on the accuracy of bearing contact in end face considering their huge vertical compression of the pylon tower and its shaped alignment.
- The trial assembly was to be carried out to ensure the geometrical alignment. The jig platform should be set in a rigid and accurate way that its features would not affect the accuracy in the trial assembly and final adjustment of sectional segments, consisting of 3D configuration of leg, main body with front and rear cable stay structures.
- Keep the temperature changing in an acceptable range to constantly maintain the precision in fabrication of the pylon
- Due to the huge size of the pylon segment with heavy weight, to avoid any deformation or prevent any damage done to the machined contact surface of the segment and the structure itself, during transportation.
- Geometrical alignment of pylon segment together with the site welding control.
- Control in painting quality.

- Pylon kink segment F01-B, a transition segment to connect steel leg and main body, is a complicated structure with machining of joint surface to be precisely controlled during fabrication.

The fabrication of pylon included base fabrication, leg fabrication, main body fabrication, front body segments fabrication and back body segments fabrication. Fabrication and erection of steel pylon segments were divided into three steps: panelling fabrication, shop assembly and trial assembly, trial assembly on site into large blocks for erection, erection and bolt connection on site.

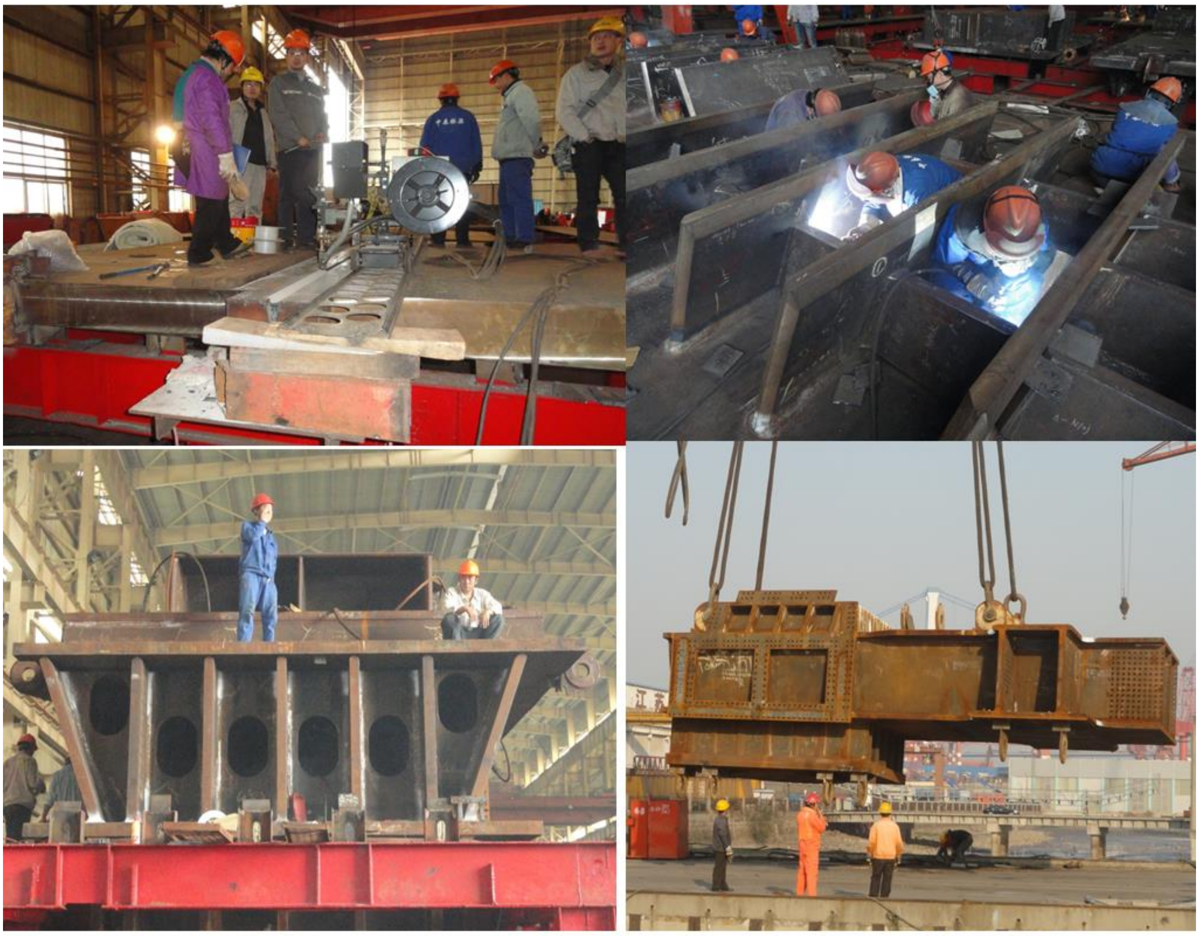

Fig.9.Pylon base fabrication

Pylon base segment (Fig.9) was fitted up and welded from bottom to top, symmetrically from middle toward outside on the jig. Ordinary fit-up method (fabricate as per the as-built drawings) and reversed fit-up method (fabricate upside down) was adopted for the fabrication of pylon base segment.

The structural configuration of the stiffeners and the varying thickness of the plates from 80mm to 250 mm was so much painstaking for fabrication that could only have been executed to the final precision by Chinese fabricators without much fuss.

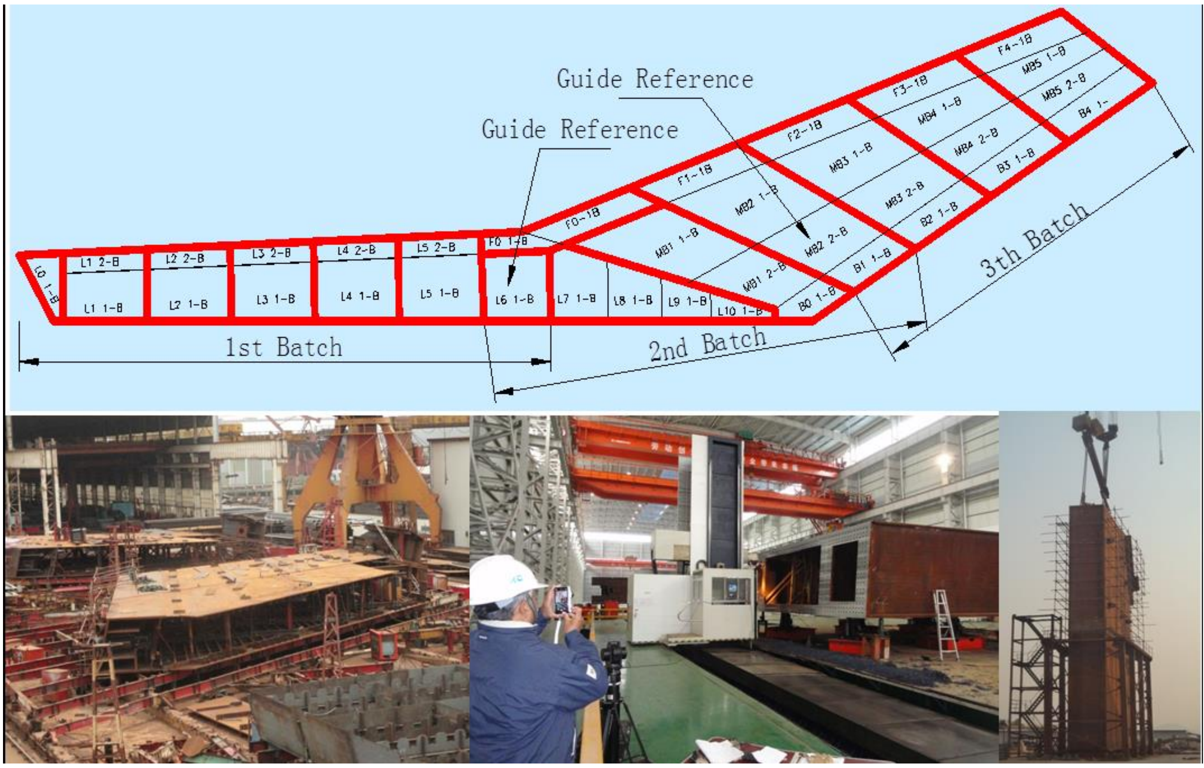

Fig.10.Above: Preassembly in batches, Below: Pylon legs fabrication, machining & trial assembly

For the pylon leg and main body components, the segment fit-up and shop assembly was carried out with 3 batches (Fig.10). The last section from the previous preassembly was included in the next preassembly as a starting guide reference to guarantee continuous linear shape of adjacent segments.

Fig.11.Fabrication, machining and trial assembly of pylon kink and L6 –L10 and M0, M1and M2, and pylon head

For the steel leg components, after completion of paneling fabrication, a longitudinal assembly line on the ground as reference datum was set and marked. Inside panel was taken as base plane, and its axis was matched with the reference datum marked on the ground. Then all the related weld panels and outside panels were continuously matched, welded and preassembled to complete all the leg segments.

Assembly for both left and right leg segments were carried out simultaneously at the same time. After all segments in the batch for the preassembly were accepted, were taken off the jig and sent for machining with appropriate identification marking.

The kink segment (Fig.11) was the most important part in fabrication. After having finished the fabrication of panel units and truss structure of the segments, the fit up of the segment was done on the jig as per the designed mark on the ground. The outside plate was to be designed as the base surface and the fabrication was carried out by the side way. The fit up, welding and shop assembly of the kink was done at the same time. After acceptance of the assembly, the temporary splicing plates was fit up and the kink segment was marked, taken off from jig and sent to machining area.

Steel leg segments of L101-B, L91-B, L81-B, L71-B was included in the second batch preassembly (Fit up and welding of the connection parts of leg and main body). L6 1-B and FO 1-B segments which included in the first batch, had to be included in the second batch as the starting guide reference to guarantee continuous linear shape of leg segments and main body. Fit-up, welding and preassembly procedures for pylon main body segment is almost the same with those for the transition segment.

Preassembly jig was specially designed according to the profile of the pylon and had to be capable of adjustments in three directions: movable in longitudinal direction when compression is put on the segments along the axial direction, movable up and down and in the transverse direction when splicing, alignment and adjusting the axis. Preassembly was performed when the ambient temperature was stable and temperature change of components was not very high under the constant monitoring of surface temperature within the control environment.

Over all there were 32 surfaces in the pylon at 16 locations including bottom and top face where machining requirements were there. The maximum length of the milling to be done at one go at the kink location was around 32m. One of the conditions for subcontracting fabrication was that the contractor had to have milling and drilling equipment capable of doing machining for 36m length at a go as such subcontractor procured the equipment from Spain, especially for Signature Bridge project.

Steel pylon segments were transported to the machining workshop to equalize the temperature 12 hours before commencement of machining. Temporary diaphragms were needed to be installed on the opening of the and before machining in order to avoid vibration of the head plates caused by machining.

The trial assembly was carried to check out precise matching with segments not less than 4 segments. The last segment from the previous trial reassembly was to be included in the next trial assembly as a starting guide reference to guarantee continuous linear shape of adjacent segments. The purpose was to inspect the surface contact rate of head plates between segment after machining, the bolt hole through rate, deviation of axis among segments and check the feasibility of machining procedures and preciseness of machining.

The steel leg segments, transition segments connecting legs to main body warranted dedicated assembling jig.

Surveying and measuring of geometric dimension and alignment of pylon segments were performed. The deviation of alignment collected was compensated during the machining of the next segment.

c. Engineering for erection

Cable stayed bridges are usually symmetrical in nature and traditionally built by cantilever construction. An unsymmetrical cable stayed bridge like Signature Bridge with an inclined pylon, supported on bearings, is a highly unstable structure during erection. This demanded for an innovative method of erection with a well-coordinated and calculated step by step erection procedure.

The pylon is composed of two legs, box girders, inclined backwards and inwards and connected at a level of +63 m by a main body that is a vertical shaft with variable cross section, which hosts the top anchorages for the stay cables. The legs have a rectangular box girder with a constant width of 2.50 m and height varying from 7.20 to 9.60 m. The Main Body, still a box girder, has a maximum width at its base of 20m and a minimum width at the top of 13 m. The two legs are hinged at the base so they would be unstable during erection, unless some sort of device was provided. The pylon was divided into segments with weights varying from 40 to 250 t. The joints between segments were flanged bolted joints with machined flanges. The connection between the Main Body and Legs is created using flanged joints, machined at the workshop, with a total length of 32m.

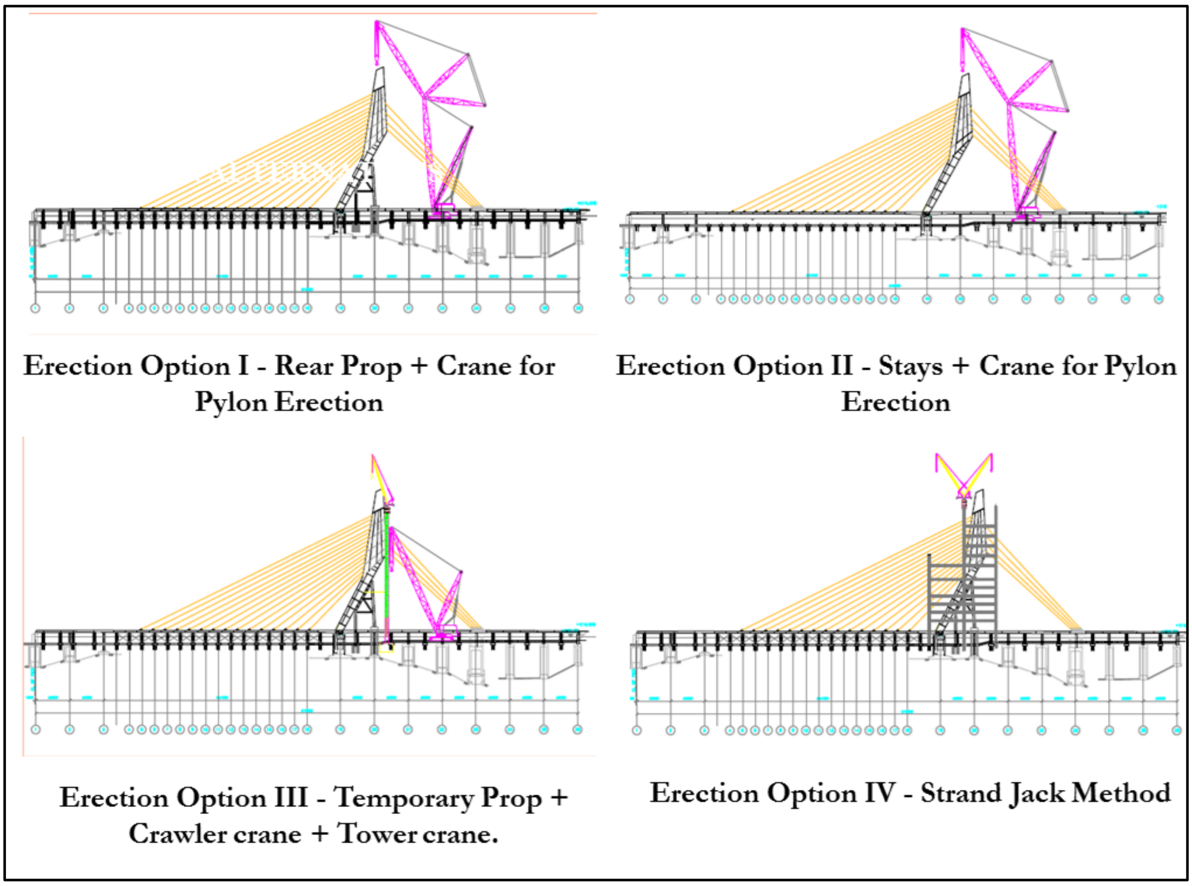

Fig.12. Various erection options studied for pylon erection

The main design problems to be solved in order to erect the pylon were essentially:

- How to stabilize an inclined structure hinged at its base during construction;

- How to recover structure deformation during erection;
- How to install large, heavy box girder segments that had to be placed, one above the other, in a position with double inclination;
- How to manage the temperature effect, together with the tight tolerance of a bolted structure.

Fig.13. Temporary supports for erection & Deck erection by Goliath gantry & crane

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 (Fig.12), it was finally proposed to erect Pylon using a 1,250t capacity crawler crane, while the pylon would be supported with a specially designed temporary strut, until the system is stable after installation of permanent cables. Segments weighting more than 40t to 250 t were required to be erected.

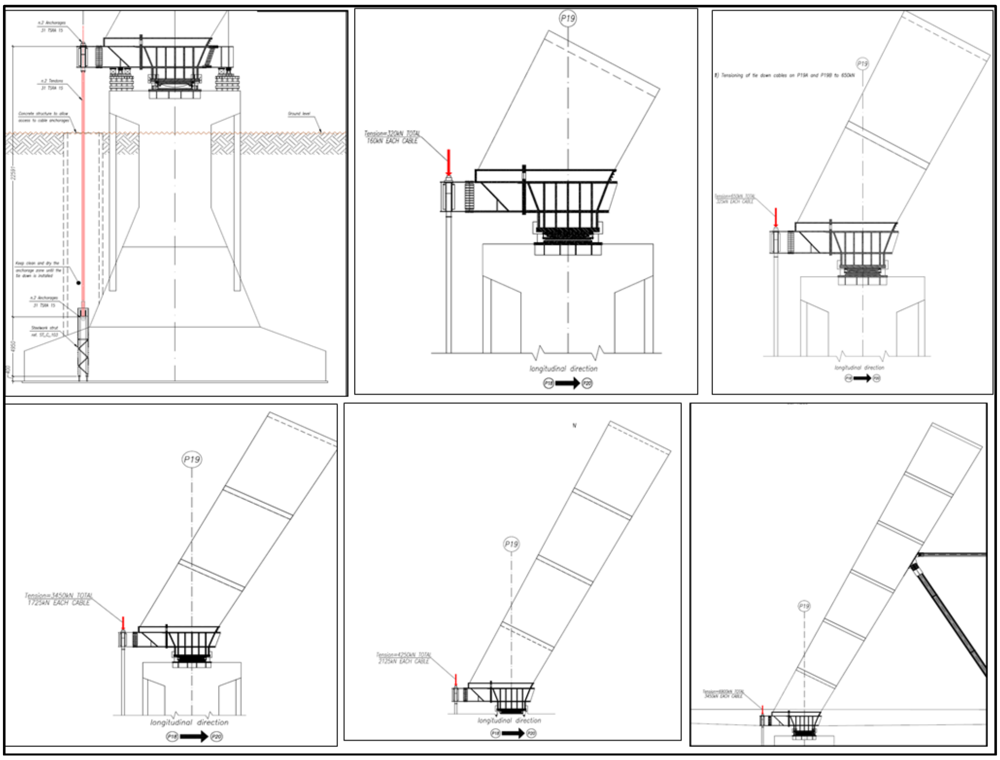

Fig.14. Tie down arrangement for initial stability of pylon during erection

Based on the methodology proposed for erection and construction stage analysis, temporary prop arrangement (Fig.13) is designed to support the pylon. These props are 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 arrangement was installed at the base of the pylon to stabilize the initial phase of pylon erection (Fig.14). During the construction of independent foundations P19 on both axes, the tie down shafts was constructed to accommodate 31T15 cables. These RCC shafts of size of 4.4m by 2.275 m were water proofed and constructed up to ground level. The anchorages were load tested before commissioning the strands for the load of 800 t. specially designed brackets were connected to pylon base. Once the L0 segments were erected, the tie down system was stressed by 32t on both the axes. As the pylon segments were erected up to L5, the loads were incrementally given to anchorages as per the design sequence. Finally when L5 was erected, the each side of the tie down system was induced with the prestressing force of 690 t. After the erection of L7 segment and installation of back supports, the tie down system was de tensioned.

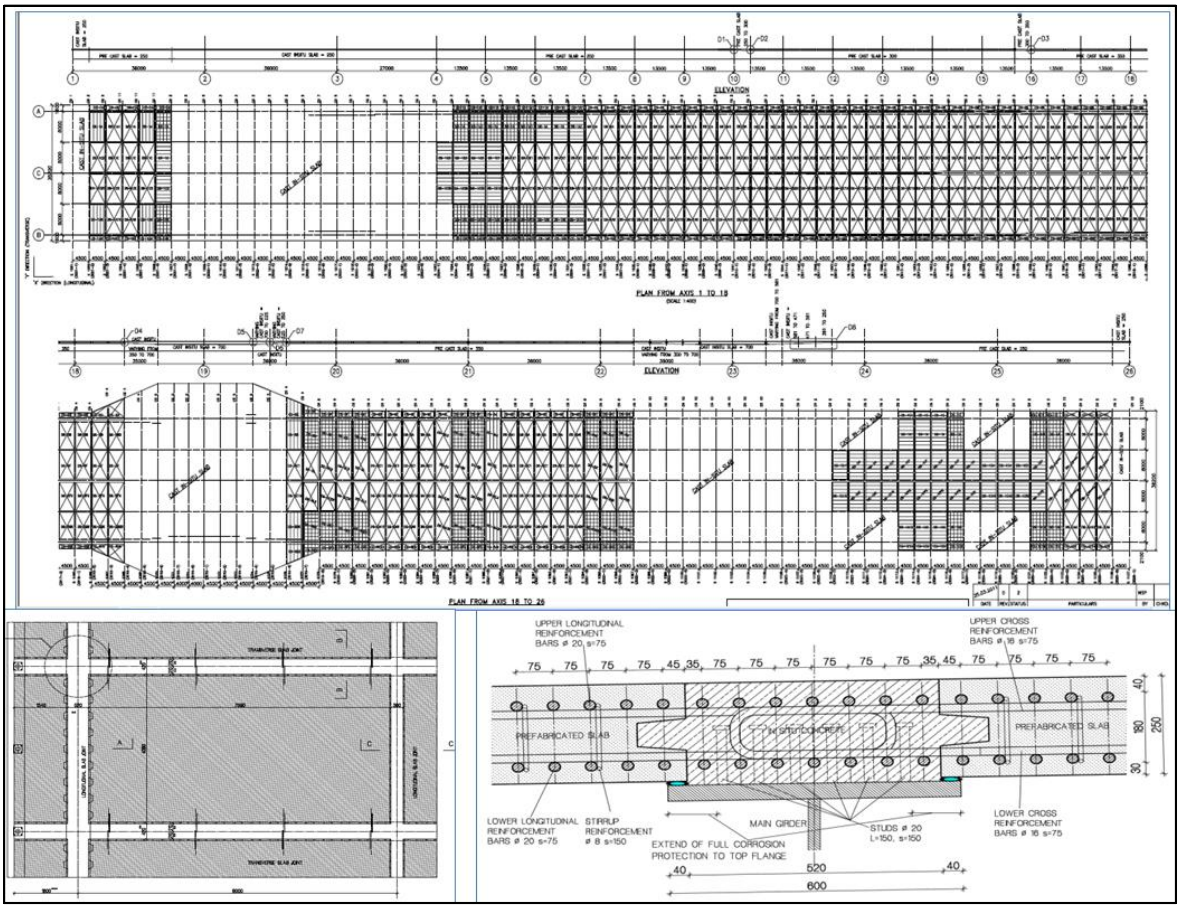

Fig.15 Composite deck configuration

Deck girders were supported over temporary trestle and erected using a Goliath gantry running over the same trestles along the bridge. Pre-cast deck panels are erected over girders using same Goliath gantry for deck erection (Fig.13) towards the river side while girders and precast panels were erected on land side with crane.

Fig.16. Fabrication of precast panels at Casting yard

The majority of the deck concrete was in precast panels(Fig.15) 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 and backstay anchor) where slab thickness was varying from 250mm up to 700mm with 7 layers of reinforcement.

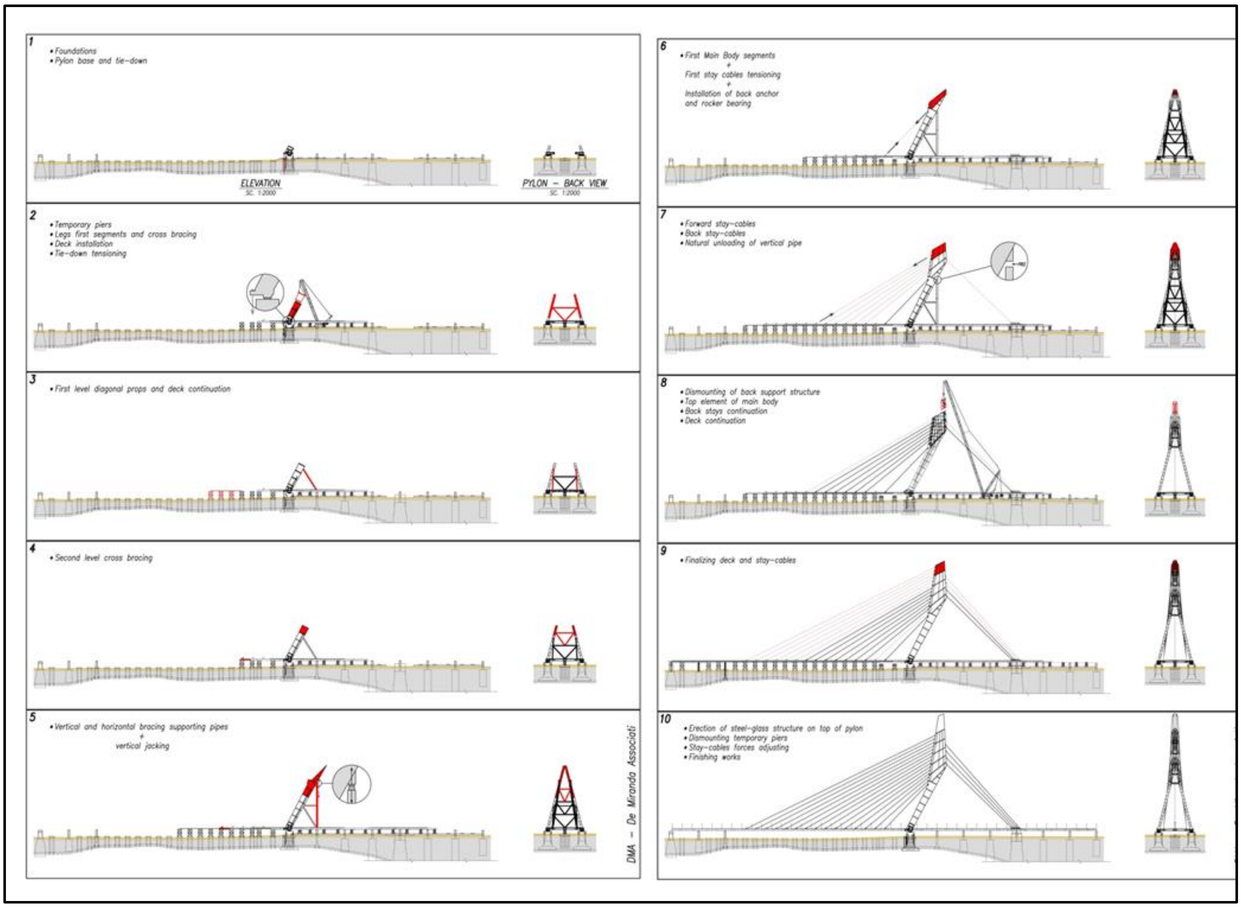

Fig.17 .Stage by stage construction stage analysis

Overall, there were 528 precast panels of 4 types, generally having plan dimension of 7.5m X 4.0m with 250mm thickness. These were cast at casting yard (Fig.16) equipped with 10 casting machines anda bed gantry of capacity to handle precast panels of around 20 t.

A detailed stage-by-stage analysis (Fig.17) was done to determine stress distributions in the structure for all intermediate stages and to perform structural adequacy checks for erection stage. Sufficient strengthening of permanent structure was done wherever required.

Fig.18 .Specially designed turn table for rigging 3 dimensionally varying pylon segments

Sufficient strengthening of ground for movement of heavy equipment was also provided. Specially designed tilting and lifting frame was designed and developed suitable for erection of segments with varying shapes and sizes to optimise permanent works design and minimise additional temporary works required during the construction stage.

The correct positioning, with double inclination, of pylon segments was achieved by a specially designed turn table (Fig.18):

- After assembling the Segments horizontally, they were shifted to a special jig made of three layers.
- Then the bottom frame was tilted longitudinally in order to get the proper longitudinal inclination.
- The top frame was then tilted transversally in order to achieve the proper transversal inclination before being propped;
- Lifting lugs were installed on the segments using the flange joint holes.
- Slings of proportionate length were finally installed.
- The position of the lifting lugs and the length of the slings were designed so that upon lifting the lifting hook would be positioned on a vertical axis passing through the Centre of Gravity of segment

In this manner the segment would travel from take-off to landing on the preceding segment, always in the same three dimensional positions, which is the 3D final position. A set of centring devices helped the final positioning.

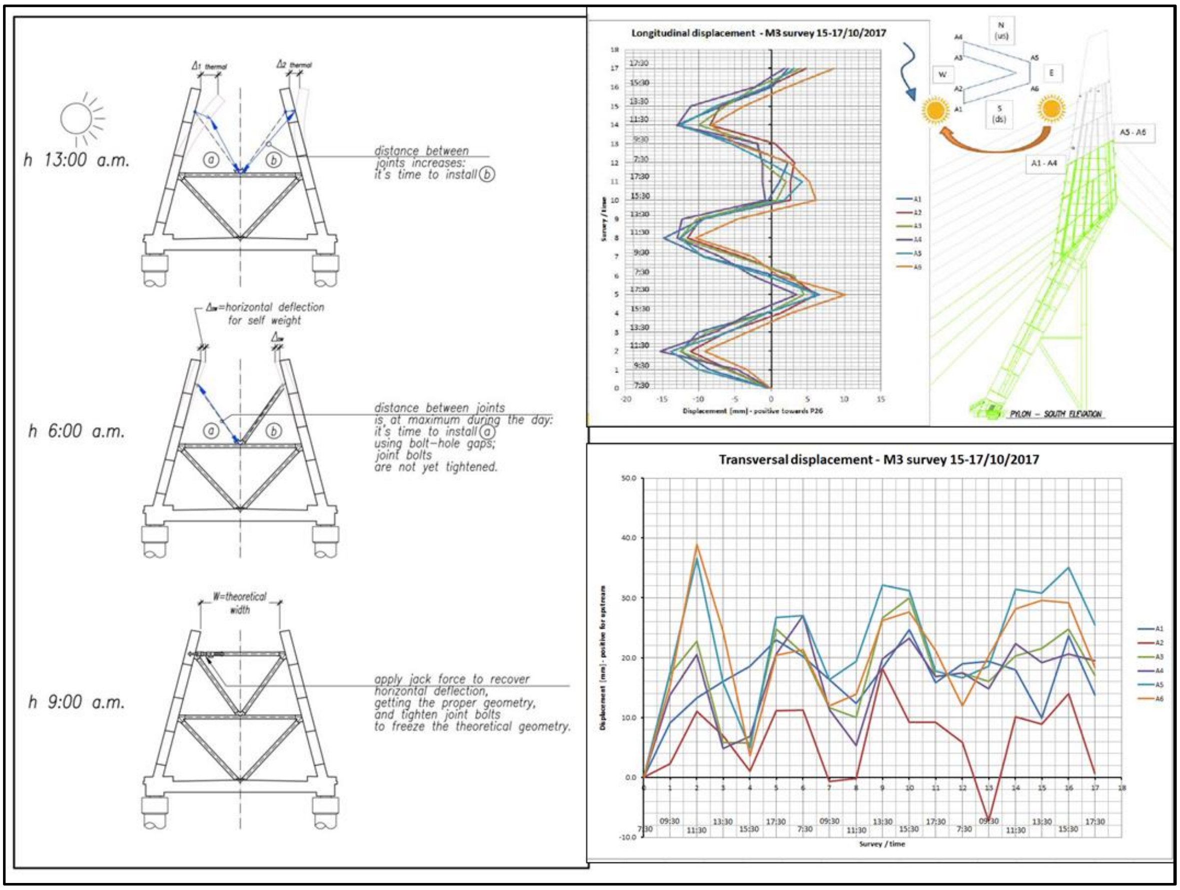

Fig.19 .Pylon movement due to environmental effect before and after merging of pylon legs

A careful monitoring of the geometry throughout construction would be required to ensure that the structure behaved as predicted and the target geometry was met. Since many of the quantities involved in the construction are only approximate values (exact elements dimensions and weight) or can be measured with a given tolerance (stay cable lengths and forces) and environmental conditions change during construction, and the calculation model itself is only an approximation of the real structure, a continuous monitoring of structural deformation during the construction is of fundamental importance. For this reason, structural geometry was checked by DMA at every element installation and a daily survey procedure started at the beginning of stay cable stressing.

Temperature (Fig.19) changes, mainly during the day due to direct sunlight, modified the real/actual geometry of the structure, continuously changing the position of working points making it almost impossible to install the pipe elements in their theoretical position. Structural movement over time, detecting the hours in which the joint distance was larger than theoretical was monitored, and these hours for installing the elements were set, fixing them only at one end and leaving the other sliding. Then, during the hours in which that distance tended to close, the other end bolts were installed and tightened only at the time in which the theoretical geometry was achieved.

Survey data were collected and examined for all the relevant erection stages, based on survey points which were marked during trial assembly. Initially especially after pylon legs merged in to pylon body daily survey of a new series of pylon and deck points started, with the aim of identifying also the movements independent from installation of new elements and cable stressing and separate environmental actions effects (temperature, sun irradiation, wind) from construction effects. A sample of results from a 3 day survey (every 2 hours) is depicted in the Fig.19

Fig.20 Cable installation, tensioning and Pylon access system during construction

While monitoring the effects of construction loadings, element loadings and cable stressing on deformation of pylon & decks, the following correction factors of the environmental effects had to be applied. The Pylon position changed rapidly during the day, with movements around 20mm in longitudinal and vertical direction and up to 40mm in transverse direction. Displacements followed the same trend during the day. Apart from survey tolerances (total station and operator), movements due to temperature, sun exposure, wind, vibrations, could also influence final acquired points coordinates. Survey data collected at different time during the day (also one or two hours) could also lead to apparent inconsistencies.

Stay cable system consisted of 19 pairs of cables with varying number of strands minimum being 55 to maximum of 127 of 15.70 mm dia. with GUTS of 1770Mpa. The reference lengths of the cables (deck bearing plate to pylon bearing plate distance) varied from 85m to 285m.

The passive anchors being at deck location, the active anchors from where stressing was to be done was at the location of pylon main body. Stay cable strand preparation consisted of pulling out the strands from coil drum, laying on the bench, un-coating, cutting and marking for identification. After having installed anchorage boxes with bearing plates at pylon top and deck levels, the welded HDPE ducts and form tubes were hoisted on the threaded initial strands.

Strands in the cables were tensioned (Fig.20) using iso-elongation method. This method utilises mono strand jack attached with a load cell, hydraulic pump, dynamometer for calibration of pump-jack system. For each stressing phase, the strands was first stressed up to the 80% of the stressing force

Each strand was stressed up to the elongation needed considering the elastic elongation of the steel strands and movement of pylon and deck during the stressing operations.

A topografic survey of the bridge during each stressing phase was provided. After reaching the 80% of the stressing force in each phase, new elongation to be applied to the strands had to be provided considering the actual load registered and the data collected from the topographic survey. After accounting for the new elongation provided, all the strands were stressed up to 100% of the stressing force.

As all the cables were fitted with load cells, after stressing of each cables, the changes in the stresses in the cables and the movements in the pylon, deck & catenary of cables were compared with theorical loads and movements for any corrections to be applied.

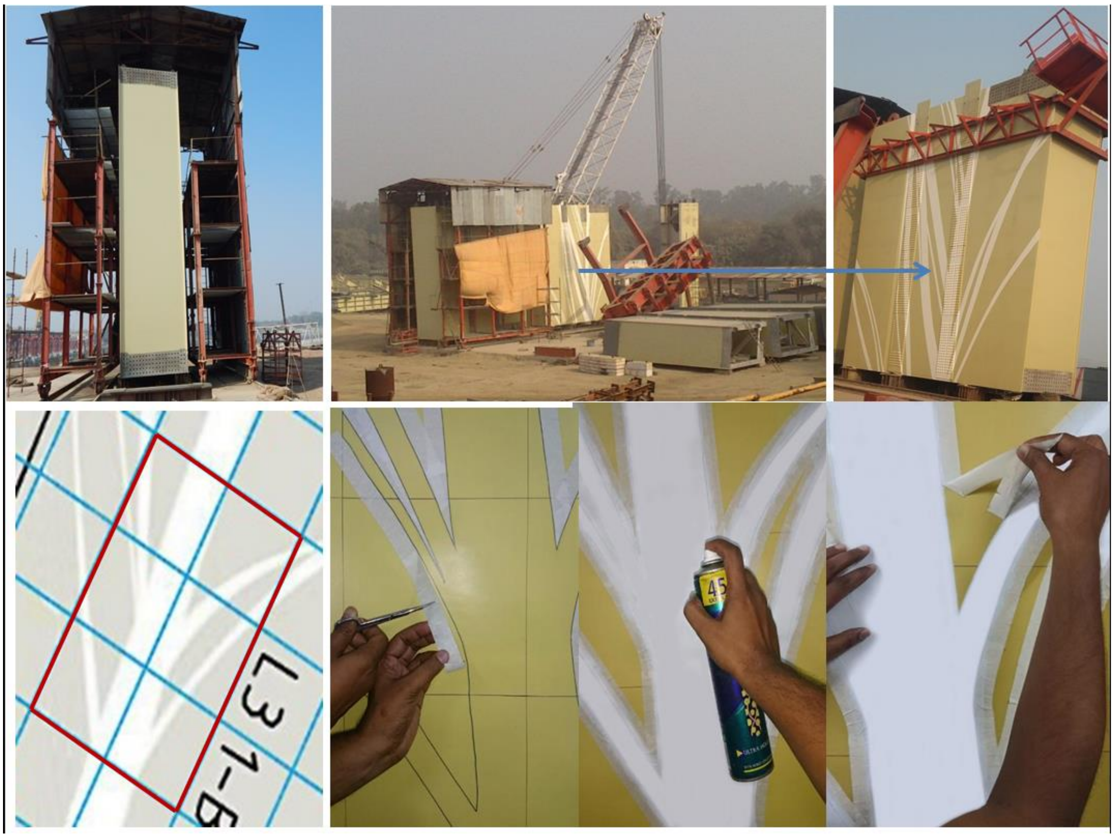

Fig.21.Graphics on pylon during construction

As the pylon grew in stature, the access (Fig.20) to the working locations of HSFG bolting, pre-tensioning, shifting of jacks and other accessories had to be enabled by specially designed platforms, cage ladders and passenger hoist equipped tower crane. The connection between growing pylon and tower crane was engineered in such a way that there is no unscheduled horizontal force either on pylon or on tower crane.

The grid method was used to create peacock feather on the pylon. In this method drawing process starts once the final coating of base colour i.e; green Beige has been applied on the pylon segments inside a specially designed shed (Fig.21). Grid is marked 1000 mm apart all over the surface. In areas comprising intricate design smaller grid is marked on the existing grid to increase the accuracy. Drawing is marked grid by grid on the whole face of the segment.

Proper measurement is kept for reference of adjoining parts of next segment up to a millimetre's perfection. Once the drawing is marked the negative areas are masked (with 3M masking tape) before painting to avoid over-painting or leakage and dripping of paint. After completion of open space painting process and once paint is thoroughly dried, masking tapes are removed and the bi-colour graphics come out. A transparent protective layer is applied if paint specification recommends so.

Fig.22 Pylon growing in stature

At the time of writing this paper, 95% (Fig.22) of the project is completed and the balance comprising the erection of M5 level main body of pylon, glass façade of the pylon head and 4 pairs of cable installation & tensioning is expected to be completed by September 2018.

v. Conclusions

This new symbol of Delhi upon completion is expected to set a standard for iconic stature for bridges in India. Bridge construction is always complex and challenging task. While designing the permanent structure of the bridge like Signature Bridge has its complexities, the construction engineering involving huge sizes, three dimensionally varying inclined tall structure and enormous weights to be lifted compounds the complexities.

This warrants a detailed and holistic study of construction methods, rigging plans and fabrication of structure to suit construction methods along with constantly checking the structural behaviour. As the segmental construction of three dimensionally varying pylons being attempted first time and being not time tested, there were many unforeseen issues which could be overcome by only proper Construction Engineering. While the completed structure is there physically standing tall to be appreciated in the years to come and gets many accolades for its design, the construction engineering which is very complex for a structure like this including, full scale digital model (Tekla) prepared by contractor, plants, enabling structures like milling machine capable of 36 m long surface at once, RCD rigs for hybrid foundations, Sarene crane which has the capacity of 1250t and the specially designed turn table to enable rigging of three dimensionally varying pylon segments, will remain un sung heroes (Fig.23).

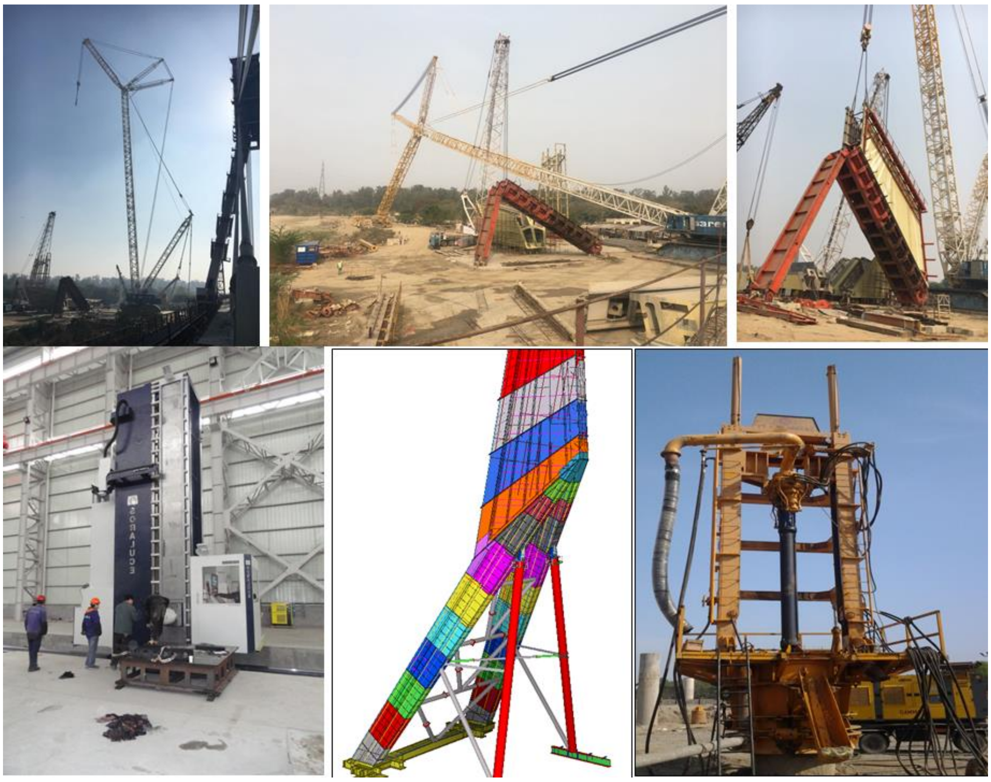

Fig.23 Unsung heroes of the project

The nature of the contract necessitated domain experts from 10 countries with diverse backgrounds, cultures as such demanded very savvy & innovative managerial skills in terms of co-ordination and contract administration that perhaps are not taught in the best of management schools.

Acknowledgements

- Owner: DTTDC - Delhi Tourism and Transportation Development Corporation
- Designer for Owner: SBP - Berlin with Construma – Mumbai.
- Contractor: Gammon - Construtora Cidade, Brazil - Tensacciai, Italy.
- Sub-contractor to JV for fabrication-ZTSS, China
- Consultant for Contractor and Construction Engineering: DMA - Studio de Miranda Associati - Milan - Italy

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